Vol. 8 No. 2 JUNE 2014

FOR THE METAL, CERAMIC AND CARBIDE INJECTION MOULDING INDUSTRIES

POWDER INJECTION MOULDING INTERNATIONAL

in this issue

Company profile: ARCMIM

Quality control in MIM

Materials focus: Titanium, Aluminium

Published by Inovar Communications Ltd

www.pim-international.com

Publisher & editorial offices

Inovar Communications Ltd
2 The Rural Enterprise Centre
Battlefield Enterprise Park
Shrewsbury SY1 3FE, United Kingdom
Tel: +44 (0)1743 454990 Fax: +44 (0)1743 469909
Email: info@inovar-communications.com
Web: www.pim-international.com

Managing Director and Editor
Nick Williams
Tel: +44 (0)1743 454991
Email: nick@inovar-communications.com

Publishing Director
Paul Whittaker
Tel: +44 (0)1743 454992
Email: paul@inovar-communications.com

Advertising

Jon Craxford, Advertising Director
Tel: +44 (0) 207 1939 749
Fax: +44 (0) 1743 469 909
E-mail: jon@inovar-communications.com

Subscriptions
Powder Injection Moulding International is published on a quarterly basis as either a free digital publication or via a paid print subscription. The annual print subscription charge for four issues is £135.00 including shipping. Rates in € and US$ are available on application.

Design and production
Inovar Communications Ltd

Printed by
Cambrian Printers, Aberystwyth, United Kingdom

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

Vol. 8. No. 2 June 2014

POWDER INJECTION MOULDING INTERNATIONAL

For the metal, ceramic and carbide injection moulding industries

MIM as part of a wider technology mix

There is a trend emerging in which producers of precision metal components are looking to multiple technologies in order to secure business by being able to offer the most effective process for a given component. MIM is increasingly being seen as one such technology that can be added to an existing component production business and Dynacast's incorporation of MIM to its die-casting business last year, for example, has recently been followed by low volume production specialist Proto Lab's investment in MIM this year.

What is also clear is that MIM producers are starting to look at alternative production technologies in order to offer their customers a more comprehensive service and secure their business, particularly if an order may not be ideally suited to MIM because of initial low order volumes. In the case of one of the world's largest MIM producers, ARCMIM, Additive Manufacturing (AM) is a technology that not only offers the capability to quickly provide existing customers with fully functioning prototypes, but also low volume series production of components (page 47).

Where MIM excels is in the high volume production of components with exceptional part-to-part consistency. Advances in process technologies and materials in recent decades, combined with the demanding quality standards set by the automotive and aerospace industries in particular, have driven MIM producers to achieve extremely low rejection rates. In an effort to further improve part quality and consistency Prof Dr Frank Petzoldt reviews the whole production process and outlines strategies that can lead to further improvements (page 37).

In this issue we also present two reports on the latest advances in MIM titanium, one from US MIM producer Praxis Technology (page 59), where process innovations are taking Ti-MIM a step closer to implantable orthopaedic applications and one on the latest Ti-MIM research from the PM Titanium 2013 conference in New Zealand (page 67).

Nick Williams
Managing Director and Editor

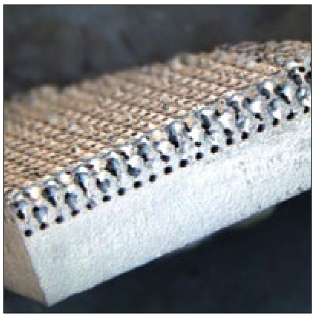
Cover image
Sintering furnace at AFT Hungary

June 2014

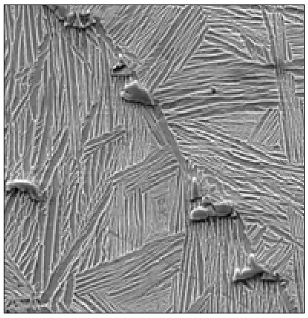
Powder Injection Moulding International

15

48



63



69

76

In this issue

37 Managing quality in the complete MIM process chain

Throughout the MIM process chain, from powder to finished parts, there are a number of areas where it is possible for small changes to directly influence manufacturing tolerances and material properties. Prof Dr Ing Frank Petzoldt reviews the influence of powder, feedstock, injection moulding, debinding and sintering as well as supporting technologies.

47 ARC Group Worldwide, Inc.: A global leader in MIM embraces the Additive Manufacturing revolution

In 2012 a new global force in MIM was created when ARC Group Worldwide, Inc. acquired Advanced Forming Technology and FloMet to create one of the world's largest MIM businesses. ARC has since moved to improve the efficiency and competitiveness of its MIM business, as well as enhancing its customer offering by embracing Additive Manufacturing. *PIM International* profiles the business and outlines the strategic vision behind the developments at ARC.

56 Is MIM just too good? High part-to-part consistency challenges forensic firearms examiners

A keynote presentation at the MIM 2014 conference revealed how MIM's excellent part to part consistency is posing new challenges for forensic firearms examiners. Detective Darin Marcinkiewicz's presentation explored the science of firearm forensics and explained how the manufacture of firing pins by the MIM process has impacted on the effectiveness of forensic examinations.

59 Praxis Technology: Enhancements to Ti-MIM processing bring medical implants a step closer

Praxis Technology's Joe Grohowski and Jobe Piemme present the capability and performance of the company's Ti-MIM process in relation to ASTM F2885, as well as additional technologies that have been developed to enhance Ti-MIM's applicability to the orthopaedic market and other markets demanding high fatigue performance.

67 MIM of titanium and titanium hydride at PM Titanium 2013

The second International Titanium Powder Processing, Consolidation and Metallurgy Conference, New Zealand, December 2-4 2013, attracted over 80 participants from around the world to discuss the latest advances in titanium PM. Prof Ma Qian reports on selected MIM highlights from the technical programme.

75 Aluminium MIM: New advanced powders and feedstocks achieve higher densities

Whist conventional PM aluminium parts are today processed in high volumes for established end-user industries, aluminium has not yet become established as an accepted material for MIM. US Metal Powders, Inc. reports on the testing of a new commercially available MIM feedstock based on a specially developed fine inert gas atomised aluminium powder.

Regular features

4 Industry news

80 Events guide, Advertisers' index

Industry News

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

Dynacast launches MIM production in Singapore and Chicago

Dynacast International, a leading global custom die caster of small size precision components with its headquarters in Charlotte, North Carolina, USA, announced its entry into the Metal Injection Moulding field in February last year using a new variant on the MIM process which is said to increase productivity whilst reducing variations and costs.

The company now reports that its two new MIM operations in Singapore and Chicago have been fully launched having a capacity for around $25 million of annual MIM revenue. According to Adrian Murphy, Executive Vice President and Chief Finance Officer, Dynacast made a capital investment of $6.6 million in establishing the MIM plants and whilst sales in 2013 were negligible, 2014 is seen as very positive with a number of MIM components already in production. The strong quote pipeline will bring in additional sales and opportunities, stated Murphy, and revenues of between $3 million and $5 million are expected in 2014.

Dynacast International's result for the year ended December 31, 2013 showed net sales of $580.0 million, a $60.6 million, or 11.7%, increase from the previous year.

Dynacast uses a new variant on the MIM process which is said to eliminate injection moulding equipment and conventional tooling. The company modified its proprietary A2 die-casting machine to make it compatible with MIM feedstocks. In addition to the A2 machine itself, the new MIM platform makes use of the company's multi-slide tooling. This tooling technology 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. The debinding and sintering steps used at Dynacast are the same as for conventional MIM processing. The parts shrink at the same rate as other MIM parts and have a final density that typically exceeds 98%.

www.dynacastmim.com

Centorr Vacuum Industries MIM-Vac furnaces at Dynacast's Singapore MIM operation

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.

Sumitomo Metal Mining sells MIM operation to Nippon Piston Ring

Two of Japan's leading MIM producers, Sumitomo Metal Mining Ltd (SMM) and Nippon Piston Ring Ltd (NPR), recently signed an agreement for NPR to acquire SMM's MIM operation based in Sagami, Yamato City. The transfer of SMM's MIM operation to NPR will formally take effect on May 31, 2014, with the full transfer of MIM production to NPR expected to be completed no later than September 30, 2015.

SMM's Materials Division began its Metamold MIM operation in the late 1980s with a number of significant successes for MIM parts produced for the automotive, industrial machinery and lock sectors. However, unlike its core business of Mineral Resources or Smelting & Refining, the Materials business is characterised by short product cycles and dramatic fluctuations, and under its current three year business plan SMM decided on structural reforms and to focus on its core competencies. The company had total group sales of Yen 808,540 million ($7.885 billion) in its financial year ending March 31, 2013.

NPR for its part is focused on the manufacture of components for the automotive sector including some MIM components used in engines such as rocker arms. The company decided to acquire the MIM business from SMM in a quest to expand its product portfolio for MIM parts in non-automotive applications. During the year ended March of 2013, group sales at Nippon Piston Ring Co Ltd were ¥47.02 billion (US$459.84 million).

www.smm.co.jp | www.npr.co.jp

Fig. 1 Nippon Piston Ring's development of rocker arm parts represents an early success in the Japanese MIM industries efforts to penetrate the automotive sector

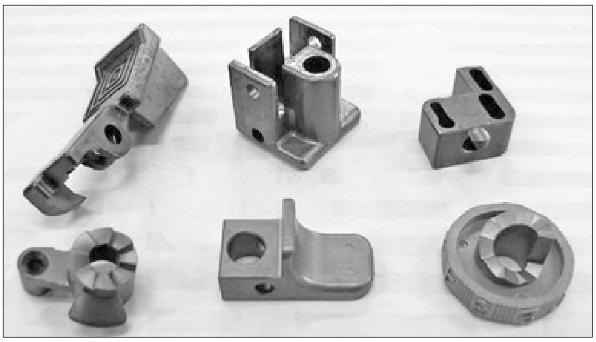


Fig. 2 Low alloy steel power tool parts manufactured by Sumitomo Metal Mining (Fe-Ni-C, Fe-Cr-C)

Schunk welcomes new member of the Executive Board

Dr Jan Gupta joins Germany's Schunk Group as a new member of the Executive Board from April 1, 2014. He will succeed Dr Heinz-Joachim Mäurer and will be responsible for the Materials Division which manufactures components from carbon, graphite, carbon fibre-reinforced carbon (C/C), silicon carbide, aluminium oxide and quartz. After 35 years with the company, seven of which as a member of the Executive Board, Dr Mäurer will retire at the end of the year. In recent years, Dr Gupta has held various managerial roles with a global manufacturer of sealing technology, nonwoven materials, household products and specialty chemicals. Most recently, he had overall responsibility for the global division of dynamic seals.

www.schunk-group.com

Metal Injection Moulding shows continuing high growth in North America

A report by Peter K Johnson published in the *International Journal of Powder Metallurgy* (No.1, 2014), states that shipments of metal powders for the Metal Injection Moulding (MIM) sector in North America grew to estimated market range of 1,125 to 1,440 metric tonnes in 2013, a rise of 15% to 25% over 2012.

Johnson put the estimated value of MIM sales in the \$300-\$350 million range. According to a survey of the sector undertaken by the Metal Injection Molding Association (MIMA) in 2013 there are around 70 MIM operations in North America of which 25% are captive (in-house). 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%. Johnson stated that aerospace and defence currently make up only around 5% of MIM parts but this is expected to increase considerably as MIM finds new applications in the next generation of aircraft engines being introduced in the 2015 to 2020 timeframe. MIM aerospace parts are expected to include small blades and retainer rings made from superalloy powders such as Inconel and Hastelloy.

Johnson also reported on the outlook for MIM which according to the recent MIMA survey will give further growth this year and in 2015. MIMA also identified technology improvements that will advance MIM applications. These include better carbon and dimensional control, improved cosmetic quality, better non-destructive testing methods for defect detection, and increased spending on R&D on special alloys and titanium.

www.mpif.org


TITANIUM

Beckett MIM receives award at Medilink for best start-up company

Beckett MIM, based in Sheffield, UK, has been awarded the prestigious Nabarro start-up award for a newly established company that shows a promising future. The start-up award was presented at the recent Medilink Awards, held in partnership with the UK's Yorkshire and Humber Academic Health Science Network (AHSN), to celebrate the achievements of Healthcare Technology and related Life Sciences companies from across Yorkshire and Humber.

Beckett MIM was established in January 2013 by Beckett Plastics Ltd to complement its Sheffield-based plastics moulding business, with the new Metal Injection Moulding operation using knowledge and expertise developed at the University of Sheffield's Mercury Centre. This allowed the new company to embark on the development of MIM parts in a wide range of metals and alloys including ferrous and titanium alloys, nickel-base alloys, tungsten and copper.

Lukas Jiranek, Beckett MIM's Technical Manager who came to work for William Beckett Plastics from the University of Sheffield as a Knowledge Transfer Associate, sees a bright future for MIM, commenting, "The market has grown almost 10-15% each year since the 1980s, and there has been lots of progress recently using lightweight materials. Aerospace companies want to reduce the weight of their components, but increasingly automotive companies want to take advantage of these benefits too. Reducing the weight of components and unit cost of parts are the main drivers of these industrial sectors. Because of the increase in use of Powder Metallurgy technologies, including Additive Manufacturing, the cost of metal powder feedstocks are coming down, so prices are getting better and better for us. Looking to the future we are investigating Metal Injection Moulding of tungsten carbide and moulding of other special alloys."

Professor Iain Todd, Centre Director at the Mercury Centre, stated, "Beckett MIM is a really successful example of how we are transferring our advanced manufacturing expertise to local industry and having a real economic impact. Our Knowledge Transfer Partnerships have been a very rewarding experience and Beckett MIM's start up award is well deserved. I'm pleased to say our relationship with them is ongoing as we continue to build on and extend our knowledge of the metal injection moulding process and materials, whilst applying it to a commercial context."

www.beckettmim.com

THE QUEEN'S AWARDS FOR ENTERPRISE: INTERNATIONAL TRADE 2010

osprey

On the leading edge of metal powder manufacture

With over 35 years' experience in gas atomisation, Sandvik Osprey offers the world's widest range of high quality, spherical metal powders for use in Metal Injection Moulding. Our products are used in an increasingly diverse range of applications including automotive, consumer electronics, medical and aerospace.

Our extensive product range includes stainless steels, nickel based superalloys, master alloys, tool steels, cobalt alloys, low alloy steels and binary alloys.

Using gas atomised powders can enhance your productivity and profitability: contact our technical sales team today for more information.

SANDVIK

Sandvik Osprey Limited
Milland Road Neath SA11 1NJ UK Phone: +44 (0)1639 634121 Fax: +44 (0)1639 630100
www.smt.sandvik.com/metalpowder e-mail: powders.osprey@sandvik.com

Phillips-Medisize celebrates 50th anniversary

Phillips Medisize Corp. based in Hudson, Wisconsin, USA, celebrates its 50th year of continuous production in 2014 with the milestone marking the company's ongoing involvement in the high growth medical and specialty commercial markets.

Matt Jennings, President and CEO, stated, "The past fifty years were built on the tried and true principles of building partnerships with our customers based around quality, innovation and service. We made these partnerships work by investing in our employees, processes, facilities and equipment which created a world class outsource design, development and manufacturing organisation. This organisation has allowed our customers to integrate their product designs with advanced moulding technologies and automated assembly, within a robust quality system."

"This milestone also marks the company's ongoing involvement in the high growth medical and specialty commercial markets serving our customers worldwide. We look forward to our next 50 years of operation by recommitting ourselves to the timeless principles of quality, service and innovation by continuing to invest in our people, processes and facilities," stated Jennings.

Phillips Medisize introduced Metal Injection Moulding technology at the Menomonie plant in Wisconsin in 1996 followed two years later with magnesium injection moulding at the same site. MIM parts produced by the company are extensively used in medical devices as well as in firearms and other applications.

The company has annual group sales of over $500 million with 75% of the total revenue coming from drug delivery, medical device, primary pharmaceutical packaging, and diagnostic products such as disposable insulin pens, glucose meters, specialty inhalation drug delivery devices, single use surgical devices and consumable diagnostic components. The company employs over 3,100 people in 14 facilities throughout the United States, Europe, Mexico and China.

www.phillipsmedisize.com

Metal Injection Moulded products manufactured by Phillips Medisize in Menomonie, Wisconsin

Japanese MIM seminars promote cooperation and technology awareness amongst young engineers

The Japan Powder Metallurgy Association (JPMA) latest two day MIM seminar took place from February 28 to March 1. The event was held in Atami, a famous hot spa resort in Japan located one hour from Tokyo by bullet train.

The JPMA's MIM committee invited young MIM engineers and related metal powder suppliers to this seminar, the fifth in the series.

Dr Yoshiyuki Kato, a specialist MIM industry consultant and former Director of Epson Atmix Corporation, told *PIM International*, "Normally young engineers have little chance to network and discuss technological challenges with their peers. This seminar was an excellent opportunity for these people to exchange ideas and opinions. Young engineers raised everyday problems and discussed them with participants."

Takuo Toda, CEO of the Castem Group gave a lecture on the MIM part design before leading a discussion on this subject and Dr Kato gave a lecture on the present conditions in the global MIM market. Seminar participants received complimentary copies of *Powder Injection Moulding International*.

The JPMA's Yusuke Watanuki, who organised the seminar, stated that the association would repeat the seminar next year.

www.jpma.gr.jp

Delegates at the Japan Powder Metallurgy Association's latest two day MIM seminar with a copy of PIM International

Advertising in our September 2014 issue

To discuss advertising in the next issue of *Powder Injection Moulding International*, to be published in September 2014, please contact:

Jon Craxford, Advertising Sales Director
Tel: +44 207 1939 749
Email: jon@inovar-communications.com

Catamold®
Imagination is the only limit!

[Catamold® – Inject your ideas]

BASF SE
GBU Carbonyl Iron Powder
and Metal Systems
Powder Injection Molding
G-CA/MI – J513
67056 Ludwigshafen, Germany
Phone: +49 621 60 52835
E-mail: catamold@basf.com
Internet: www.basf.de/catamold

Discover the amazing possibilities of metal and ceramic components manufacturing using Power Injection Molding with Catamold® and BASF.

With Catamold®, conventional injection molding machines can be used to produce geometrically demanding components economically. You can do injection molding of metal and ceramic feedstock as easily as plastic.
And this opens up new means of producing complex components that provide economic and technical benefits in sectors ranging from Automotive, Consumer Products, and Mechanical Engineering to Medical Products and Communications/Electronics.

Take advantage of the new diversity in Powder Injection Molding with Catamold®.
Get in touch with us – we'll be glad to help you on the road to success.

BASF
The Chemical Company

Feronyl invests in its Metal Injection Moulding production

Feronyl, a family owned company situated in Mouscon, Belgium, has been specialising in the production of technical parts in metal, composite and plastic materials since 1950. The company initially built injection moulding machines and moulding tools for sale worldwide and when this part of the business was sold it used its know-how in mould design and production for its own part production.

One of its early successes was converting an iron gear to an injection moulded nylon gear for use in the textile industry in the region, and today Feronyl operates a range of moulding presses having clamping force ranging from 10 to 1300 tons to produce parts from 0.5 g to 6.5 kg in weight.

Metal Injection Moulded products manufactured by Feronyl show in the green, brown and as-sintered state

The company has introduced Metal Injection Moulding (MIM) which it sees as a new technology for future growth, and is investing in the automation of its production with the introduction of robots on its moulding machines.

www.feronyl.com

Cremer acquires majority share of SOF Equipment GmbH

Cremer Thermoprozessanlagen GmbH, based in Düren, Germany, has announced the acquisition of the majority of shares in SOF Equipment GmbH. Based in Eschweiler, Germany, SOF manufactures a range of furnaces for various industries including Powder Metallurgy applications.

Cremer has been a manufacturer of industrial furnaces with a focus on the Metal Injection Moulding and Powder Metallurgy and technology sectors for almost 50 years. The company produces a range of furnaces including walking beam, belt, pusher, multi-tube, drum type, batch type and rotary-hearth systems.

"The acquisition of SOF by Cremer strengthens the market position and will provide an extended product range, more powerful technology and innovation support, plus an optimum service from a single source," stated Dipl.-Ing. Ingo Cremer.

Following the transaction, SOF Equipment GmbH has been renamed as Cremer-SOF Engineering GmbH and Ingo Cremer has been appointed General Manager (CEO).

www.cremer-ofenbau.de

Submitting News

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

Liquidmetal Technologies appoints MIM expert as VP of World-Wide Sales and Support, losses continue in 2013

Liquidmetal Technologies Inc., the US based developer of amorphous alloys and composites, has appointed Paul Hauck as VP of World-Wide Sales and Support. Hauck, whose background includes a primary focus on Metal Injection Moulding, has spent his entire career in contract manufacturing businesses that produce precision metal components utilising various metallurgy technologies. Prior to his position at Liquidmetal Technologies, Hauck served as Director of Engineering, Marketing and Sales at Kinetics Climax, Inc., a MIM company based in Wilsonville, Oregon, USA.

"With a highly successful track record of creating and implementing tactics to identify and develop new business, Paul Hauck is an ideal candidate with a track record of consistently fostering profitable new business in the Metal Injection Moulding arena," stated Tom Steipp, Liquidmetal Technologies' President and CEO.

In 2013 Hauck received a MPIF Distinguished Service to Powder Metallurgy Award and is a three term President of the MPIF's Metal Injection Molding Association.

Liquidmetal reported continuing high losses in 2013 to $5.85 million despite a 58% rise in sales to $1.3 million. The company stated that 18 prototype shipments were made in 2013 to customers in the aerospace/defence, medical and other industries, which was up 80% over the previous year.

"2013 was noteworthy in that we saw the solidification of our Certified Liquidmetal Partners programme and the commercial availability of a standard injection moulding machine from Engel and both beryllium and non-beryllium containing alloys from Materion," said Steipp. "These events set the stage for our attracting a top industry sales and support executive in Paul Hauck, who will now lead the sales and marketing activities as we push beyond the prototype phases into full production of customer parts."

www.liquidmetal.com

The Swatch Group's Omega Seamaster Planet Ocean Liquidmetal Limited Edition, the world's first watch to bond ceramics and Liquidmetal

SLM Solutions looks to purchase metal powder supplier

German Additive Manufacturing equipment maker SLM Solutions is reported by Reuters to be considering the purchase of a metal powder producer. SLM Solutions, based in Lübeck, Germany, specialises in manufacturing selective laser melting machines and plans to use some of the proceeds from its upcoming flotation on the Frankfurt stock market to fund the acquisition.

SLM's Chief Executive Markus Rechlin is quoted as saying, "We have earmarked a third of our targeted €75 million ($103 million) in proceeds to develop the powder business. We do not want to produce the powders ourselves but can imagine an acquisition of a producer or entering into a close cooperation."

The company also stated that it plans further investment in its sales and service business, opening offices in the US, Japan and Singapore.

"3D printing technology is just about to take off and big industrial customers will shortly start ordering not single machines but start placing multiple machine orders," Rechlin added.

SLM counts companies such as GE, Alstom and Space Exploration Technologies (SpaceX) as customers, all of which have interests in Additive Manufacturing technology.

www.slm-solutions.com

The SLM 500 HL provides a build chamber of 500 x 280 x 325 mm and a powerful double/multi laser technology

Euro PM2014 conference and exhibition heads to Austria

Europe's annual Powder Metallurgy conference and exhibition, organised by the European Powder Metallurgy Association (EPMA), will be held in Salzburg, Austria, September 21-24, 2014.

Euro PM2014 will be an all topic PM event. The full technical programme, to be published at the end of May, will include sessions on Additive Manufacturing (AM), hard materials, Hot Isostatic Pressing (HIP), PM structural parts and Powder Injection Moulding (PIM).

Inovar Communications will be exhibiting at Euro PM2014, distributing both *Powder Injection Moulding International* and *Powder Metallurgy Review* from its booth in the exhibition hall.

www.epma.com/pm2014

INTRODUCING **ELNIK'S**

MIM-telligence™

CUTTING EDGE TECHNOLOGICAL ADVANCES THAT CAN SAVE YOU THOUSANDS $$

The **Metal Injection Molding** process can be both risky and very costly unless you have a company like **Elnik Systems** working with you. The reason is simple. For over 18 years, **Elnik Systems** has made technological innovation its cornerstone. And innovative thinking leads to smarter **MIM** performance, we call ***"MIM-telligence™".***

Taking it a step further, once **Elnik** innovates, extensive field testing is done before their new technology hits the market with the help of the full-sized production furnaces at **DSH Technologies LLC,** a research and development sister company of **Elnik. Elnik** also offers free DSH services for one year with the purchase of each new piece of their equipment, providing every **Elnik** customer with additional customized technical support and dependability. Another **Elnik** ***"MIM-telligence™"*** benefit.

INNOVATIVE SYSTEM FEATURES

- ***AccuTemp™*** proprietary thermocouple control resulting in tight temperature control
- **Automatic Cleaning Features** of binder trapping components and Dry Vacuum Pump.
- ***ColdFinger™* Debind Trap** forced flow enhanced binder trapping.
- **Gas Tight Retort Design** Superior gas control throughout process zone, eliminating escaping gas as compared to competitive designs.
- **Laminar Gas Flow** efficient and effective gas management for debinding and sintering.
- **Simple Ease of Use** PLC controls via Excel spreadsheet.

ELNIK SYSTEMS

Innovation. Experience. Excellence.

107 Commerce Road | Cedar Grove, NJ 07009 USA | +1.973.239.6066 | www.elnik.com

HC Starck looks become world's largest independent tungsten provider

In a recent statement from HC Starck the company has announced that one of its aims for 2014 will be to noticeably expand its market position in the tungsten segment, becoming the world's largest independent tungsten provider. HC Starck stated its plans to commission two major tungsten joint ventures, one in China and one in Vietnam, were under way.

"Thanks to our joint ventures, we are in an outstanding position to leverage Asia's market potential and use the demand in the tungsten segment for our growth," stated Andreas Meier, CEO of H.C. Starck. "Together with our existing tungsten powder production activities in Germany and Canada, this will make us the world's largest independent tungsten producer."

HC Starck stated that the products from the two joint ventures will be used as high-performance materials in many growth industries, particularly tool construction, medical technology, the automotive and aviation industry, as well as in the energy sector; in wear parts for the mining, tunnel and road construction sectors; as metal for alloys, and in catalyst production for the chemicals industry.

In financial results published by HC Starck it reported that after two years of strong growth, the company posted group sales of €703.9 million in 2013, below the previous year's figure of €862.9 million. The report stated that the tungsten metal powder business was affected by a sharp decline in the European market and decreases in raw material prices, especially in the first half of the 2013. Toward the end of the year, however, this segment experienced a noticeable recovery that brought a positive start to fiscal 2014.

www.hcstarck.com ■

Ceramitec 2015 to develop its PM focus

Ceramitec 2015, the international trade show for the ceramics industry, will take place in Munich, Germany, from October 20 to 23 2015.

The organisers state that a further development of the Technical Ceramics and Powder Metallurgy areas is planned for Ceramitec 2015 in addition to the mainstream areas of raw materials, heavy clay ceramics, fineware and refractory ceramics

A total of 613 exhibitors from 42 countries showcased their innovations at Ceramitec 2012. Nearly 60% of exhibitors came from abroad and for the first time China was the strongest international exhibitor country. The event attracted some 16,800 trade visitors from 106 countries, 57% of whom from were from overseas. Compared with the previous event, this corresponds to an increase of 15%.

www.ceramitec.de ■

Call for Presentations issued for MIM2015 Conference, Tampa, Florida

The program committee for MIM2015, the International Conference on Injection Molding of Metals, Ceramics and Carbides, has issued a Call for Presentations. The focus of the technical program is dimensional accuracy and consistency.

Sponsored by the Metal Injection Molding Association, a trade association of the Metal Powder Industries Federation (MPIF), and its affiliate APMI International, the conference will be held in Tampa, Florida, February 23–25, 2015, at the Sheraton Tampa Riverwalk hotel.

The Sheraton Tampa Riverwalk, venue for the MIM2015 conference

Technical program Co-Chairmen Thomas K. Houck, ARCMIM, USA, and Uwe Haupt, Arburg GmbH + Co KG, request abstracts of 100–150 words, covering any aspect of metal injection moulding, including processing, materials, and applications.

The program committee requests that abstracts be submitted by September 30, 2014, for consideration. Complete details on the conference and on submitting abstracts are available from the Metal Injection Molding Association's website or by contacting Jim Adams at jadams@mpif.org

www.mimaweb.org

International Journal of Powder Metallurgy celebrates 50 years and announces new Editor

The *International Journal of Powder Metallurgy* (IJPM), published by the American Powder Metallurgy Institute (APMI) is celebrating its 50th anniversary in 2014. During this time the journal has had only two editors, Henry Hausner (1965-1984) and Alan Lawley (1985-present).

The APMI has announced that in the coming months Dr W. Brian James will take over from Lawley as Editor of the IJPM. Dr James, formally of Hoeganaes Corporation, was awarded APMI International Fellow status in 2003 and is currently chairman of the MPIF and MPPA Standards Committees.

www.mpif.org

Improved moulding productivity with 3D-printed conformal cooling

Linear Mold & Engineering based in Livonia, Michigan, USA, is a producer of low to high volume injection moulded components which six years ago invested in a Direct Metal Laser Sintering (DLMS) machine from EOS GmbH in Germany to produce tooling inserts with cooling lines already designed inside. These completely dense and highly accurate inserts allowed the company to put the cooling lines where they need to be in order to achieve maximum part quality and lower costs.

This includes conformal cooling channels that follow, or conform, to the shape of the moulded part in order to get cooling close to the critical areas that would otherwise be difficult to manage, such as thicker wall sections. Linear states that conformal cooling technology, which has been around for a couple of decades, offers a more uniform way to cool parts, thus reducing cycle time and improving productivity and quality. Linear now provide this unique cooling channel technology not only to the moulds it builds for its OEM customers, but to also to other mouldmakers. The company recently installed its seventh 3D printer from EOS.

www.linearmold.com

GKN reports first quarter 2014 results

GKN plc has reported group sales for the three months ended 31 March 2014 reached £1,915 million. This represented a 7% organic increase which was offset by 6% adverse currency translation due to sterling's strength against most major currencies. Trading profit for the group during the first quarter increased 19% to £166 million, with a trading margin of 8.7%.

"We have delivered a strong performance in the first quarter despite adverse currency translation impacting the reported sterling results. Looking forward to the rest of the year, tougher prior year comparators mean that organic growth is likely to be more modest. However, our market leading positions, advanced technology and extensive global footprint should make 2014 another year of progress," stated Nigel Stein, Chief Executive, GKN plc.

GKN's Powder Metallurgy division, incorporating GKN Sinter Metals and Hoeganaes Corporation, also showed a strong first quarter. Sales of £237 million were reported for the first quarter, representing organic sales growth of 8% but offset by 7% adverse currency translation. Trading profit increased 30% to £26 million at a margin of 11.0%. GKN's MIM plant in Germany is one of the largest in Europe.

www.gkn.com

Nickel price soars amid export ban and sanctions fear

The price of nickel, a key alloying element in low alloy steels, stainless steels, high alloy steels and non-ferrous alloys, broke the US$17,000/t barrier in early April, a rise of 16% since the start of 2014. The strong performance of the nickel price is forecast to continue as a result of reduced supply of nickel ore following an Indonesian ban on exports. Until this ban, Indonesia was the world's top high-grade nickel ore supplier.

According to a report from Standard Bank quoted in the Financial Times on April 10, if the export ban remains in place beyond July's presidential election in Indonesia, the global nickel market will see significant deficits of 134,000 tonnes in 2015, 106,000 tonnes in 2016 and 77,000 tonnes in 2017. "In the absence of a change in Indonesian policy, we think that by 2016, the market will get tighter than in 2006-7, when prices traded in the $30,000-$50,000 a tonne range," the bank stated.

Potential sanctions by the EU and the US against Russia could impact on the supplies of nickel from Russia's Norilsk Nickel, a producer that accounts for 17% of the global nickel production. According to CEO of Norilsk Nickel, Vladimir Potanin, the company is considering measures to shield against possible sanctions from the US and EU by looking to Asia. "We have large volume of operations in the Chinese market, but the main payment currencies are dollar and euro. In principle, nobody hinders settlements in such currencies as the yuan for deliveries to China. We decided to explore this issue, to look how it'll function," Potanin told *Russia Today*.

Potanin stated, however, that he does not believe there will be tough sanctions as "they are unnecessary, uninteresting and harmful to both parties. But in a case of specific emotional actions of regulators or of certain countries - just in case - it is necessary to study what we will do in this situation." ■

Engel creates new subsidiary in China

The Engel Group based in Schwertberg, Austria, has established an 100%-owned subsidiary called Wintec in Changzhou, Jiangsu province, China, which will start producing injection moulding machines this summer. Peter Auinger, who has transferred within the Engel Group from Mexico to China, will be the subsidiary's CEO. Whilst the new production plant for injection moulding machines will have China as its main target market, Engel also expects to serve injection moulding customers in Southeast Asia, Korea, Taiwan and India.

www.engelglobal.com ■

PyroGenesis to supply $15 million metal powder production system

PyroGenesis, a developer and manufacturer of plasma waste-to-energy systems and plasma torch systems based in Montreal, Canada, has announced that it has signed a letter of intent (LOI) to supply a major international manufacturer with several plasma-based metal powder production systems for use in Additive Manufacturing. At this stage the customer's name is being withheld for competitive reasons.

"One of the limiting factors in the full commercialization of 3D printing for metal products is the availability of high-quality, high-purity metal powder," stated P Peter Pascali, President and Chief Executive Officer of PyroGenesis. "Our platform is a proven product with completed commercial sales having already taken place in North America and Europe. A successful conclusion of this LOI will result in the rapid deployment of our powder production platform for 3D printing, thus accelerating the adoption of Additive Manufacturing worldwide."

"Our customer is looking to PyroGenesis and its plasma-based technology to ensure a strategic and continuous supply of metal powder feedstock for their own internal 3D printing production use," added Gillian Holcroft, Executive Vice President, Strategic Alliances. "3D-printed metal components will transform manufacturing in the coming years in a wide range of industries, including automotive, aerospace, medical, and consumer goods."

"This is only at the LOI stage," cautions Pascali, "and one should consider this news in that light. However, we have made sufficient progress to be highly confident that a contract will be concluded in short order."

www.pyrogenesis.com

HIP'14 conference programme published

The Technical Programme for the 11th International Conference Hot Isostatic Pressing, HIP '14, Stockholm, Sweden June 9-13, can now be viewed on the conference website. Organised by the International HIP Committee (IHC) and Jernkontoret, the Swedish Steel Producers' Association, the event will also include an exhibition and offers a number of optional site visits.

The conference will focus on developments in HIP technology. Aspects related to PM processing, diffusion bonding and part densification will also be included.

The Technical Programme includes sessions focussing on oil and gas, power generation, aerospace, materials, modelling and HIP processes.

www.hip14.se

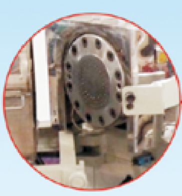
GREENLONG
MACHINERY

Special for Ceramic/Cer-Met/Metal Powder Injection Molding
Knead mixing, pelletizing, and injection molding

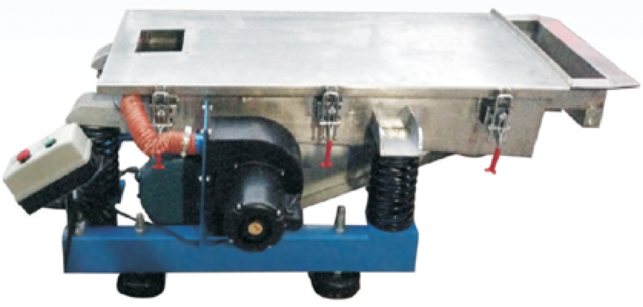
Hybrid of knead mixing and pelletizing machine

Characteristics of this machine

- One process of knead mixing and pelletizing without material transfer
- Length and surface smoothness could controlled of each pellets
- Auto temperature control for mixing process
- More efficient and stable performance of this machine
- Manual and auto switchable easy
- Servo control system and chamber easy for cleaning
- Raising powder and gas college device
- Wearable design of barrel and screw with hard coating surface
- High torque design of screw to push feedstock moving



Pelletizer Cutter



Vibration mesh machine

ADD:Zhengyang east Road of Chengyang No177 Qingdao China
TEL:86-532-81155768 FAX:86-532-81155645
E-mail:cdj086@163.com Http:www.greenlong.cn

Arburg's Technology Days 2014 attract a record 6900 guests

A view of the main display area at Arburg's Technology Days 2014

Arburg GmbH + Co KG, a leading injection moulding machine manufacturer based in Lossburg, Germany, has stated that its Technology Days 2014 were more popular than ever before with nearly 7000 invited guests attending the unique event in Lossburg from March 19-22.

Michael Hehl, Managing Partner and Spokesperson for the Arburg Management Team stated, "Our Technology Days have been a major attraction for the international plastics world for many years. This year, the interest has been absolutely overwhelming with approximately 6,900 trade visitors from 52 countries learning about our innovative and production-efficient solutions for plastic part production at first hand in Lossburg. That's nearly a quarter more than in the previous record year 2013."

A highlight for visitors was Arburg's Freeformer machine. The new system, which enables the Additive Manufacturing of functional components from standard plastic granulates, received its global premiere at the K 2013 trade fair, was available to experience at first hand and, stated Arburg, generated a great deal of enthusiasm.

In addition to innovative applications and product innovations, the visitors also had the opportunity to see injection moulding production for themselves and to participate in extensive factory tours, including Arburg's dedicated Powder Injection Moulding laboratory.

www.arburg.com

Dates announced for China's 7th "Powder Metallurgy Technology and Business Forum"

China's "PM Technology and Business Forum", organised annually since 2008, is one of the largest PM and MIM industry events in China. The 7th event in the series takes place from June 12-14, 2014 in the HaiZhou Hotel, Haining, Zhejiang Province, China, and is sponsored by the China PM Business Website, www.pmbiz.com.cn.

The event organisers told *PIM International*, "In 2013 the economic and political situation was complex in China as well as overseas, which impacted on the PM industry. Generally, however, the PM industry in China sustained strong growth over this period. Leading businesses enjoyed the advantages of scale and more advanced technology and are playing an increasingly important role in the international supply chain."

"Whilst some small and medium scale enterprises experienced difficulties, PM enterprises in China closely follow developing trends and are looking to integrate technology advantages, improve quality systems and seek business opportunities. The PM Technology and Business Forum provides a good platform for this." The forum's Technical Program includes:

- Automobile keynote reports: Trends in PM parts adoption by automobile OEMs
- Materials selection, design and processing of PM moulds
- Current situation and developing trends of PM additives
- Iron powder consumption in China and its position in the world
- Cutting-edge technology of PM and MIM
- PM2014 Congress overview
- Invited keynote: Current situation of MIM industry in Europe, combined with situation in China

Discussion forums will enable the direct communications between experts and participants to solve production problems. There will also be an exhibition featuring the latest PM and MIM equipment, technology and products. A visit to a PM related enterprise is also planned. The delegate fee is RMB 1200 per person.

www.fmyj.org

Submitting News

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

European Powder Metallurgy Association to celebrate 25th anniversary at General Assembly

This year marks 25 years since the formation of the European Powder Metallurgy Association (EPMA) in Brussels, Belgium. The EPMA will celebrate reaching this milestone with a number of special events beginning with a VIP Dinner and a 25th Anniversary Seminar to be held following the association's Annual General Assembly in London, UK, June 5 - 6, 2014.

The members only VIP Dinner will take place at the historic Stationers Hall in London on June 5. This will be followed by a one day seminar on June 6, with presentations from international PM experts focussing on the theme of "past and future development of the European PM industry".

Celebrations will continue later in the year at the Euro PM2014 Congress & Exhibition to be held September 21 - 24 in Salzburg, Austria. The event will include a special commemorative reception for delegates.

Established as a not-for-profit organisation in 1989 the EPMA is an international trade Association representing manufacturers of all types of PM products, suppliers of materials and equipment, end users of PM components as well as research institutions and individuals who have an interest in PM. The EPMA has been fully involved in the development of MIM in Europe. A MIM group was established as early as 1992 which organised a MIM Technology Day in Brussels in April 1992 funded by the EC, and a MIM short course was held in Delft in the same year. Further MIM short courses and conferences followed and the MIM Group was successful in obtaining EC funding for a three year thematic network project to develop MIM standards. The EuroMIM group will hold its next meeting at Euro PM2014 in Salzburg.

www.epma.com

The historic Stationers Hall in London

Metalysis receives boost for titanium powder production

Iluka Resources Ltd, headquartered in Perth, Australia, recently invested £12.2 million in UK based Metalysis Ltd to boost titanium powder production. The deal will see Iluka, a mineral sands exploration company and the world's second largest producer of titanium dioxide minerals, become the largest shareholder in Metalysis with an 18.3% stake in the company.

Metalysis has demonstrated that it is able to produce titanium powder directly from Iluka's main high grade titanium feedstock products of rutile. The Metalysis Process is reported to offer both economic and environmental benefits over traditional titanium powder production methods. The production of a relatively low cost Ti powder could significantly expand the use of this material in a number of areas of growing demand, including metal injection moulding, powder metallurgy and Additive Manufacturing.

"Iluka's involvement as a major shareholder and funding partner provides Iluka shareholders with access to a new, potentially disruptive technology which is close to commercialisation, and the potential benefits of a new source of high grade titanium dioxide feedstock demand, as well as a commercial involvement in a potential new growth pathway for high value metals and alloys and new manufacturing processes such as MIM and 3D printing," stated David Robb, Iluka's Managing Director.

Metalysis Chairman Tony Pedder added, "Iluka coming in as a funding partner to Metalysis is an important part of the company's journey. Iluka's expertise in titanium dioxide as a feedstock, process engineering experience and access to global markets can make a significant impact on Metalysis' development. The Metalysis process has applications across metals in the periodic table including: titanium, tantalum and rare earths and with Iluka's access to titanium dioxide feedstock there is the potential to produce titanium powder with much greater efficiency and at a much lower cost than is currently possible."

www.iluka.com
www.metalysis.com

The main building of Metalysis in Rotherham, UK, houses the R&D facility as well as the production plant

Arburg's Managing Director Herbert Kraibühler retires

On April 4, around 180 guests, friends and associates from the industry, gathered together at the Arburg Customer Centre in Lossburg, Germany, to say farewell to Managing Director Herbert Kraibühler, who has retired after 50 years of service to the company.

Kraibühler was presented with a newly created golden Arburg logo by Senior Partner Eugen Hehl as a special honour for his life's work.

On April 1, Heinz Gaub took over as Arburg's new Managing Director Technology & Engineering.

www.arburg.com


Partner Eugen Hehl presents Herbert Kraibühler, who entered into retirement after 50 years at the company, with the Arburg logo in gold

"Apple or Android?"

No problem! We have you covered.

The first MIM app of its kind, designed by engineers for engineers, this app will cure your engineering headaches by providing the versatility of our industry leading design guide and material solutions in the palm of your hand.

The unique powerful tools of this app allow you to find a material solution based on the material property needs of your application, while simplifying your search for critical part design criteria.

Both features help you leverage the greatest design flexibility and economic value of MIM

Insist on the best, deal directly with the world's technology leader in MIM.

Download FREE today utilizing one of these QR codes

iPhone

Android

www.kinetics.com kinetics@fmi.com 503.404.1200

Proto Labs launches new quick-turnaround MIM service, adds Additive Manufacturing operation

Proto Labs, Inc., based in Maple Plain, Minnesota, USA, has announced that product designers can now order Metal Injection Moulded (MIM) parts as a standard option under its Protomold injection moulding service. Utilising the same approach that the company claims has revolutionised plastic injection moulding, Proto Labs has applied its proprietary technology to make short-run MIM stainless steel parts available faster than ever before. The company has also added Liquid Silicone Rubber (LSR) to its materials portfolio, a thermoset engineering material that is particularly suitable for applications in medical, electronics and consumer products industries.

"Over the past year our research and development program has quickly advanced Liquid Silicone Rubber moulding and Metal Injection Moulding with the quality and quick turnaround that is the trademark of Proto Labs. I'm excited to begin my tenure at Proto Labs with the launch of these new moulding processes to our customers. Incorporating LSR and MIM into our existing list of materials allows current and future customers more diversity in prototyping and small-volume manufacturing - something every product developer focused on taking products from idea to market faster can appreciate," stated Vicki Holt, President and CEO of Proto Labs.

MIM parts manufactured at Protolab

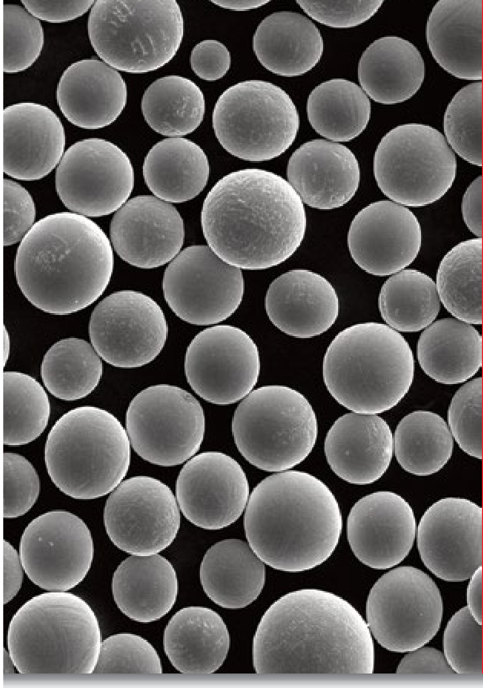
The company has also announced the launch of its Additive Manufacturing service through the acquisition of privately held FineLine Prototyping, Inc. The addition of Additive Manufacturing expands Proto Labs' services to address a wider spectrum of need for the product developer. FineLine, based in Raleigh, North Carolina, USA, offers Stereolithography, Selective Laser Sintering and Direct Metal Laser Sintering services to corporate customers in a wide variety of industries, including medical, aerospace, computer/electronics, consumer products and industrial machinery, among others.

FineLine generated revenues of approximately $9.7 million in 2013. Under terms of the agreement, Proto Labs will acquire FineLine for a total consideration of $38 million. Proto Labs will continue to operate the FineLine facility out of Raleigh and expects to retain the services of all key employees, including FineLine principals Rob Connelly and Craig Goff to lead the global Additive Manufacturing services.

The addition of an Additive Manufacturing service is, states Proto Lab, highly complementary to its existing CNC machining and injection moulding services. Historically, 70% of Proto Labs customers also utilise an Additive Manufacturing service in their product development process. Proto Labs will announce its new Additive Manufacturing service to its substantial database of over 300,000 product developers to leverage the inherent synergy this new service provides.

"We are excited to launch our new Additive Manufacturing service," stated Holt. "The FineLine acquisition is the first step in building this new service. We will look to expand our Additive Manufacturing capabilities in the US, as well as globally, through both organic growth and potential new acquisitions. Our customers have been asking us to provide Additive Manufacturing services for quite some time, and now we can address that need. We're accepting orders starting today."

www.protolabs.com



Your Premier Source for Hydride–Dehydride (HDH) and Plasma Spheroidized (PS) Titanium Powders.

AMETEK Specialty Metal Products – Reading Alloys is a leader in producing specialty alloys and fine powders. The company uses a variety of manufacturing processes to produce titanium powders that meet ISO 9001 / AS 9100 requirements.

The company utilizes a new plasma manufacturing method which combines an established powder manufacturing process with the Plasma Spheroidization (PS) process to offer customers an alternative high volume, spherical titanium powder production process.

HDH Powders: Greater Control of PSD

- Available in Ti Sponge, CP Ti, Ti-6AL-4V Standard (Grade 5) & ELI (Grade 23)
- Particle sized from 45 microns (325 mesh) to 500 microns (35 mesh)
- Solid, angular, block or sponge morphology

PS Powders: Free Flowing

- Available in CP Ti, Ti-6AL-4V Standard (Grade 5) & ELI (Grade 23)
- Particle sized from 45 microns (325 mesh) to 500 microns (35 mesh)
- Spherical morphology, tight PSD, no satellites, agglomerates or entrapped argon

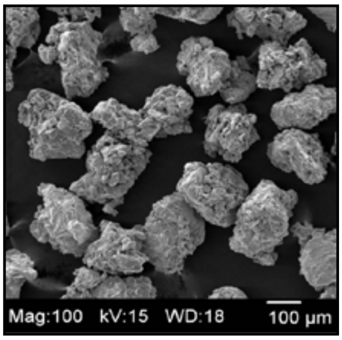
Powder Metallurgy Applications

- Plasma Spray/Coating
- Cold Isostatic Pressing / Sintering
- Hot Isostatic Presssing
- Metal Injection Moulding
- Additive Manufacturing

Markets Served

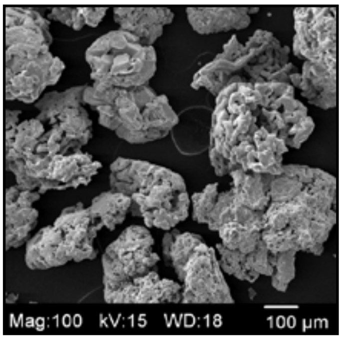
- Medical Device
- Thin Film (Sputtering Target)
- Feedstock
- Electronics
- Net Shape

Morphology: HDH Magnesium Reduced Titanium Sponge Powder



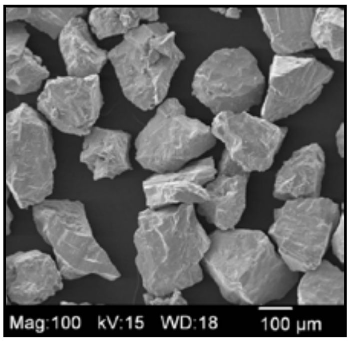
SEM image (x100) of HDH Magnesium Reduced Ti Sponge Powder, 70 mesh (212µm) x 100 mesh (150µm)

Morphology: HDH Sodium Reduced Titanium Sponge Powder



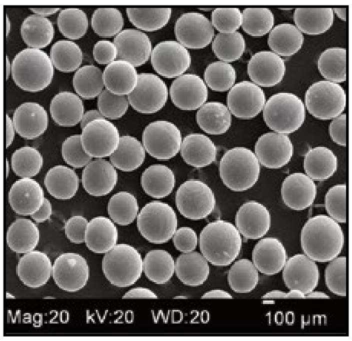
SEM image (x100) of HDH Sodium Reduced Ti Sponge Powder, 70 mesh (212µm) x 100 mesh (150µm)

Morphology: HDH CP Titanium Powder



SEM image (x100) of HDH CP Ti Powder, 70 mesh (212µm) x 100 mesh (150µm)

Morphology: PS CP Titanium Powder (99%+ spherical)



SEM image (x20) of PS Ti powder, 35 mesh (500 microns) x 45 mesh (355 microns)

ReadingAlloys advanced engineered materials® AMETEK® SPECIALTY METAL PRODUCTS

AMETEK-Reading Alloys | 220 Old West Penn Ave. | Robesonia, PA 19551 | Phone: (+1) 610.693.5822
www.ametekmetals.com | rai.technicalpowders@ametek.com |

Progress in the simulation of microPIM

Professor Jan Korvink and his research team at the Laboratory for Simulation, University of Freiburg, Germany, have been developing simulation technology for micro Powder Injection Moulding of both ceramics and metals using Smoothed Particle Hydrodynamics (SPH) in order to meet the computational challenge for complex, strongly deformed materials.

The researchers state that feedstocks for microPIM possess a significant yield stress which can be modelled by means of the viscosity regularisation technique, the approximation of the yielded and unyielded domains of the material by two different viscosities. Incorporated into the particle based SPH-formalism, the model successfully reproduces an experimental observation of splitting in a channel with cylindrical obstacle.

Shear induced powder migration was incorporated by means of the diffusive flux model developed by R. J. Phillips, *et al* (*Phys. Fluids A*, 4(1):30-40, 1992). This model was discretised by formulating an SPH-equation of motion for the occupied volume of the solids fraction with exact conservation properties. The simulations correctly predicted powder migration to regions with the lowest shear rates. For Powder Injection Moulding into complex geometries the simulations help to predict an accumulation of the solids fraction at convex corners (pointing outside of the cavity) and a depletion at concave corners (pointing inside the cavity).

www.simulation.uni-freiburg.de

Presentation on 'Best Practice' for carbon control in ferrous MIM parts at PM2014

MIM producer Megamet Solid Metals Inc., based in St. Louis, Missouri, USA, and sintering atmosphere producer Linde Group will give a presentation on the best practice to provide optimum carbon control in the sintering of Metal Injection Moulded parts at the 2014 PM World Congress scheduled for Orlando, Florida, May 18-22.

The practice involves advanced monitoring and control of the 'carbon potential' in the sintering atmosphere using Linde's patented Sinterflex™ technology. The presentation will also explore the causes of decarburisation and the theory behind the sintering atmosphere control practice. By establishing a carbon-neutral atmosphere during sintering, decarburisation, a frequently encountered problem, is completely avoided.

Phil J. McCalla, Operations Manager at Megamet's MIM plant, stated, "Sinterflex has greatly improved our ability to maintain carbon in our carbon steel materials. Linde worked through the challenges with us to meet our continuing goals for process quality."

www.megamet.com
www.lindeus.com

ECN extends DLP technology for 3D printing to metals

Energy Research Centre of the Netherlands (ECN) has reported that Digital Light Processing-based technology (DLP) that has been developed in cooperation with its partners for the 3D printing of ceramic materials can also be made suitable for metals, providing a higher-quality alternative to existing 3D metal-shaping techniques. The advantage of this technology, states ECN, is that the material is constructed in a way that does not involve melting the metals, resulting in well-compacted, homogeneous and therefore high-grade materials.

ECN has now demonstrated that it is feasible to use DLP technology for printing metals. "We can develop these kinds of techniques because we have expertise in building up thin layers of material and in powder metallurgical shaping," stated Jan Opschoor, researcher in Materials, Testing & Analysis at ECN.

To date, ECN has shown that it is feasible to use DLP technology to build up metal products in layers. ECN is seeking partners in the private and public sectors to further the development of the technology and get it ready for the market. "We think that this technology will make a large number of new applications possible that could not be produced, or could hardly be produced, in the past," added Opschoor.

Previously, ECN had already supported the development of this Additive Manufacturing technology for the 3D printing of ceramic materials. This was achieved in partnership with InnoTech Europe B.V. and Formatec Ceramics. This collaboration led to the founding of the company Admatec Europe B.V. Admatec uses 3D technology to manufacture high-grade ceramic materials and parts for industrial and aesthetic applications.

www.ecn.nl ■

PM2014 World Congress mobile app now available to download

The Metal Powder Industries Federation (MPIF) has developed a smartphone app for use by delegates and visitors to the PM 2014 World Congress and Exhibition, Orlando, Florida, USA, May 18-22. The app, available in both Android and Apple formats, is free to download and provides a host of essential information.

The app incorporates a full conference schedule, presentation abstracts, exhibitor list and floor plan, along with a full list of delegates. It allows you to plan your time during the congress and will alert you to any schedule changes over the five days.

www.mpif.org ■

Summer 2014 issue of Powder Metallurgy Review available for free download

The latest issue of *Powder Metallurgy Review*, the magazine for the PM industry, has just been published and is available to download free of charge from the publication's website.

The Summer 2014 (Vol. 3 No. 2) issue includes a detailed look at metal Additive Manufacturing (AM) processes and applications. The review offers an insight into the development of the technology to-date. Case studies illustrate just how revolutionary the freedom to "design for function" rather than "design for manufacture" will be on component development in the future.

A review of the second International Titanium Powder Processing, Consolidation and Metallurgy Conference, which took place in New Zealand, December 2-4 2013, includes the developments in both titanium PM and AM processing.

There is also an extensive 23 page review of the key non-ferrous powders used in the PM industry. The article looks at production and properties of copper, aluminium, titanium and nickel powders.

www.ipmd.net/pmreview ■

Managing quality in the complete Metal Injection Moulding process chain

To produce high quality MIM components in production volumes with a low rejection rate a comprehensive understanding of the whole production process is required, along with the establishment of an appropriate quality monitoring system. Throughout the MIM process chain, from powder to finished parts, there are a number of areas where it is possible for small changes to directly influence manufacturing tolerances and material properties. In this article Prof. Dr. Ing. Frank Petzoldt looks at the influence of powder, feedstock, injection moulding, debinding and sintering as well as supporting technologies such as mould filling simulation and HIP on the quality of MIM parts.

There is fierce competition between a number of different production technologies to produce complex shaped metallic parts in high volumes. Metal Injection Moulding (MIM) is today a successful and mature global production technology and vast quantities of complex MIM components are in use across many different industries. In order to further grow market share MIM has to continue to prove itself as a reliable and cost effective manufacturing process for high volume production. Thanks to advanced quality assurance systems and improvements at each step of the production process very low rejection rates are achieved. Moreover MIM offers some unique opportunities to produce components with special design features, or combine multiple functions into one component.

At the most basic level the Metal Injection Moulding process chain consists of four steps: mixing powder and binder to form the feedstock, injection moulding the desired shape, debinding and sintering. Depending on the application or specific requirements, post-treatment steps such as heat treatment, Hot Isostatic Pressing (HIP), improvement of surface finish or metal-cutting processes can be applied.

At each processing step along the MIM process chain, there are a number of factors that may affect the properties and quality of the final component positively or negatively and these have to be monitored.

The most important factors that influence the quality of MIM

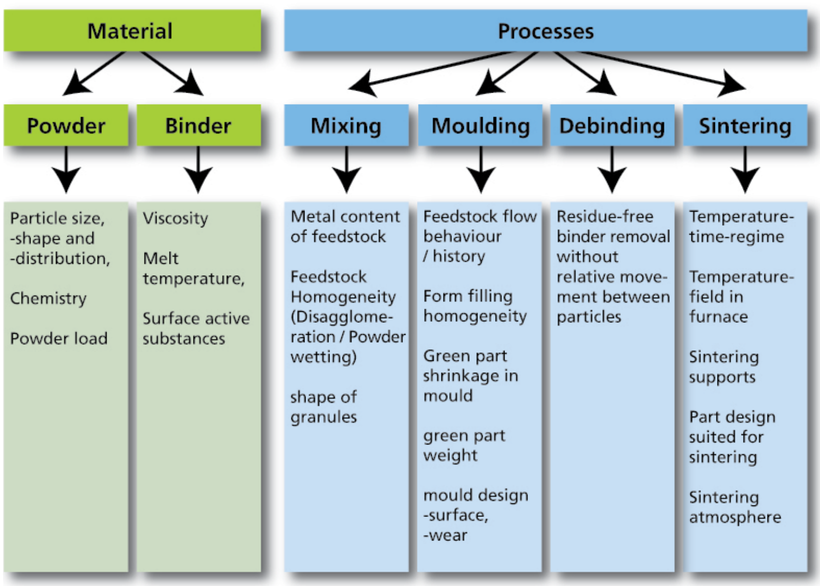


Fig. 1 Possible factors influencing the quality of MIM components

Fig. 2 The GKN Sinter Metals Quality System (GQS) [2]

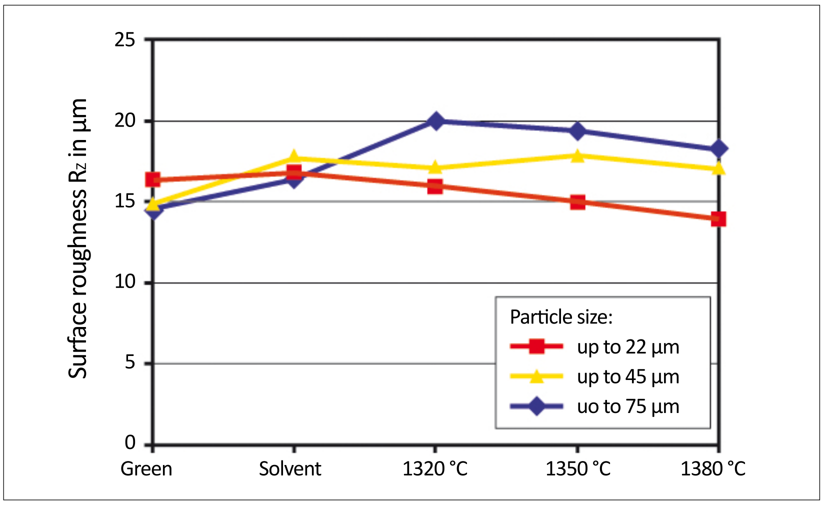


Fig. 3 Surface roughness as a function of the particle size and sintering temperature for gas-atomised 316L powder

components are summarised in Fig. 1. Unfortunately it is not enough to simply understand the influence of each individual factor on quality independently - the interactions between many of these individual factors have to be considered. A deeper understanding of the whole process is therefore necessary to achieve a low finished part rejection rate. During the past twenty years numerous lessons have been learned from many manufacturing problems and a number of critical component defects are now understood and can therefore be avoided in advance [1].

For a manufacturer of MIM components complete documentation of the quality management criteria is necessary to ensure the reliable long-term quality of its products. For example, GKN Sinter Metals GmbH created its own comprehensive database system [2], which is a learning-based system in conjunction with the collection of production data from its various manufacturing plants. Based on this data, batch-specific and multi-batch statistics can be created, comparisons can be drawn and optimisation approaches derived.

The necessary measurement data acquired in each process step are based on part-specific test plans. A test plan contains the reference dimensions, determines the measuring device and the testing accuracy. The preparation of the test plan is carried out by authorised quality assurance staff in collaboration with the production team and the customer. A test plan is created for each production order. Thus, the clear allocation and traceability of each production lot is guaranteed.

The implementation of a test plan is carried out at the same time as part production and the system ensures that data can only be entered in the prescribed order. The testing of sintered parts, for example, requires a completed green part test. Only by completing and confirming the necessary data input can the test plan allow the next process step to be undertaken. Such a quality control cycle is shown schematically in Fig. 2 and is explained in more detail in the analysis of the individual process steps.

Powder, binder and feedstock

Quality assurance in the MIM process starts with the production of the metal powder and the feedstock. Here, especially with regards to feedstock homogeneity, batch-to-batch uniformity and the shrinkage factor have to be recognised as critical quality influencing characteristics. Quality variations in feedstock affect the entire production process and cannot be corrected at a later point, ultimately causing an increase in the rejection rate of sintered parts.

There are several feedstock manufacturers in the market that offer "ready-to-mould" feedstocks and standard feedstock materials such as stainless steels and ferrous alloys are delivered in huge quantities to MIM part producing companies. Special alloys are also manufactured according to customer specifications. World consumption of feedstock is currently estimated at around 9,000 tons per year, about half of which is produced by specialist feedstock producers and half mixed in-house. Regardless of where the feedstock production is carried out all input materials have to be fully assessed, in terms of technical characteristics and chemical composition, against defined specifications.

For feedstock blended in-house,

powders and binder materials are subject to a receiving inspection and forwarded to the mixing area only after quality approval. The particle size distribution of the powder and the chemical composition of the binder are important parameters as they have a significant influence on the shrinkage factor, sintered density and material properties.

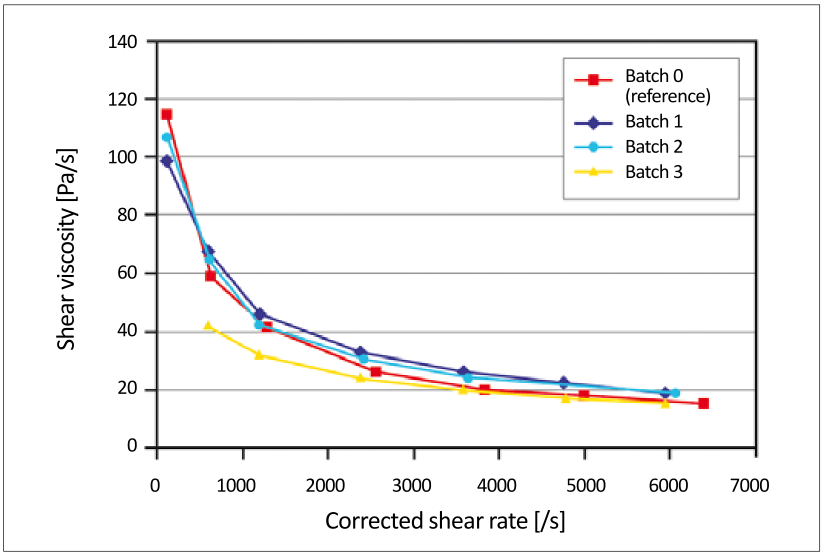


Fig. 4 Shear viscosity of different feedstock batches at 100°C

Powder particle size

The influence of particle size on the surface roughness of a component is shown in Fig. 3. It is striking that both in the green state and after solvent debinding no influence of particle size variation on the roughness is evident, although the average particle size varies between 22 µm and 75 µm. After sintering, however, the effect is clear: the greater the average particle size, the higher the surface roughness Rz. Although this correlation certainly exists, differences in the particle size distribution or agglomerates within the powder batch are very difficult to detect and have a direct influence on the injection moulding parameters and ultimately on dimensional accuracy.

Binder content and chemicals

It is obvious that finer powders need a higher binder content to achieve a similar viscosity, which then automatically results in a different shrinkage of the component itself. In order to accurately adjust the shrinkage factor it is also important to test the binder base chemicals of each binder lot for a consistent product quality as variations can affect the behaviour of the feedstock during injection moulding. Feedstock is tested for its binder content in order to guarantee a uniform shrinkage from batch to batch.

Viscosity testing

Rheological data can be very helpful for the development of moulding parameters for a feedstock. Measuring the viscosity is carried out in a capillary rheometer. The shear rate ranges up to 10,000 1/s and corresponds approximately to the conditions in the injection moulding machine. Fig. 4 shows the shear viscosity for different feedstock batches. Distinct differences from batch to batch can be seen. Compared to the reference batch there are variations in the viscosity. Deviations in the viscosity curves affect the mouldability of the feedstock and ultimately the quality of the component. However, up to now the correlation of viscosity data and moulding parameters has not been analytically proven but can only be considered empirically. Each new feedstock batch therefore has to be tested for its workability directly on the moulding machine.

Testing ready-to-mould feedstock

The quality cycle for parts producers who purchase ready-to-mould feedstock begins with the incoming inspection of the feedstock. For this purpose certificates are validated, documented and verified by random

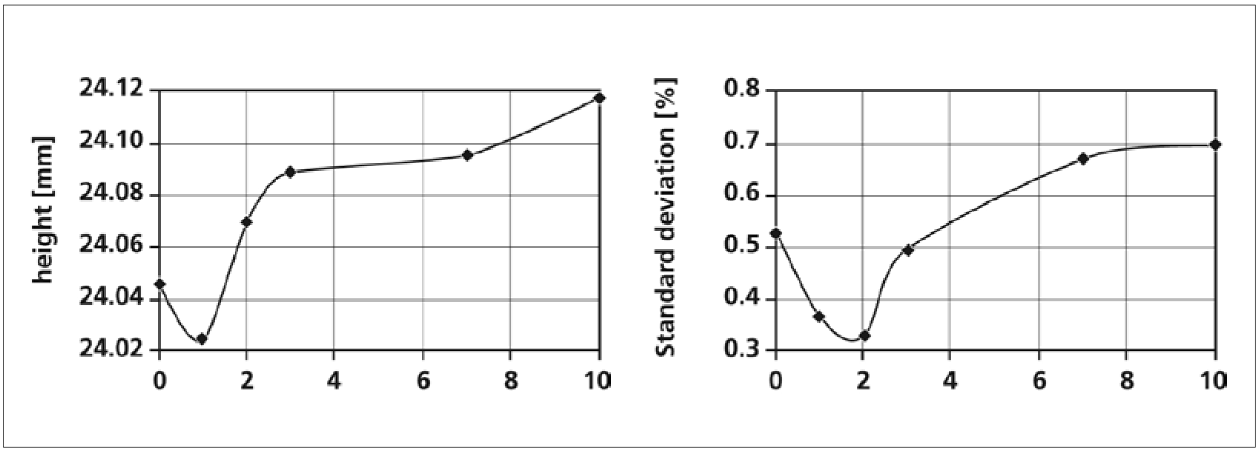


Fig. 5 Variation of the height (left) and the resulting standard deviation (right) as a function of the re-granulation of feedstock [3]

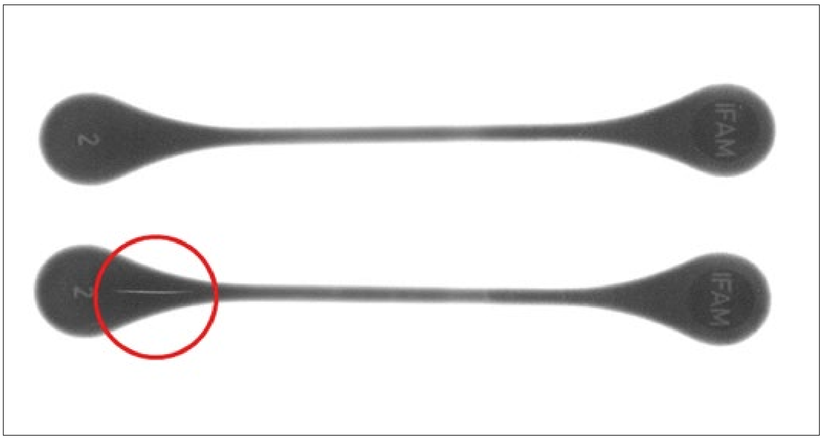


Fig. 6 X-ray of a tensile test bar according to ISO 2740. A flawless green part can be seen at the top, and a green part with defect below

sampling. Typical criteria are the chemical composition of the feedstock, the shrinkage factor for the tool and the flowability index. Only following the successful completion of the inspection can the material batch receive clearance to go through to production.

'The quality control of feedstock at a MIM manufacturer gains extra importance when it comes to the recycling and re-granulation of feedstock that has already been moulded once before'

Recycling feedstock

The quality control of feedstock at a MIM manufacturer gains extra importance when it comes to the recycling and re-granulation of feedstock that has already been moulded once before, for example from green parts with defects or sprues and runners.

Fig. 5 shows the variation of part tolerances depending on the number of re-granulation cycles. It can be clearly seen that after the first re-granulation of feedstock the dimensions of the sintered part decrease slightly. This effect could indicate an improvement in feedstock homogeneity due to re-granulation. But even after multiple re-granulations there are variations in the dimensional tolerances. Aging effects of the polymers caused by the thermal cycles may play a role.

In series production, this means that one should always work with a constant percentage of recycled material. Dust from the re-granulation process should be avoided and the granulate material should be as free as possible of fine dust. The maximum size of the granules should not be greater than the thread depth of the screw used in the feed zone.

Injection moulding

The vast majority of defects in component, such as cavities, air pockets, segregation, incomplete mould filling etc., occur during injection moulding and these are often invisible to the naked eye. The causes of such errors are numerous, ranging from poor component design, mistakes in tool design, and inappropriate injection moulding parameters to incorrect operation of the injection moulding machine. The resulting errors cannot be rectified in the following processing steps and therefore lead to increased rejects. The systematic analysis and documentation of the possible errors and their correlation to quality characteristics of injection moulded components leads to a continuous improvement of process stability and the reduction of scrap rates in production [1, 4].

Temperature

Generally, the ambient temperature at the location of the injection moulding machine, as well as the temperature of the cooling water, should be kept as constant as possible. The barrel temperatures must be adjusted according to the feedstock manufacturer's instruction. The maximum permissible temperature must not be exceeded otherwise there is a risk of feedstock decomposition.

Injection speed

The dosing speed should be adjusted for a constant dosing rate. Excessive shear (due to high transport speed or high back pressure) should be avoided during dosing. In all heating zones, the temperature should never constantly deviate upward. During speed controlled injection it must be ensured that the injection pressure is not limited - pressure limited injection should be avoided.

The switchover from speed controlled injection to holding pressure should be chosen so that the part is filled to 90 - 99 % of the volume during speed controlled injection. In general, the pressure at switchover should be selected as the pressure for holding and should be as constant as possible from shot to shot.

Testing a new mould

When a new mould is used for the first time, a mould-filling analysis should be performed to determine the necessary process parameters. During this mould-filling study, the injection volume, starting at 10% fill, is raised in 10% increments and is injected at different speeds to determine critical areas of the tool, weld line formation, cold spots etc. Based on this mould-filling study, the appropriate injection speed for actual production can be selected.

To avoid deviations in quality during ramp-up of the injection moulding production cycle, and to establish a thermal equilibrium in the entire machine / mould system, the parts from the first injection cycles either at the beginning of the production or after any modification of the machine parameters should be discarded. How many rejects must be discarded has to be determined anew for each mould.

During production

The moulding process is monitored and documented by the machine itself via the preset injection moulding parameters. The quality control of green parts is based on a component-specific test plan. The criteria required by the system, for example weight and selected dimensions, are checked at a statistical process control (SPC) measuring station.

The following parameters should be as constant as possible:

- Dosing
- Cylinder temperatures
- Mould temperatures
- Nozzle temperature
- Switching Pressure
- Melt cushion
- Cycle time
- Monitoring of the pressure curve during injection and holding pressure.

After process interruptions of more than ten to fifteen minutes the temperature in the plasticising unit should be lowered in order to avoid thermal damage to the feedstock. When production is resumed the parts from the first cycles should once again be discarded until the entire system (mould and injection moulding machine) has reached thermal equilibrium. The number of discards must be determined individually for each component.

Mould maintenance

It is vital to pay attention to regular cleaning and lubrication of the major running and guiding surfaces in the mould. The mould must be checked regularly for a constant and sufficient flow of cooling liquid. After completion of a component series, or at regular intervals, the mould has to be checked in terms of wear because this can cause deviations in component tolerances. For this, the mould cavity must be measured and the results should be compared with a reference sample retained from the start-up cycle of the mould in order to detect wear-related geometric and dimensional deviations. At specified intervals, the return valve must also be checked for defects and wear [4].

Green part testing

If all of the above-mentioned aspects have been taken into account during injection moulding, the green parts produced should at the very least be randomly examined for weight deviations. The green part weight gives information about possible feedstock separation and subsequent defects or deviations in the finished part. A correlation of the recorded data from the injection moulding sensor signals (different pressure sensors and temperatures) with the component quality allows for in-line control during series production with a high level of reliability. A more advanced approach is quality control with the help of neural networks [5].

It would be highly desirable to be able to make use of non-destructive testing methods for proper green part characterisation. So far, however, there are no non-destructive test methods available that can be used during series production for green part inspection. There are several reasons for this. It is possible with today's X-ray micro focus systems to make defects visible such as segregation in the green part, yet differentiation between moulding defects or normal porosity in the green part is blurry. Fig. 6 shows an X-ray inspection of a defect-free tensile test bar according to ISO 2740 in comparison with a tensile test bar with a moulding defect. Additionally, the

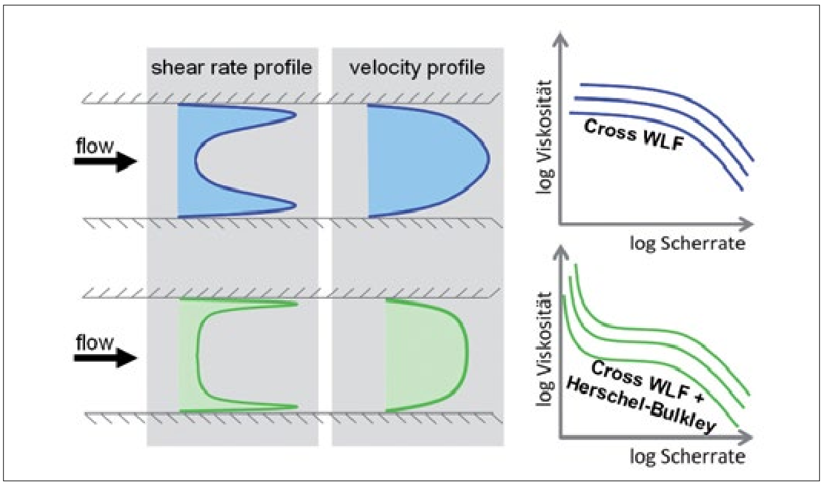


Fig. 7 Different flow profiles for the Cross-WLF model and the Cross-WLF + Herschel-Bulkley model [7]

typical high geometrical complexity of injection moulded parts rather complicates a reliable quality monitoring with non-destructive testing methods. Finally, the necessary time and expenditure for non-destructive testing is possibly only justifiable during component development.

Simulation

Since the quality of a MIM component is largely determined by the mould filling behaviour, the use of 3D simulation is an increasingly important tool for the improved design of moulds. There are typically several iterations necessary for each new mould until the production with the required component specifications runs at a stable speed. In practice, process engineers are developing solutions based on experiences, measurements and design of experiments (DOE) studies.

Conventional simulation software, such as it is used for the injection moulding of thermoplastic materials, cannot be recommended for Metal Injection Moulding. The high degree of metal powder in the feedstock affects the thermo-physical properties and rheology. Therefore, to obtain a reliable simulation of the mould filling, feedstock parameters such as thermal conductivity, heat capacity and pvt-behaviour must be known and additionally, the model used for the simulation must be adapted to the specific rheological behaviour of the feedstock.

By collecting data on the mould filling and the temperature distribution in the mould an ideal gate position and parting line can be simulated even before the mould is actually made. With the help of modern simulation software production-related problems and weaknesses in the mould design can be detected before they arise. This applies not only to product and mould design, even at mould proving and during production potential problems and their causes can be determined efficiently. Injection moulding simulation software takes into account the entire mould with all components as well as all process steps and times. This enables the analysis of the tool behaviour across multiple injection moulding cycles and the influence of cycle interruptions on the number of rejects and quality, cost, and energy efficiency.

Fig. 7 explains schematically the effects that result from different rheological models in the form-filling profiles. The Cross-WFL model, as applied for thermoplastic materials, is compared with the extended model according to Herschel-Bulkley which is adjusted for MIM. It shows that the typical behaviour of MIM feedstock is reproduced over the entire shear rate range [6, 7]. The sharp increase in viscosity at low shear rates is particularly characteristic for the behaviour of MIM feedstock, behaving rather like a solid body in this area and not as a polymer melt.

Experimental studies verify the quality of form filling simulation with the extended model. Both the form-filling phase and the solidification of the feedstock could be significantly improved.

Fig. 8 shows a mould that is being used to compare the experimental form filling study with the simulation results. Due to its numerous generated flow lines, it can provide information about a feedstock's tendency to form cold weld lines that can appear as cracks after sintering.

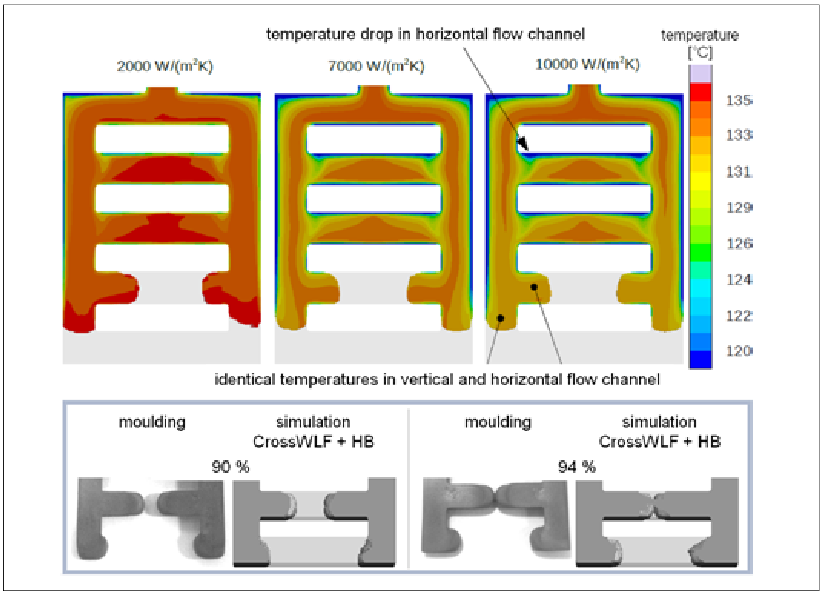


Fig. 8 Validation of the viscosity model with the "ladder" mould insert [7]

Debinding and sintering

The most important quality parameter for debinding is the weight loss of the binder. In a two-stage debinding process, the weight loss can be measured by weighing the part after the first process step, for example solvent debinding. For the mechanical properties of the finished part it is extremely important to remove all binder residues. The thermal decomposition of binders results in gaseous products which can alter the set furnace atmosphere for sintering and may lead to undesirable chemical reactions. This influence can be detected with a mass spectrometer and the process can be adapted accordingly [8].

'The thermal decomposition of binders results in gaseous products which can alter the set furnace atmosphere for sintering and may lead to undesirable chemical reactions'

Sintering is carried out under the constant monitoring of the furnace parameters. Variables such as temperature, pressure, gas flow and cycle time are monitored online and documented via the furnace control interface. Quality control based on the test plan for the sintered parts must be performed after sintering at the SPC measuring station. Typical criteria are density, hardness, strength, dimensional accuracy and optical characteristics.

Temperature measurement and furnace calibration

Temperature measurement accuracy is crucial for the quality of the sintered parts and is regulated in various guidelines. Here, factors such as the application, processes and types of furnace play a critical role. The aim is to abide by recognised benchmarks [9].

The general German standard for temperature distribution in heat treatment furnaces is DIN 17052-1. Special requirements of the North American Automobile Association (AIAG) are defined in the CQI standards. CQI-9 is the relevant standard for the evaluation of thermal treatment systems. Special requirements of the aviation industry are defined in AMS2750 (Aerospace Material Specification). Methods for the determination of system accuracy by, for example comparative measurement at operating temperature of the measuring, recording and control system, are applicable without restriction with both walking beam

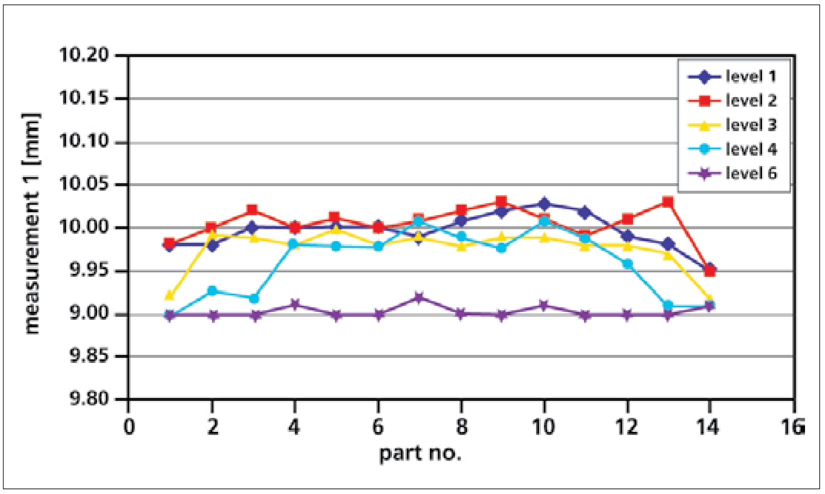


Fig. 9 Systematic measuring of sintered parts to determine the tolerance range depending on the oven position: - horizontal impact by heating conductor (Part no.) - vertical impact (sintered level)

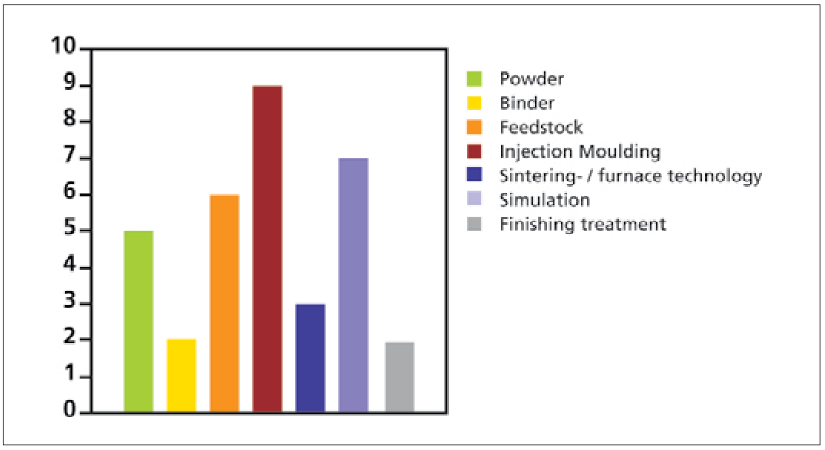


Fig. 10 Relative influence of process steps on the part quality on a scale from 1 to 10

furnaces and pusher furnaces. Methods for the direct determination of the temperature distribution by introducing calibrated sensors in the furnace chamber under production conditions are not applicable because of the necessary insertion of the reference elements through the double door system of the furnace's inlet and outlet.

Since the introduction of thermocouples into closed furnace systems is difficult, alternative methods can be used to determine temperature homogeneity, for example, by the introduction of temperature-sensitive products which react to temperature changes by changing size. These single-use process temperature control devices, in the form of tablets or discs, are widely used and provide information on the amount of heat absorbed (integral formation over the run length) Despite the sometimes difficult circumstances, the demand for a quality standard according to DIN 17052-1, CQI-9 or AMS2750 can be implemented in both continuous and batch systems.

Fig. 9 depicts specific measurements of a component dimension taken from a sintering batch from across all six furnace levels. Significant dimensional deviations can be recognised which are due to the temperature distribution in the furnace. The components in the vicinity of the heating elements have experienced greater shrinkage.

HIP treatment

In case additional processing steps need to be carried out after sintering, these must also be documented in the test plan. Even contracted-out machining processes can be added to the quality management system of the component manufacturer, for example with the measurement protocols of the service provider.

Due to the fineness of the metal powders used in MIM, the parts achieve sintered densities above 95% of the theoretical density. They can therefore be further densified in a HIP process without the need to be encapsulated. Discolorations are easy detectable by visual inspection, and should be taken into account, as they represent possible carbide or oxide indications at grain boundaries. In such cases, the parts must be discarded and, assuming the customer's consent, treated again. Experience shows that with the help of getter scrap, the used gas can be cleaned and discolorations can be reversed. The same effect can also be achieved by cycles of fresh gas. Consequently, the used argon gas needs to be pure enough for the HIP process [10].

Conclusions

Our understanding of the complete MIM process and the complex relationships between component faults and manufacturing parameters has grown significantly in recent years. Considering the current status of MIM production it is realistic to believe that scrap rates in high volume series production could in some cases be minimised to less than 2%. This can be achieved through the establishment of comprehensive quality monitoring systems. Such systems, however, have to be adjusted and verified for each specific component. Fig. 10 shows a subjective assessment of the importance of each MIM processing step, along with supporting technologies, for achieving zero-defect production.

By tailoring powder production to the special requirements of MIM a further improvement in the quality of the component is to be expected. In particular, minimising the differences between individual powder batches, but also tailoring particle morphology and particle size distribution will play a role in achieving tighter tolerances and better surface roughness.

The influence of the organic binder as a temporary additive in the process is widely understood and has, just like the debinding technology, rather less potential for further improvement of component quality. With feedstock, the need for improved batch-to-batch consistency is a particularly important step for compliance with tight manufacturing tolerances.

The injection moulding process itself has the greatest impact on product quality. The quality of the finished component is strongly influenced by the mould filling of the green part. There are many parameters for optimising the green part quality. One of these is mould-filling simulation, which can predict with increasing reliability where problems are to be expected in the green part. Further improvements in the simulation can be expected by an accumulation of a refined database (for example PVT data for various polymer mixtures) and the prediction of powder-binder segregation. There is, however, still a long way to go until component distortion can be simulated reliably.

Furnace technology has a distinct influence on dimensional tolerances. Through further development of measurement and sensor technology, temperature and atmospheric homogeneity are being continuously improved. Through finishing treatments such as HIP, a further increase in the mechanical properties of parts can also be achieved.

MIM is today mature and advanced technology for the mass production of complex metallic components that can meet customer demands at the same time as achieving low scrap rates. Our understanding of the process has already reached a high level however there is still room for improvement in all manufacturing steps on the road to zero-defect production. This is especially true for the systematic control of complex relationships in the overall process chain.

Acknowledgements

The German MIM Expertenkreis works on the task to develop MIM process understanding and to contribute to the dissemination of MIM technology. This article is based on the cooperation and information provided to me by members of the MIM Expertenkreis. Special thanks to the following companies:

- Arburg GmbH & Co. KG
- Bodycote HIP Ltd.
- Cremer Thermal Process Systems GmbH
- GKN Sinter Metals GmbH
- Inmatec GmbH
- Schunk Sintermetalltechnik GmbH
- SIGMA Engineering GmbH

Author

Prof. Dr. Ing. Frank Petzoldt
Deputy Director
Fraunhofer IFAM
Wiener Str. 12
28359 Bremen
Germany
Tel: +49 421 2246 134
Fax: +49 421 2246 300
Email: petzoldt@ifam.fraunhofer.de

References

[1] German, R. Understanding defects in Powder Injection Moulding: Causes and Corrective Actions, *PIM International*, Vol 6, No. 1, January 2012, 33-44
[2] Schwarz, J., Lenk, T; GKN Sinter Metals GmbH, personal communication
[3] Fridman, G. Effect of some technological parameters on the properties of injection moulded and sintered powder materials, Proceedings EuroPM 2001, Vol 3 (2001) 141-146
[4] Walcher, H.; Maetzig, M; Arburg GmbH & Co. KG, personal communication
[5] Schwenzel, J.; Petzoldt, F. Process stability and quality surveillance in the MIM process - towards zero rejection based on artificial neural networks, Proceedings EuroPM 2009, Vol 2 (2009) 129-134
[6] Thornagel, M.; Florez, L. Successful cycle optimization and quality improvements based on process simulation results, Proceedings EuroPM 2012 Basel
[7] Thornagel, M. Injection molding simulation: New Developments offer rewards for the PIM industry, *PIM International*, Vol 6, No. 1, January 2012, 65-68
[8] Hartwig, T.; Mueller-Schroeder, R. Analysis of the debinding and sintering of MIM parts by mass spectrometry, Kolaska H. (ed.) *Pulvermetallurgie in Wissenschaft und Praxis*, Vol 27 (2011), 273-284
[9] Cremer, I.; Cremer Thermoprozessanlagen GmbH, personal communication
[10] Graf, W.; Porst, O.; Volker, K.-U.Quality assurance during Hot Isostatic Pressing, Vandewiele, B. (Ed.), Proceedings "Quality in Heat Treatment" (2005)

ARC Group Worldwide, Inc.: A global leader in MIM embraces the Additive Manufacturing revolution

In 2012 a new global force in Metal Injection Moulding was created when ARC Group Worldwide, Inc. (ARC) acquired Advanced Forming Technology, Inc. (AFT) and FloMet LLC to create one of the world's largest MIM businesses. ARC has since moved to improve the efficiency and competitiveness of its MIM business, as well as enhancing its customer offering by embracing Additive Manufacturing. *PIM International's* Nick Williams profiles the business and outlines the strategic vision behind the developments at ARC Group to-date.

ARCMIM, the combined MIM businesses of the publicly traded ARC Group Worldwide, Inc. (NASDAQ: ARCW), is a relatively new name on the global MIM scene but the operations that make up the business are amongst the most widely recognised names in the industry.

Advanced Forming Technology, Inc.(AFT Colorado) and FloMet LLC, both based in the USA, along with AFT Hungary Kft. (AFT Hungary), are three MIM facilities that make ARCMIM one of the world's largest MIM producers. The ARC group as a whole appears to be set on a course that will see a significant expansion of its precision components capabilities through growth in existing businesses and also acquisitions.

ARC was founded in 1987 and the company today has a stated mission of bringing innovation and technology to precision components manufacturing. The group's core manufacturing businesses are in precision components, flanges, fittings, and wireless technology. Through the continued adoption of automation, robotics, artificial intelligence, 3D imaging and Additive Manufacturing, ARC believes that manufacturing will again become more of a local business as new technologies disrupt the conventional global supply chain. Additionally, the group is focused on consolidating its customers' supply chain by providing a holistic product offering in plastic and metal fabrication, with a primary focus on helping its customers get to market quickly.

It was in 2012 that ARC acquired the operations of AFT as well as Quadrant Metals Technologies, LLC, a holding company that owned a majority interest in several manufacturing businesses including FloMet LLC. At the time of the

Fig. 1 A view of an injection moulding area at AFT Colorado

Fig. 2 A sintering furnace at AFT Colorado

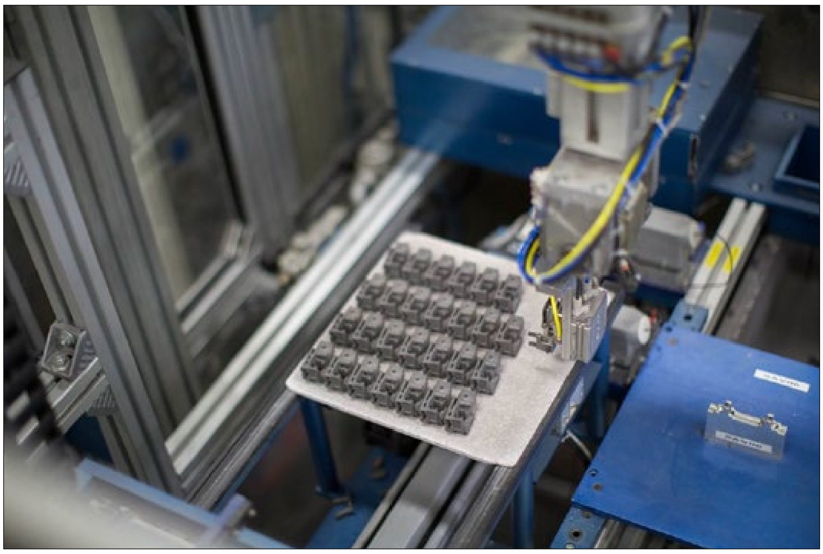


Fig. 3 Automation plays a vital role at AFT's Colorado plant

transaction Jason Young, Chairman and CEO of ARC, stated that the ambition of the group was to create the world leader in MIM production, with the individual operations benefitting from the synergies that a larger organisation can provide.

ARC today operates four business segments:

- The Precision Components Group, consisting of FloMet, AFT Colorado, AFT Hungary, Thixoforming LLC, and Tekna Seal LLC;
- The Flanges and Fittings Group, consisting of General Flange & Forge LLC;
- The Wireless Group, consisting of ARC Wireless LLC, ARC Wireless Ltd, and ARC Wireless, Inc.; and
- The 3DMT Group, consisting of 3D Material Technologies (3DMT) and Advance Tooling Concepts, LLC.

The Precision Components Group achieved 2012-2013 fiscal year sales of nearly US$60 million, of which approximately 90% related to MIM component sales with the balance relating to the Tekna Seal business. Precision Components Group sales for the six months ended December 2013 were $32.0 million, an increase of $6.9 million or 27.6% compared to the comparable prior year period. In the 2012-2013 fiscal year the MIM businesses received a record number of 51 new tooling orders representing some US$ 17.6 million in incremental revenue at anticipated production volumes.

In comparison to the majority of MIM producers worldwide, ARCMIM is an industry giant. Commenting on the driving factors behind the creation of ARCMIM, Young told *PIM International*, "Building ARC's scale has been thirty plus years in the works. Our consistent mission has been to create the leading MIM company in the world. As such, we have focused on growing our operations through both organic and external growth avenues. One of the primary reasons for this approach is that while MIM technology has been around for more than three decades, its acceptance by OEMs and industry outsiders is still very much in its infancy. Our scale eliminates much of the reluctance among end users to investigate MIM and therefore enables the introduction of MIM technology into more markets. While scale is important, our focus on quality, on-time delivery, and proprietary material technologies is equally important to our global customers and their applications."

ARCMIM facilities

AFT Colorado

Founded in 1987, AFT Colorado, based in Longmont, operates more than 46 injection moulding machines, 14 sintering furnaces and four de-binding units in nearly 15,000 m^2 (160,000 ft^2) of manufacturing space. The facility has more than 120 employees.

AFT Colorado has a wide range of capabilities but specialises in NiFe components that are generally used in the firearms and consumer markets. The facility also produces MIM high temperature alloys and superalloys for the automotive, aerospace and medical markets.

AFT Hungary

Founded in 2002, AFT Hungary, located in Rétság, one hour's drive north of Budapest, is one of the largest MIM plants in Europe.

The 6,500 m^2 (70,000 ft^2) facility employs over 170 people. It is centrally located to serve the needs of the entire European region but specialises in high volume automotive components made from HK30 and 440C stainless steels.

The facility has a fully automated grinding cell for the mass production of turbocharger vanes as well as secondary equipment capable of producing parts for the consumer and medical markets. The plant features an extremely high degree of automation. Both the AFT Hungary and AFT Colorado plants compound their own proprietary feedstock in-house.

Fig. 4 View of an injection moulding area at AFT Hungary

FloMet

Whilst FloMet was founded in 1990, the history of the company's MIM operation traces its roots back to the early 1980s when MIM was in its infancy. Today FloMet manufactures complex components that are used for a wide range of applications across an array of industries including orthodontics and orthopaedics. FloMet operates out of a 3900 m^2 (42,000ft^2) facility in DeLand, Florida. The company operates 14 injection moulding machines and employs around 150 people. FloMet's injection moulding machines have clamping forces ranging from 50 to 165 ton and almost all are Milacron all-electric machines.

FloMet also compounds all of its feedstock in-house, however the binder technology that the company has refined over several decades is different to that developed at AFT. It is stated that FloMet's feedstock system, combined with advanced hot runner technology, has the advantage of enabling the moulding of MIM parts that many competitors are simply unable to process. Today, ARCMIM benefits from having both feedstock systems available at all three facilities, allowing the production team to make the best selection according to the characteristics of the part that is being developed.

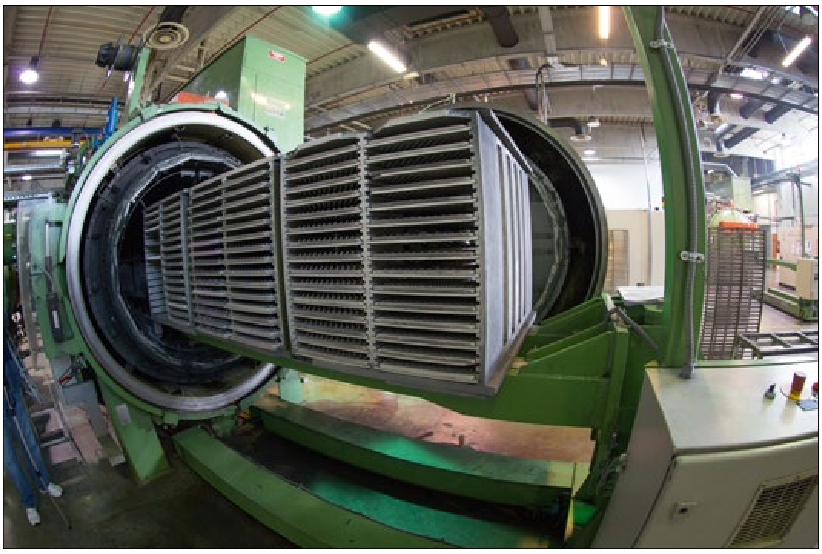


Fig. 5 A forklift loading a sintering furnace at AFT Hungary

Growth and capacity expansion

Since acquiring its MIM operations ARC has focused on the integration of certain shared services as well as sharing of best practices amongst the manufacturing sites. These efforts, it was stated, have led to increased efficiencies, a stabilisation of the work force, a reduction in scrap, improvements in first pass yield and cost reductions due to purchasing leverage between locations.

In addition to growth through capacity expansion at existing plants and lean manufacturing initiatives, ARC is not ruling out plans for further expansion through acquisitions.

In April 2014 ARC announced the acquisition of Advance Tooling Concepts, LLC (ATC) and Thixoforming LLC. ATC is a leading US plastic injection moulding company with a specific focus on the medical device, electronic, consumer, and defence industries, whilst Thixoforming is a leading provider of magnesium alloy components. The ATC acquisition, stated ARC, not only offers significant new customer bases that will enable cross-selling opportunities across the full suite of ARC products and services, but it also adds significantly to ARC's MIM tooling capability as ATC is a key supplier to ARC for MIM tooling. The acquisition, stated ARC, will therefore reduce tooling lead

Fig. 6 Sintering furnace at AFT Hungary

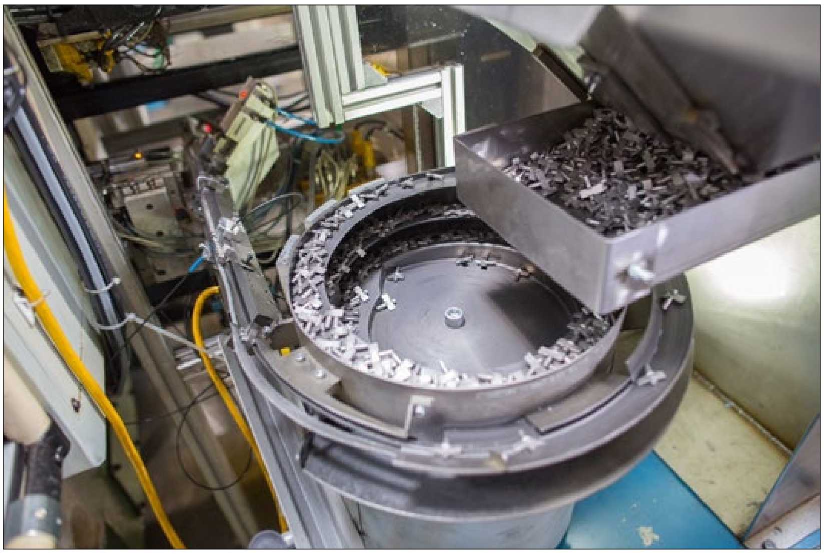


Fig. 7 Automotive turbocharger components being processed at AFT Hungary

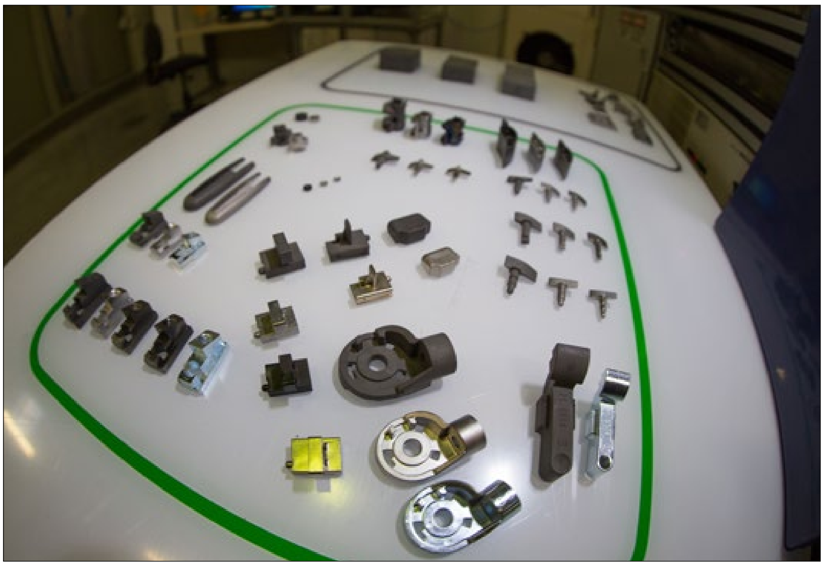


Fig. 8 A selection of MIM parts manufactured by AFT Hungary

times and costs through vertical integration and will shorten the time to market for ARC customers. ATC generated revenues of more than $17 million in 2013.

Young told *PIM International*, "We continuously evaluate the best method of expansion for our company, from both a client and shareholder perspective. Overall, we believe the MIM industry remains poised to continue its robust growth, and believe ARC is well positioned to benefit from this improvement. Further, by increasing our abilities to be a holistic solution to our customer base - offering additional forms of metal and plastic fabrication, rapid prototyping, low volume production, etc. - we stand to reap outsized gains from this industry wide growth. Therefore we expect to not only continue to grow our existing MIM operations, but also add new forms of fabrication in order to provide a 'one-stop shop' for our customer base. Additionally, another major strategic initiative is to help our customers get to market quickly by shortening lead time and delivery. We plan to accomplish this initiative through a combination of organic growth, acquisitions, and through the utilisation of proprietary online instant quoting software."

With plants in both the USA and Europe, ARCMIM sees itself as a global MIM provider. Young commented, "Our approach has always been to focus on both the domestic and international market opportunities. Our global sales force is very focused on selling our products in key markets around the world, including Asia and other emerging markets, given the size of the respective opportunity."

Rapid prototyping of MIM parts from feedstock

ARCMIM also offers what it calls the RapidMIM process at all three of its MIM facilities. The RapidMIM process, which involves the precision machining of components from a green feedstock block, enables customers to validate not just the form, fit and function of a product, but also the MIM material properties and surface finish.

Ashley Nichols, General Manager at 3DMT stated,"3D printing doesn't exactly replicate the MIM process in terms of material properties and surface finish, so we also developed the RapidMIM process this last year. In this process, we use the same material, debind and sintering process as with traditional MIM, but have shortened the development time for the first part to just one week."

"RapidMIM is also very good for short run production when volumes are too low to justify mass production MIM tooling. Often parts can be prototyped with 3D printing in one or two days, then RapidMIM can provide five to ten parts in one to two weeks and ultimately provide low volume production while the customer validates and does initial market testing on a product."

MIM and the automotive industry

The automotive industry is a market with huge potential for MIM and in Europe MIM technology enjoys a much higher level of acceptance within the automotive community than in Asia and North America. One of the factors behind MIM's historic success in Europe was the adoption of MIM turbocharger components, initially fuelled by the widespread use of turbocharged diesel engines amongst Europe's passenger vehicle fleet.

Commenting on ARCMIM's position as a leader in the production of MIM automotive turbocharger components, Laszlo Nagy, Managing Director at AFT Hungary, told *PIM International*, "ARCMIM definitely sees the market for turbocharger components and high temperature alloys expanding in the near future. As automotive manufacturers move to lower displacement engines, they will need to get more power from these smaller engines. The turbocharger fits in perfectly with this market scenario for lower displacement and more power. ARCMIM is also seeing an interest in higher temperature and lighter weight alloys that can help improve performance of the turbochargers."

Fig. 9 A component inspection area at AFT Hungary

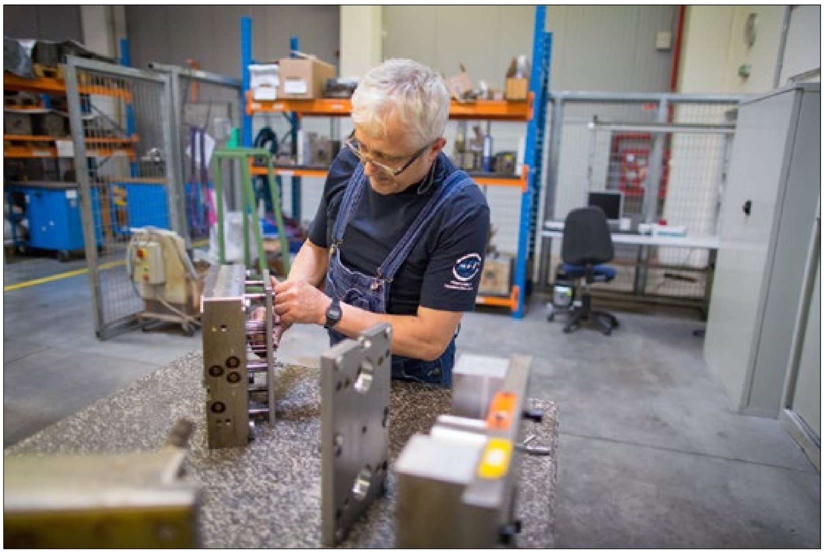


Fig. 10 Tool maintenance at AFT Hungary

"The automotive market is a particularly challenging market due to the fact that it is very demanding in terms of quality, price and delivery. It is essential that parts meeting specification get to the customer to maintain production lines at the right prices in a highly competitive marketplace. The challenges that the MIM technology faces in the automotive market are the continuing strive for scrap reduction and increasing first time product yield. The advances that can be made for the automotive market place to capitalise on opportunities are going to rely on the successful introduction of new MIM materials as automotive customers move to more stringent specifications for their emerging products. These new materials will begin to form the backbone of automotive manufacturing in the future."

ARCMIM also believes that thanks to its automotive expertise in Europe it is well positioned to grow through increasing demand for turbocharged engines to help meet the higher fuel efficiency (CAFE) requirements in the US automotive industry. The CAFE requirements are expected to promote the transition of the US car fleet to smaller engines as has happened in Europe over the last ten years.

Fig. 11 An injection moulding area at FloMet

Fig. 12 Automated placement of green parts prior to debinding and sintering

Fig. 13 MIM parts stacked for debinding and sintering at FloMet

Aerospace

Aerospace is another sector that offers significant opportunities for both MIM and Additive Manufacturing. Kevin Schwindt, VP of Sales and Marketing at ARCMIM, told *PIM International*, "We believe there are significant opportunities for both our ARCMIM and 3DMT businesses in the aerospace sector and we are positioning ourselves to be a market leader. Just like in other industries there are challenges to gain customer confidence and business. The first challenge was to become AS9100 certified. This is a very long and rigorous quality process, however we found that it was extremely helpful in managing our businesses. Secondly, you need to have an experienced materials development staff to work with aerospace customers on material requirements. Finally, you ensure that staff who are working with aerospace companies really understand that industry."

"ARCMIM has demonstrated the attention to detail and quality needed for the aerospace market. With our superior metallurgical properties we have demonstrated the know-how to develop aerospace products and are currently in production on several aerospace components," added Schwindt. The company states that viable MIM aerospace components include bushings, fasteners, compressor blades, rotors, brackets and inlets.

In what is believed to be a first for the MIM industry ARCMIM recently manufactured a MIM component that was an integral part of a rocket propulsion system that launched into space. Commenting on the project, Schwindt stated, "It is our understanding that this is one of first MIM parts in space, which we are extremely excited about. We had a very tight timeline to get this product manufactured and we were one of the few companies capable of producing it. We were able to produce a rapid prototype and get the part into production very quickly in order to deliver on time for launch."

Common aerospace materials processed by ARCMIM in Colorado include the high temperature alloys Nimonic 90 and Hastalloy. The company also has the capability to manufacture MIM titanium components. Schwindt commented, "We have developed a Ti-MIM process but do not currently have anything in production. We are actively looking for new product developments to break the Ti barrier within both MIM and 3DMT. We know this is a market place which can lead to significant growth for our company."

Firearms

ARCMIM states that it is the largest manufacturer in the USA of MIM components for the firearms industry. Demand for MIM parts in this industry, suggested ARC, continues at record levels for its customers and AFT Colorado has added capacity to accommodate this growth, which it expects to continue through 2014.

Looking to the future, Schwindt commented, "We wish we could accurately predict the impact of political factors on the firearms industry. We are constantly discussing forecasts within the firearms industry, as well as other industries, to ensure we have adequate production and manpower capacity. We will continue to work with our current and future firearms customers where we can produce MIM parts and continue adding 3DMT capabilities to help them grow their businesses. We are working on reducing lead times for both new product developments as well as production cycles for existing parts, allowing firearms customers to be more flexible to adjusting to the constant market changes."

Medical

The medical devices market is a valuable and high growth area for the MIM industry and all three ARCMIM facilities supply this market to some degree. The FloMet business, whose processes and feedstock systems are particularly suited to high volume, extremely small components, often with thin wall sections, has received a number of MPIF awards for its medical device and orthodontic components, some of which are as small as 0.05 g and with wall sections as thin as 0.254 mm.

ARCMIM stated that in the 2012-2013 fiscal year it received significant new tooling orders from a medical device company that is an industry leader in robotic surgery techniques.

Fig. 14 Visual quality inspections at FloMet

Fig. 15 Quality inspection at FloMet on a coordinate-measuring machine

Marketing MIM

It is widely accepted that there is still very poor awareness of MIM technology in the global design engineering community. AFT has for nearly ten years taken a pro-active role in addressing this issue through its "MIM School" seminars taught at its Longmont, Colorado, facility. This tradition is now continued under the leadership of ARCMIM.

The MIM School consists of a two day training seminar for new and existing customers, vendors and shareholders who wish to learn more about the MIM process. Since the start of the school in 2005 AFT has trained over 250 students in MIM technology. The seminar guides students through the technical aspects of MIM, from the materials technology of metal powders, to the compounding of feedstock and secondary processes, through to the use of both classroom and hands-on

Fig. 16 The 3DMT operation is focused on prototyping and short run production

training on the manufacturing floor. Four MIM schools are being held in 2014 with this year seeing the incorporation of Additive Manufacturing into the programme. In addition to the MIM School and conventional marketing activities such as trade show participation, ARCMIM sees social media as a key route to promoting MIM technology.

Commenting on the future evolution of the MIM industry, Young concluded, "The MIM industry has shown spectacular growth over the last two decades, and we believe this trend should continue as the general awareness of MIM technology improves. We are quite excited about the opportunities and believe ARC is uniquely positioned to remain the world leader in MIM."

3DMT: ARC's Additive Manufacturing business

In addition to its ARCMIM operations, ARC made a move into the world of Additive Manufacturing with the creation of its 3DMT business. Nichols explained to *PIM International*, "ARC expanded into 3D printing for two reasons. First, current MIM customers all want a full service provider that can do rapid prototyping and short run production as well as MIM for mass production. Adding 3D printing capability provides the customer with a solution from the very first plastic prototypes used in concepts to functional metal parts for initial fit and function testing, as well as low volume prototype lots to validate the product before making investments into mass production tooling."

However, ARC does not see the 3DMT business just for MIM prototyping, but also for the series production of additively manufactured parts. "MIM doesn't have the design freedom that is possible in 3D printing. Metal 3D printing is a natural fit for ARC with our experience in metal powders and we can provide customers with new solutions that MIM can't provide. The greatest strength of 3D printing is to design new solutions that aren't even possible with conventional manufacturing technologies. 3D printing is a great strategic complement to our MIM business and allows us to expand into new products and markets by providing a solution to our customers that wasn't available in the past," explained Nichols.

Various Additive Manufacturing technologies are currently installed and these capabilities are available in both Europe and the US. Nichols stated, "Currently 3DMT can offer Fused Deposition Modelling (FDM), Multijet Printing (MJP) and Stereolithography (SLA) for plastic parts. For metals we have powder bed laser melting technology from three different equipment manufacturers. Each technology and piece of equipment has its strengths and fits certain applications. We went with several different metal printing equipment suppliers so that we can select the best equipment for each type of part. Having multiple printers also allows us to run several different alloys without having to switch out a machine. Always having a machine ready with the right alloy reduces the lead-time for the customer."

"Along with having multiple printing technologies, 3DMT provides all of these capabilities at multiple locations. Currently we have plastic printing capability in three facilities, two in North America and one in Europe. Metal printing is currently available in both North American facilities and will expand into Europe this summer. 3D printing is not just making parts, but providing a solution to the customer on a very compressed timeline, so localising production close to the customer is important."

In February this year the 3DMT division announced the purchase of three 3D Systems Corp. ProX™ direct metal sintering (DMS) machines. With a build size of 250 x 250 x 300 mm (9.8 x 9.8 x 11.8 in.), these new machines have the capability of making a wide variety of parts out of metals and ceramics. "The technology in the ProX machines is what attracted us to the 3D Systems equipment. In particular, the ability to make stainless steel, titanium, aluminium, and alumina with fine powders, high-quality surface finishes, and thin walls complements our sister companies' MIM capabilities. These are the capabilities that our medical, aerospace, automotive, and defence customers are demanding," stated Nichols.

Commenting on the feedback that has been received from MIM customers to the availability of Additive Manufacturing and prototyping capabilities within ARC, Drew Roberts, Engineering Manager at 3DMT, stated, "The reaction of our customers to this new capability has been extremely positive. 3DMT brings a new level of early stage development to the MIM process. This includes rapid prototypes through

3D printing and Rapid-MIM, as well as short run production, used to fully test functionality of part designs. This gives our customers the ability to test multiple variations of part designs for minimal costs and dramatically shortened lead-times. This carries over into a shortened time frame for MIM development, eliminating the need for prototype tooling as well as greatly lowering the chance for tool modifications, which can be very costly and time consuming."

Roberts added, "The prototypes, as well as our 3D printed production parts, are fully functional right out of the printers. Depending on the process and application there will be some clean up and support removal involved. There are also options for different cosmetic finishes, including sanding, painting and coatings, as well as a variety of processes to improve different mechanical properties, such as heat treating and HIP."

3D printing also offers the potential to speed up the development time of MIM tooling through the production of 3D printed tool inserts. Roberts stated that 3DMT is currently in an engineering development stage with regards to the use of 3D printing technology for MIM tooling. "With the various technologies and applications 3DMT is pushing development of rapid tooling combined with Rapid-MIM and 3D printed prototypes, 3DMT will be able to offer a full range of rapid 3D solutions."

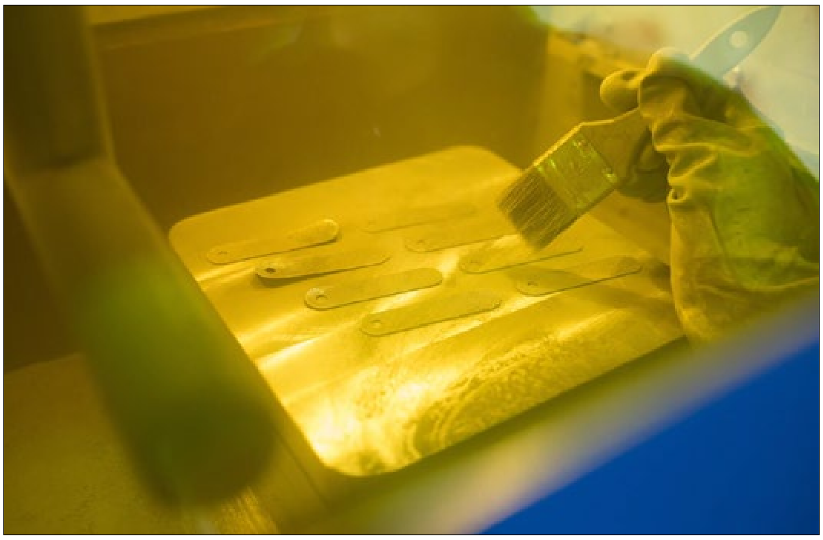


Fig. 17 Inside the build chamber of one of 3DMT's AM machines

Competing on a global stage

The global MIM business is becoming increasingly competitive and a combination of excess capacity in, for example, the Chinese MIM industry, combined with that region's increasing technical competence, continues to force producers in higher cost economies to innovate to remain competitive.

Kevin Schwindt, VP of Sales and Marketing at ARCMIM, stated, "We are hearing from our customer base that Asia is not necessarily the lowest cost provider when you look at landed costs or total delivered costs. There is a cost to ship product all around the world to both the United States and Europe. Customers want more robust delivery methods that are focused on shorter lead times. In particular customers with smaller components and batch sizes that are required to ship ocean freight do not fit this model. Thus Asian suppliers are forced to pay higher freight costs to achieve shorter delivery times. Another significant change is the use of automation to reduce the number of employees required to produce MIM parts. We are spending significant resources and capital dollars to purchase equipment with automation. We have our own internal automation group focusing solely on reducing future headcount requirements through automation."

Outlook

Commenting on the outlook for the ARCMIM and 3DMT businesses over the next decade Schwindt stated, "The driving force of our company is to bring innovation to manufacturing. We plan to dominate the MIM and 3D printing markets. We have to help customers solve their problems in manufacturing and delivery. We see our new strategy of 3DMT as a key driver to open new markets that have not been served by MIM due to shorter run counts or material requirements. Adding 3DMT to our business model was a strategic move to provide a competitive advantage to our ARCMIM customer base. The technology, capabilities and resources of 3DMT gives our customers the ability to get their components to the market first."

"MIM is still a relatively new technology and it is our goal to create awareness across all markets of the advantages and benefits versus traditional manufacturing methods. There have been advances in the capabilities of MIM that have just surfaced over the past few years. The addition of 3DMT to our portfolio will also enable us to bridge the gap between the market segments that typically turn to alternative technologies due to lower annual volumes. R&D engineers are always searching for the next best thing and we believe that the capabilities of MIM paired with the core values of ARC Group Worldwide will open doors to multiple opportunities across all market segments."

Contact

Kevin Schwindt
VP of Sales and Marketing
ARCMIM
810 Flightline Blvd
DeLand, FL 32724
United States
Tel: +1 303 833 6012
Fax: +1 303 833 6464
www.arcmim.com

Is MIM just too good? High part-to-part consistency challenges forensic firearms examiners

A keynote presentation at the MIM 2014 Conference, Long Beach, California, February 24–26 2014, reviewed how MIM's excellent part to part consistency is posing new challenges for forensic firearms examiners. Detective Darin Marcinkiewicz, St. Louis County Police Department, Missouri, USA, in his presentation "Forensic Challenges Attributable to MIM Part-to-Part Consistency" introduced the science of firearm forensics and explained how the manufacture of firing pins by the MIM process has impacted on the effectiveness of forensic examinations. Nick Williams reviews the presentation for *PIM International*.

Metal Injection Moulding (MIM) has for many years been a leading technology for the production of firearms components. The ability of the process to manufacture complex, high-performance components in high volumes whilst maintaining tight tolerances has led to the technology's widespread adoption internationally. North America in particular has in recent years been an extremely strong market for MIM firearm components thanks to the surge in gun sales driven by the fear of future ownership restrictions. The firearms sector is today the leading market for MIM in the US. Initially the production of MIM firearms components was dominated by the larger gun firms; however in recent years smaller manufacturers have started to adopt MIM technology. The success of MIM in the firearms industry has, however, started to pose new challenges for forensic firearms examiners.

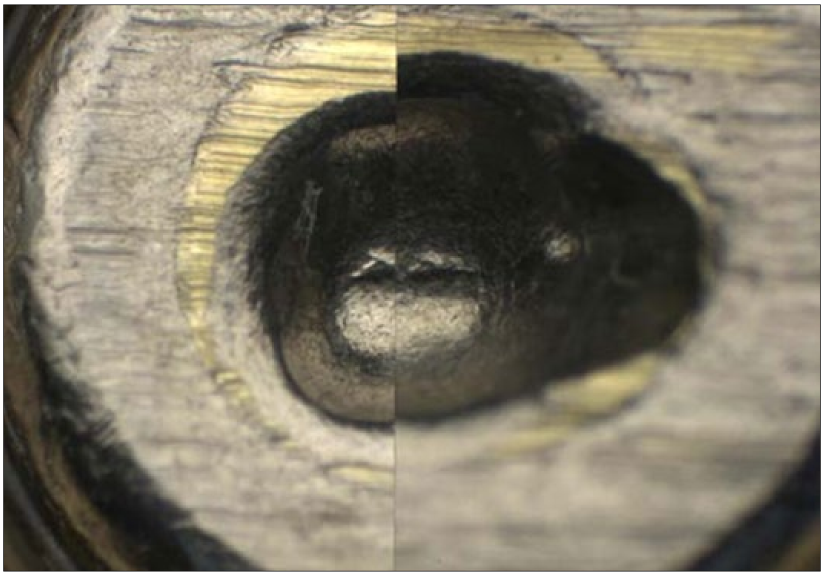


Fig. 1 Comparison microscopy of test shots from two pistols of the same model type using a MIM firing pin

The importance of the firing pin in forensic examinations

Detective Marcinkiewicz briefly introduced delegates to the various components in a firearm, explaining in detail the operation of the firing mechanism and its related parts. When a semi-automatic firearm is discharged the bullet exits the barrel and the cartridge case, which contained the bullet and powder charge, is ejected. During this discharging process, working surfaces in the firearm make

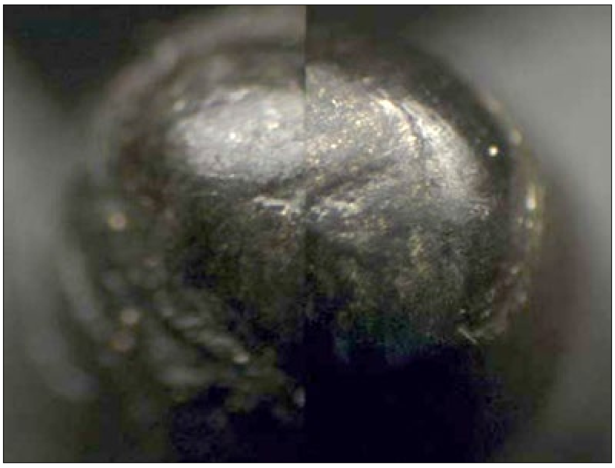


Fig. 2 Comparison microscopy of MIM firing pins from two pistols of the same model type

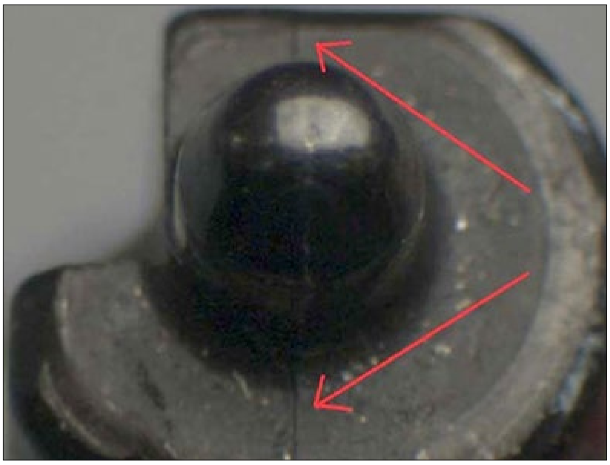


Fig. 3 Detail of a MIM firing pin. The arrows point to the mould parting line

microscopic marks on various areas of each bullet and cartridge case. The firing pin is one of the key working surfaces, striking either the back of the cartridge case or the base.

The microscopic markings that are made on the cartridge case by the firing pin are one of the key sources of evidence used by forensic firearms examiners when attempting to solve firearm-related crimes. Other markings can also be identified on the case, including marks on the rear of the case from its being forced against the breach under very high pressure, from the case extractor mechanism, and marks from the ejector system. The identification process is highly time consuming as the number of microscopic toolmarks that must be compared can vary in position, illumination and orientation and identification requires specialised equipment, training and extensive experience.

For the purpose of forensic examinations, the markings on cartridge casings have both class, subclass and individual characteristics. Class characteristics are intentionally designed. For example, the barrel rifling of a gun is designed with a specific number of lands and grooves and rate of twist; that design will be standard for all barrels produced for that model unless the manufacturer decides to change it.

Subclass characteristics are defined as discernible surface features of an object which are more restrictive than class characteristics in that they are produced incidental to manufacture and relate to a smaller group source (a subset of the class to which they belong). Subclass characteristics can arise from a source which changes over time and are not specific to a single tool, for example, but to a smaller group.

Individual characteristics are markings, imperfections and striations that are transferred to the cartridge case by a specific firearm and these can serve as crucial evidence in the identification of the weapon.

These firing-pin markings, along with the other cartridge markings, are used as "fingerprints" during investigations, stated Detective Marcinkiewicz. Comparisons between microscopic images are then conducted to determine if a match can be made between the evidence cartridge case retrieved from a crime scene and a test-fired specimen obtained from the firearm in question.

Data from the examination of cartridge cases can also be checked against the IBIS database (Integrated Ballistic Identification System), a program designed by Forensic Technology Inc. and managed in the United States by the Bureau of Alcohol, Tobacco, Firearms and Explosives. The NIBIN programme tracks a large volume of guns used in crimes and can potentially help to link a suspect firearm to crimes across the United States.

MIM firing pins

Firing pins have traditionally been manufactured by conventional metalworking processes such as machining, but more and more commonly they are being manufactured using MIM. It is becoming clear however that MIM

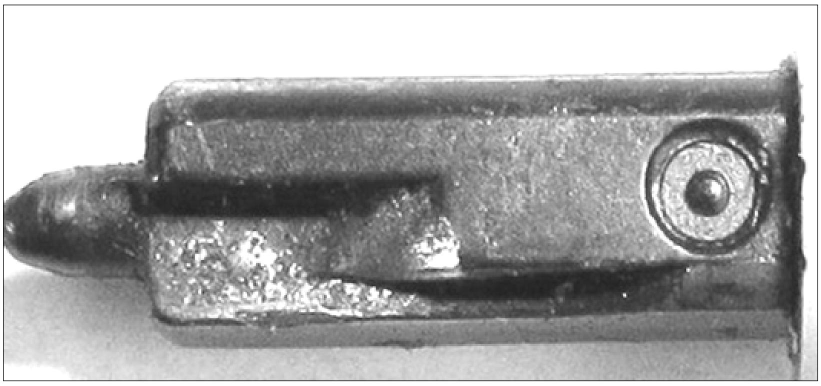


Fig. 4 A MIM firing pin investigated by the forensic team. The impression of a circle with a dot is the Cavity ID mark

Fig. 5 Comparison microscopy of test shots. Both images are from pistols of different model types, but sharing the same MIM firing pin design from the same mould cavity as identified by cavity identification markings

firing pins have such high part-to-part consistency that established techniques that are used to identify individual characteristics now need to be refined, or new techniques developed, to ensure proper identification confirmation. Firing pin impressions are, however, only one area used during an examination.

Detective Marcinkiewicz explained to MIM2014 conference delegates that a routine examination of a firing pin mark at the St. Louis County Police Crime Laboratory revealed that what appeared to be an individual characteristic of a suspect firearm, that is to say a characteristic that is unique to a single weapon, actually was common to multiple weapons, and thus a subclass characteristic.

The discovery of duplicate subclass characteristics was only made because one of the impressions that came from a cartridge case used in a recent shooting was matched with a gun that was in the possession of the police department's Property Control Unit at the time of the incident, so could clearly not have been used in the shooting.

The test cartridge cases from both firearms were compared and further tests with different types of ammunition were carried out. The firing pin impressions from both pistols, stated Marcinkiewicz, had a characteristic "D" shape to them and showed a distinct impressed mark at the base of the firing pin impression (Fig. 1).

The firing pins were removed from the firearms and photographed as well as compared side-by-side on the comparison microscope [Fig. 2]. Mikrosil casts were also made of the tips of the firing pins. Both of the firing pins exhibited the same cavity ID mark of a circle with a single dot in it (Fig. 4).

Following communications with the manufacturer of the firearms in question it was discovered that the firing pin type was used in two pistol models and the forensic team was informed that the pins were manufactured by MIM. This in turn led the St. Louis County Police Department to contact Megamet Solid Metals Inc., a MIM manufacturer based in St Louis with significant experience of firearms components, to learn about the process and visit Megamet's facility. The forensic examiners were keen to understand whether the features observed in the firing pin impression were due to a characteristic in the tooling or from the MIM manufacturing process itself.

Future impact on firearms forensics

This discovery, stated Detective Marcinkiewicz, shows that because of the high part-to-part consistency of MIM parts, an identification cannot now be based on a single MIM part impression but examinations must be based on other markings as well.

Looking to the future, Detective Marcinkiewicz raised the question with the audience as to how the MIM industry could assist in enabling the incorporation of identifiable individual features into firing pins. There was general agreement that component uniformity was a desirable and fundamental characteristic of high volume MIM part production and this could not cost-effectively be adapted, however technologies such as laser marking are potentially available to gun manufacturers themselves to add identification marks to firing pins post-production.

A bright future for MIM firearms components

One positive aspect of the issues raised in this case is the recognition of MIM's ability to deliver high volume components to the firearms industry with exceptional part-to-part consistency. By using the MIM process, firearms manufacturers benefit from the ability to design highly complex components that can potentially incorporate several separate parts into one, consolidating a weapon's mechanical components and thereby reducing total manufacturing costs.

MIM offers end-users significant savings, in some cases up to 40%, on investment cast equivalents thanks to the elimination or reduction of machining and finishing operations. If finishing operations are needed, these are often limited to tapping and nitride finishing. A trend towards smaller firearm designs with smaller, more intricate parts also offers MIM some distinct advantages over investment casting. MIM has the advantage of offering more net shape potential, thinner walled sections and deep holes.

Acknowledgments

Thanks to Detective Darin Marcinkiewicz, St. Louis County Police Department, Missouri, USA (DMarcinkiewicz@stlouisco.com) and Bruce Dionne, Megamet Solid Metals, Inc., Earth City, Missouri, USA, for their cooperation in the preparation of this report

Praxis Technology: Enhancements to Ti-MIM processing bring medical implants a step closer

Praxis Technology, a US-based manufacturer focused exclusively on titanium products has made substantial progress in the area of titanium Metal Injection Moulding (Ti-MIM). In this article Joe Grohowski and Jobe Piemme provide an insight into the capability and performance of Praxis' validated Ti-MIM process in relation to ASTM F2885, as well as additional technologies that have been developed to enhance Ti-MIM's applicability to the orthopaedic market and other markets demanding high fatigue performance.

The Metal Injection Moulding (MIM) of titanium for medical applications has been referred to as the "holy grail" of MIM. The challenges of forming a highly reactive, very fine metal powder are well understood within the industry. Titanium has the dual challenge of being both reactive and very sensitive to contamination. Over the years there has been tremendous activity in academia and some activity in industry with regards to overcoming the challenges of Ti-MIM [1]

The most relevant of those challenges is meeting the chemical and mechanical requirements of the Grade 5 (Ti-6AL-4V) alloy. In 2011, ASTM adopted a standard for the Metal Injection Moulding of titanium (ASTM F2885). This standard contemplates two versions of the product. Type 1 is a densified version having higher mechanical properties meeting conventional Ti-6Al-4V ASTM requirements. Type 2 is an as-sintered version having lower mechanical requirements. The interstitial requirements for both are the same. Praxis' development efforts have focused on Type 1 because the specification for Type 1 is most similar to other ASTM specifications used for titanium implantable devices, presenting less adoption challenges to the device OEMs.

During validation, the consistency of the Ti-MIM process was evaluated at many points along the process.

This article focuses on testing the outputs of the process from both a perspective of interstitial content and mechanical properties. Both of these characteristics cannot be non-destructively inspected and must be monitored by a statistical sampling plan to ensure quality during production. In order to develop a sampling plan that meets the quality requirements of the customer, it is necessary to determine the capability of the process.

	Oxygen	Carbon
Average	0.174	0.0375
Standard deviation	0.007	0.005
Difference	0.0052	0.0085
Based on 95% confidence and a power value.95		
Calculated sample size	25	5

Table 1 Data set for basis of sample size determination

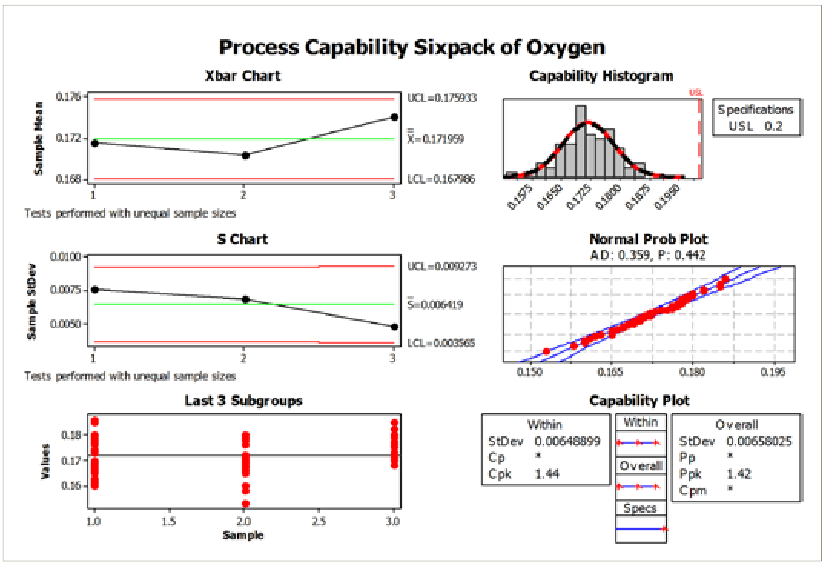


Fig. 1 Results of a Minitab analysis for oxygen capability

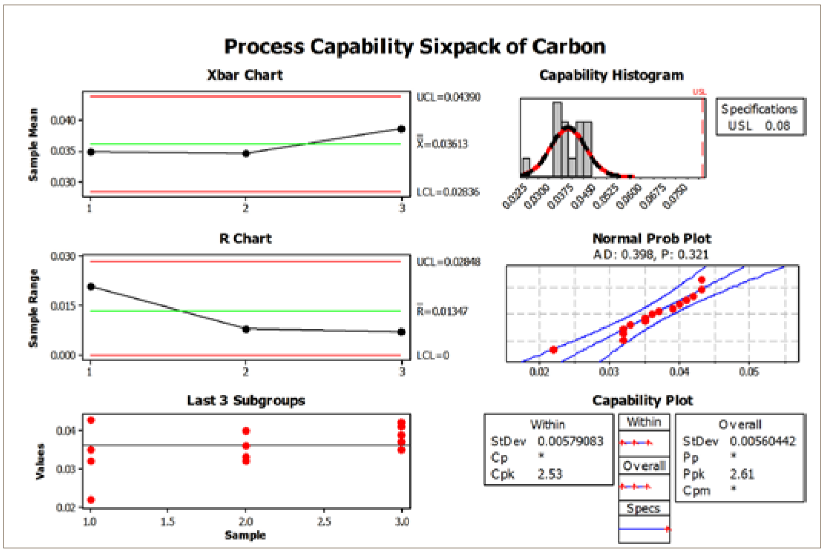


Fig. 2 Results of a Minitab analysis for carbon capability

Controlling oxygen and carbon

With respect to interstitial contamination, oxygen and carbon are widely understood to be the most challenging to control. To evaluate our ability to control these elements a sample size for the capability studies must first be established. Sample size calculations were based on historical data that was collected during an engineering study performed prior to the validation; the data was used to calculate sample sizes based on 1-sample z-tests. A summary of the data used to determine sample sizes is presented in Table 1.

The calculation of average and standard deviation is straightforward. Next the difference value had to be calculated. Because a batch operation is being evaluated, the difference calculation was based on the desire to detect a shift in the mean value. The mean shift difference was selected to be 20% of the span between the average and the upper specification limit. This yields roughly a 50 ppm mean shift for oxygen and an 85 ppm mean shift for carbon. In order to enhance the accuracy of detecting a true mean shift the power value was increased to 0.95 from the widely used value of 0.80. Based on 95% confidence, the samples sizes for both oxygen and carbon were 25 and 5 respectively.

Consistent with performance qualification (PQ) requirements capability studies for oxygen and carbon were based on three full, consecutive furnace runs. Oxygen content was determined using inert gas fusion according to ASTM E1409-08 and carbon content was determined using combustion according to ASTM E1941-10.

Prior to the capability analyses, normality and equal variance tests were conducted on the three data sets. All three were normally distributed with equal variance. Fig. 1 shows the results of Minitab analysis for oxygen capability. Analysis of the oxygen data indicated that the distribution was normal and that the process had a Ppk of 1.42, exceeding the objective of 1.33.

Samples for carbon capability were randomly selected from the sample sets used for oxygen capability. Based on the preliminary results a much smaller sample size of five tests per run was used. Fig. 2 shows the results of the Minitab analysis for carbon capability. The capability analysis provided a Ppk of 2.61, exceeding the PQ objective of 1.33.

Meeting the requirements of the medical industry

Developing a sintering process window and proving capability at the boundary conditions is critical to meet the stringent requirements of the medical industry. When qualifying equipment and processes, not only is it important to quantify the temperature variation within the processing window but it is equally important to understand the effect the variation imparts on final product properties.

Although the determination of the sintering window is based on numerous characteristics, capable mechanical properties are paramount. After target sintering temperature and the temperature window were established, boundary condition tests were conducted to determine mechanical property capability.

The approach used to determine the sample size for mechanical properties was different to that of interstitial content. In the case of mechanical properties, confidence that the properties met a certain minimum was the objective. In the case of interstitial content, the detection of a mean shift was of the most interest.

Using engineering studies developed to determine the target sintering temperature window, sample sizes were selected based on the baseline Cpk's for tensile strength, yield strength and elongation. The lowest baseline Cpk exceeded 1.41 but was less than 1.55. Using Wayne Taylor's sampling plan tables, a minimum sample size of 20 is needed for variable data, one-sided, applying 95% confidence and 99% reliability assuming high risk [2]. Tensile tests were conducted on a sample size of 25 at both low and high sintering temperatures to determine capability at the boundary conditions of the sintering window.

The acceptance criteria for a minimum sample size of 20 is a Ppk = 1.10. The mechanical properties determined outside of the sintering temperature window proved process capability outside of the temperature variation when processing at the target sintering temperature. Table 2 summarises the properties and statistical results of the process at the upper and lower temperature limits. All of the resulting Cpk values exceed the qualification objective of 1.33.

The challenges of orthopaedic devices

Orthopaedic devices are often cited as applications that could benefit from commercially viable Ti-MIM. However, there are several barriers to Ti-MIM being widely adopted in the orthopaedic industry. Among these are fatigue performance and the increasing demand that orthopaedic implants have complex integration surfaces. In order to overcome these barriers Praxis developed two technologies that complement the Ti-MIM process, expanding its applicability into various orthopaedic markets.

Increasing fatigue strength of Ti-MIM

As mentioned above, a major challenge to using Ti-MIM to manufacture orthopaedic devices is that conventional Ti-MIM components do not have adequate fatigue strength for load bearing applications. The commonly accepted minimum for load bearing applications is around 620 MPa (90 ksi) at 10 million cycles When measured in rotating beam fatigue (ASTM E468-11) typical Ti-MIM fatigue strength is around 480 MPa (70ksi) at 10 million cycles. In order to overcome this limitation, Praxis developed a processing route to improve the final microstructure of the sintered titanium. This process, branded "TiRx™" provides fatigue strengths in excess of 620 MPa. TiRx achieves this performance while still meeting the chemical and mechanical requirement of ASTM F2825. Fig. 3 compares the rotating beam fatigue life of conventional Ti-MIM material and Praxis TiRx material.

'a major challenge to using Ti-MIM to manufacture orthopaedic devices is that conventional Ti-MIM components do not have adequate fatigue strength for load bearing applications'

		Low temperature			High temperature		
Property	ASTM F2885 limit	Avg.	Std. Dev.	Cpk	Avg.	Std. Dev.	Cpk
UTS (MPa)	900	982	2.81	9.80	964	3.77	5.70
Yield (MPa)	830	871	9.65	1.42	860	6.68	1.47
Elongation (%)	10	19.9	1.05	3.13	19.8	1.19	2.74

Table 2 Summary of mechanical properties and capability for high and low temperature

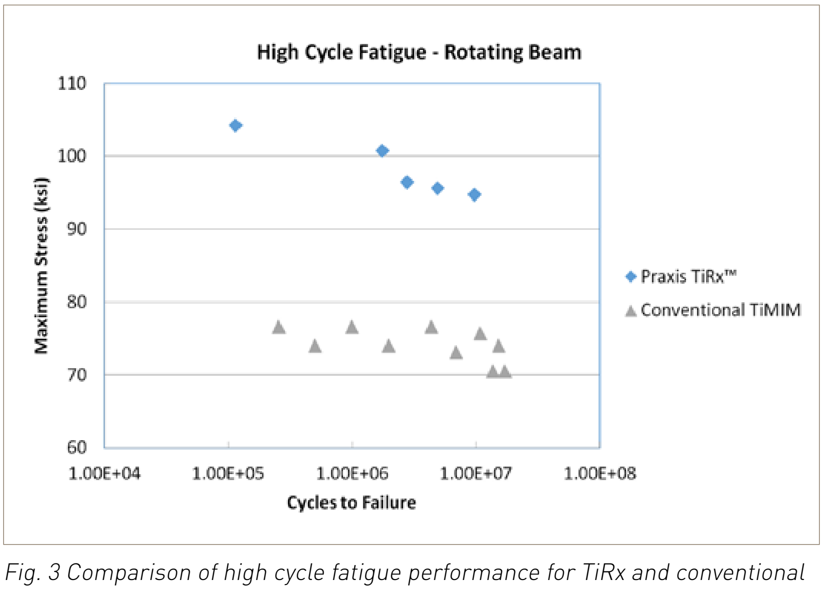


Fig. 3 Comparison of high cycle fatigue performance for TiRx and conventional Ti-MIM

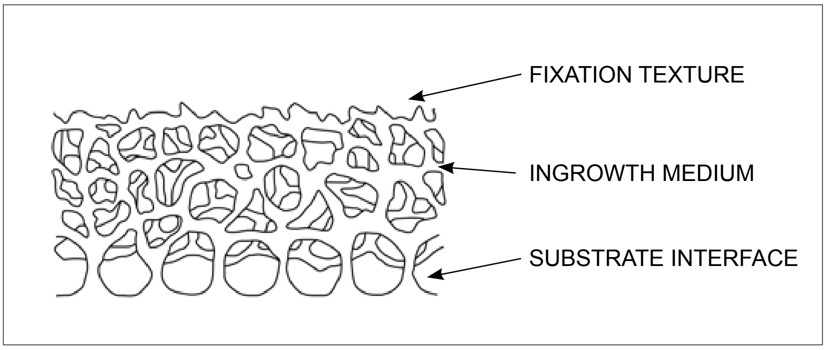


Fig. 4 Schematic of an idealised ingrowth surface

Improved osseointegration using Additively Manufactured sacrificial inserts

A further challenge to Ti-MIM in orthopaedics is that many orthopaedic devices are required to have integration surfaces to provide improved osseointegration. These surfaces are typically added to the device after it is initially formed by conventional methods, most typically forging followed by machining. This additional step represents additional manufacturing costs. The cost of adding a surface to an implant is often a substantive portion of the cost of manufacturing the implant and often also incorporates an additional thermal cycle that compromises the microstructure and diminishes the fatigue performance of the device.

The possibility of net-shaping the integration surface with the implant body is an opportunity for Ti-MIM to add value to the end product. This offers both additional savings to the customer and makes Ti-MIM more competitive. In addition, this surface is formed in the same thermal cycle allowing the possibility of complex ingrowth surfaces on implant bodies having superior fatigue performance. For these compelling reasons, Praxis developed its 3DT process for the net-shape forming of a variety of complex surfaces on injection moulded titanium articles.

The patent pending 3DT process uses an Additively Manufactured sacrificial insert to form the desired surface on a Ti-MIM part. The sacrificial insert can be removed after moulding by a variety of steps, preferably during first stage debinding. The technique can be adapted to many different applications requiring complex surfaces, among them uncemented, cemented and monoblock or unitised devices. Because the surface is formed by an insert and is removed with the moulded article, these surfaces can be applied to areas of a part that cannot be addressed by in-mould texturing. In addition to the insert being created by Additive Manufacturing, the surface can be very complex, easily possessing attributes such as highly interconnected porosity or multiple undercuts.

'The possibility of net-shaping the integration surface with the implant body is an opportunity for Ti-MIM to add value to the end product'

The approach of using a sacrificial insert enables the creation of very complex surfaces and allows the surfaces to be applied to areas of a part such as undercuts and inside diameters that would otherwise be very challenging to access using conventional line-of-sight processes.

Complex surfaces for specific applications

Different types of orthopaedic devices require surfaces of different natures. A cemented device is often required to have a rough but not porous surface, often referred to as a 2D or ongrowth surface. An uncemented device not only requires a certain roughness to the surface, but also needs a layer of interconnected porosity that communicates with the outer surface. Surfaces intended for uncemented devices are often referred to as 3D or ingrowth surfaces. In addition to surfaces intended for contact with bone, some devices need surfaces intended to contact and bond with a polymer, most typically UHMWPE. Unitised or monoblock devices incorporate permanently bonded polymers as their bearing surface and require a surface that can securely bond to the polymer.

Ingrowth surfaces

Ingrowth surfaces currently demonstrate the fullest potential of the 3DT technology. A schematic of an idealised ingrowth surface is shown in Fig. 4. These surfaces are very complex and possess separate requirements for each surface region. The outermost portion is engineered to be rough with very open porosity. Rough surfaces are preferred by surgeons to provide initial fixation during implantation. This rough surface provides a "grippiness" to the outer surface and allows the surface to scrape bone and tissue matter into the porosity, which is thought to give osseointegration a head start and improve healing times. It is also important that this surface not be too sharp; while roughness is desired, extremely sharp edges are detrimental to bone growth. This fixation texture is a critical attribute of any ingrowth surface.

Ingrowth medium

Situated underneath the fixation texture is the ingrowth medium. This provides the network of interconnected pores to act as a scaffold for bone to grow onto and then into the ingrowth surface. Among the critical

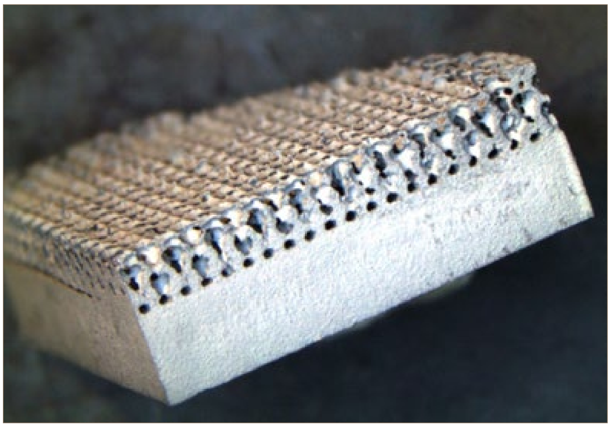


Fig. 5 Three dimensional ingrowth surface manufactured using 3DT technology

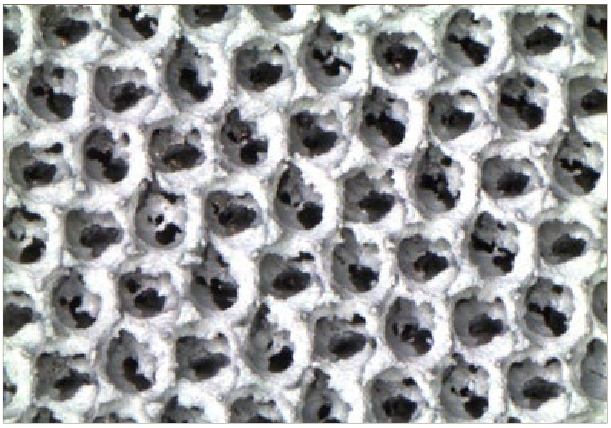


Fig. 7 Close-up of highly interconnected ingrowth medium and fixation surface

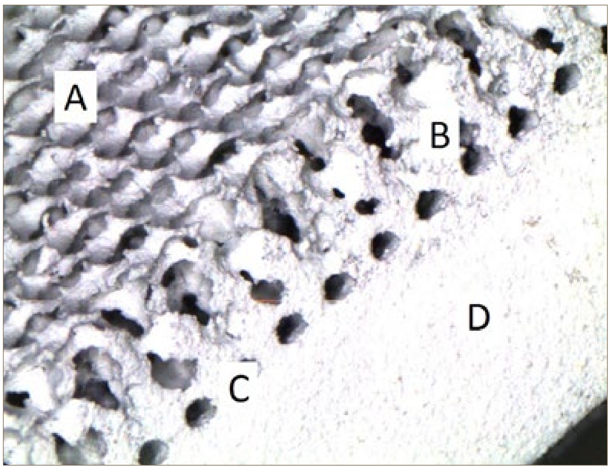


Fig. 6 Cross-section of a titanium integration surface manufactured using the 3DT technology

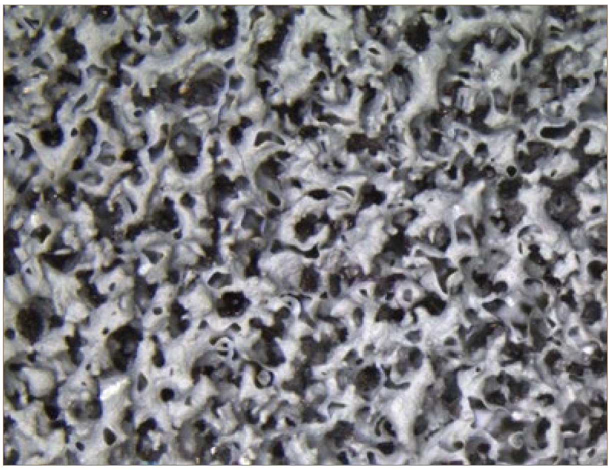


Fig. 8 3DT surface with finer porosity and more organic appearance

attributes of a titanium ingrowth medium are major and minor pore diameter, porosity and tensile strength. The major pore diameter of these regions can range from 50 – 750 microns. The minor pore diameter, or interconnecting pore diameter, is generally preferred to have an average value over 100 microns although ingrowth has been demonstrated below 50 microns. Porosity can range from 55% to 75%. A minimum tensile strength of 20 MPa is set forth in FDA guidance documents. Ingrowth mediums are generally between 0.8 mm (0.03 in.) and 2.3 mm (0.090 in.) in thickness.

Substrate interface

Lastly, underneath the ingrowth medium is the substrate interface. In this region the ingrowth medium attaches to the solid implant body. This region is of importance because titanium is especially notch sensitive, and small stress concentrators on the surface can substantially diminish the fatigue performance of an implant. Most methods of forming an ingrowth surface focus on creating the porosity and the fixation texture. The substrate interface is generally not the result of an intentional design, but rather of the method used to form the porosity of the ingrowth medium.

Shown in Fig. 5 is a cross-section of an integration surface manufactured using a sacrificial insert. The fixation texture, ingrowth medium and the substrate interface are all defined precisely, repeatably and independently by different sections of the sacrificial insert. Furthermore, these surfaces can be created on geometries without line-of-sight access.

Fig. 6 is a close up of the cross-section visible in Fig. 5. Area A indicates the aggressive net-shape fixation texture, area B indicates the highly interconnected ingrowth medium, area C indicates the tailored substrate interface and area D indicates the substrate.

The three dimensional ingrowth surface made using 3DT technology is seen in Fig. 7. The pores are highly interconnected and the struts are well formed. The ingrowth medium is 70% porous and the major pores have an average diameter of 500 microns and the minor pores have and average interconnecting pore size over 100 microns. Tensile bond strength testing performed on these surfaces yielded an average bond strength of 64MPa.

The surface depicted in Fig. 7 is highly regular and repeating with

Fig. 9 Ti-MIM tibial tray with net-shaped 3DT ingrowth surface

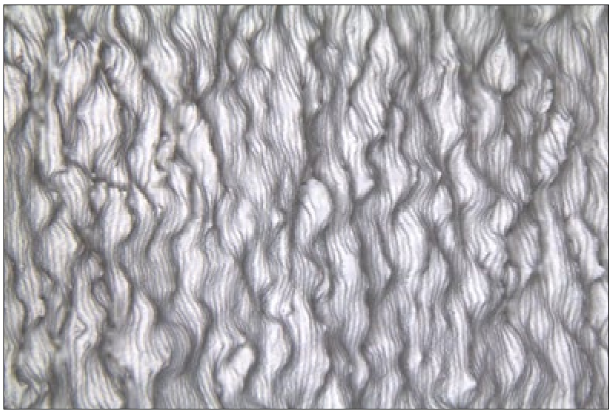


Fig. 10 Ongrowth surface created using 3DT technology

respect to pore size and location. From a marketing perspective it is often desired that three dimensional ingrowth surfaces have a less regular and more organic appearance. This can be accommodated by adjusting the program used to generate the sacrificial insert. Fig. 8 shows the versatility of the process, this surface has finer porosity and a much more organic appearance.

The 3DT technology has been demonstrated to enable conforming of ingrowth layers on large orthopaedic devices. Fig. 9 shows three stages of the 3DT process. The left background shows a green moulded part that has been co-moulded with a sacrificial insert using an insert moulding operation. The right background shows the green part after the sacrificial insert has been removed, and the foreground show the device after being debound and sintered.

Ongrowth surfaces

The 3DT technology can also be used to form ongrowth surfaces. These are less complex, providing an aggressive initial fixation texture, but without a porous ingrowth medium. A close-up of an ongrowth surface created using this technology is shown in Fig. 10.

Conventionally ongrowth surfaces are applied in a coating process and consequently delamination is always a concern. Because the 3DT surface is co-formed with the implant body, no boundary exists between the surface and the body, precluding delamination as a failure mode. Also, because the process is not a line-of-sight process, these aggressive textures can be applied to undercuts, inner diameter and other difficult to reach areas. Furthermore, the process is highly repeatable and tailorable.

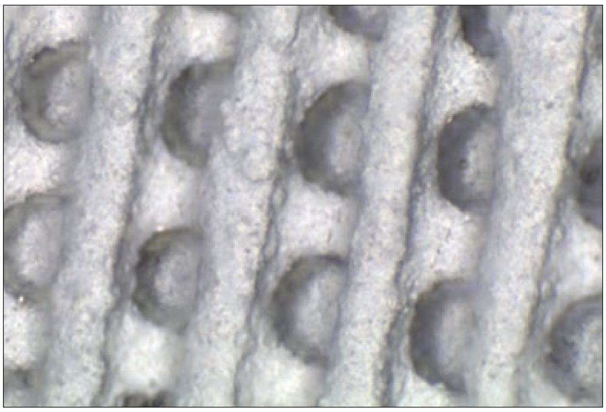


Fig. 11 Polymer anchoring surface with interlocking loops

Fig. 12 Cross-section of moulded UHMWPE bonded with an anchoring layer

Providing a bond between metal and polymer surfaces

Monoblock or unitised devices present another unique challenge that the 3DT technology addresses. These devices need a surface that UHMWPE can be moulded against to create a strong bond between the metal substrate and the polymer surface. Polymer anchoring layers can be used to create these bonds and there are several designs that have been demonstrated to provide excellent bonding between the polymer and the metal substrate. Two examples of these types of designs are interlocking loops and undercuts.

Interlocking loop design

A close-up of an interlocking loop design can be seen in Fig. 11. This approach provides for many loops that polymer can flow around to anchor to the surface. The surface shown is approximately 0.5 mm (0.02 in.) in thickness.

A cross-section of an interlocking loop surface that UHMWPE has been moulded against is visible in Fig. 12. The polymer is shown to have connected through the loops in an uninterrupted manner.

Undercut design

Undercuts can also be used to form strong bonds between a polymer bearing surface and a metal substrate. By moulding the plastic material into undercuts on a surface, the plastic becomes mechanically bonded to the surface. Fig. 13 shows an undercut surface that can be used as a polymer anchoring layer. This surface is approximately 0.35 mm (0.014 in.) in thickness.

Both interlocking loops and undercuts create very strong bonds with moulded UHMWPE. Test coupons tested in tension using a modified ASTM F1147 protocol demonstrated tensile bond strengths in excess of 14 MPa (2000 psi) for either approach. The polymer anchoring layers also have the same advantages of eliminating delamination concerns and great flexibility with regard to where they can be applied.

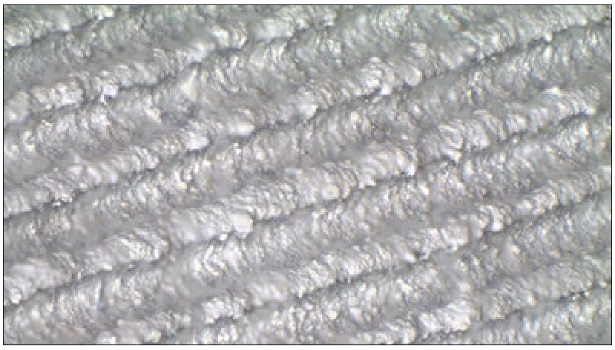


Fig. 13 Undercut surface for use as a polymer anchoring layer

Conclusion

In conclusion, implantable grade Ti-MIM has moved from an academic undertaking to a production capable process. In a validated process, robust capability has been demonstrated with both interstitial contamination and mechanical properties. Further, the technology has been augmented to provide fatigue strengths suitable for load bearing implants and economical, net shape integration surfaces.

Author

Joe Grohowski
President
Praxis Technology
604 Queensbury Ave.
Queensbury, NY 12804, USA
Tel: +1 518 812 0112 x105
Fax: +1 518 812 0115
Email: joeg@praxisti.com

References

[1] German, R.M. Progress in Titanium Metal Powder Injection Molding. In *Materials*, 2013, 6, 3641-3662.

[2] Wayne Taylor. Guide to Acceptance Sampling. First Edition. 1992, Taylor Enterprises, Inc.

Metal Injection Moulding (MIM) of titanium and titanium hydride reviewed at PM Titanium 2013

The second International Titanium Powder Processing, Consolidation and Metallurgy Conference took place in Hamilton, New Zealand, from December 2-4 2013. The event, organised by the Titanium Industry Development Association, New Zealand, in partnership with the University of Waikato, CSIRO and GNS Science, attracted over 80 participants from around the world to discuss the latest advances in titanium Powder Metallurgy. Prof Ma Qian of RMIT University (Royal Melbourne Institute of Technology) reports on selected MIM highlights from the technical programme.

Effect of carbon on microstructural development and mechanical properties

The solubility limit of carbon in titanium alloys containing a high level (e.g. ≥ 10 wt.%) of molybdenum (Mo), niobium (Nb) and vanadium (V) can be less than 100 ppm by weight. MIM of such titanium alloys can lead to a noticeable presence of titanium carbides in the as-sintered microstructure, often distributed along grain boundaries, due to the unavoidable pick-up of carbon (300-500 ppm by weight) from the polymeric binder used. The formation of such grain boundary carbides can be a killer to the tensile ductility of the MIM-processed titanium alloys.

Recent systematic experimental studies of the MIM of Ti-6Al-4V (wt.%) by Miura [1] and Ebel *et al.* [2] have defined a critical level of oxygen content for as-sintered Ti-6Al-4V, which is around 0.33 wt.%, beyond which the tensile elongation decreases dramatically. Carbon is another important interstitial impurity for titanium and titanium alloys, particularly for MIM-processed titanium and titanium alloys due to the massive use of polymeric binders in the process. In general, a carbon pick-up of 300-500 ppm by weight is common after solvent debinding, thermal debinding and sintering. ASTM Standard Specification 988-13 (Table 1) specifies the maximum carbon limit as 800-1000 ppm by weight in PM titanium and titanium alloys. The binary Ti-C phase diagram

Fig. 1 The University of Waikato hosted PM Titanium 2013 (Photo ©The University of Waikato)

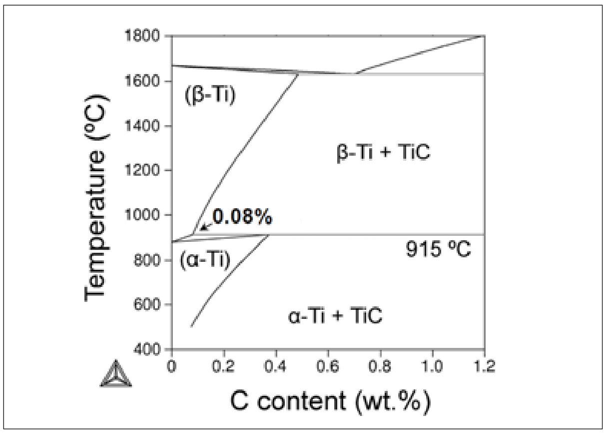


Fig. 2 Ti-C phase diagram up to 1.2 wt.% C, predicted using Thermo-Calc Software 2008 and Ti-alloys database V3 (TTTI3) [3]

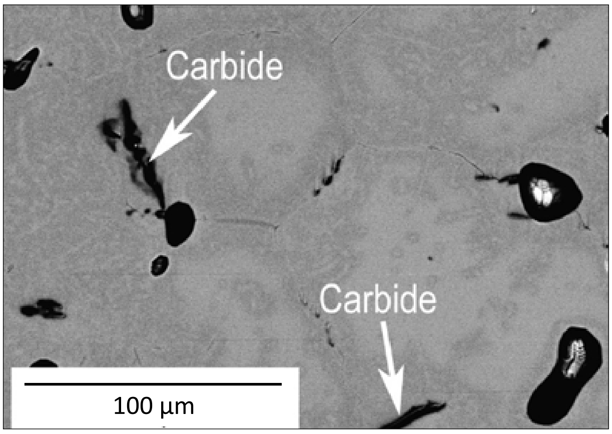


Fig. 3 MIM-processed Ti-15V-3Al-3Sn-3Cr, sintered in vacuum at 1400ºC for 120 min and then treated at 500ºC for 12 h

constructed using Thermo-Calc (Fig. 2) explains where this carbon limit (800 ppm) comes from. The solubility limit of carbon in β-Ti at 915ºC is predicted to be exactly 0.08 wt.% beyond which carbon will precipitate out as titanium carbides in β-Ti during subsequent cooling from the isothermal sintering temperature.

MIM of beta-titanium alloys

Thomas Ebel, Dapeng Zhao, and Firat Kafkas of Helmholtz-Zentrum Geesthacht Centre for Materials and Coastal Research, Germany [4] discussed the influence of carbon on the microstructural development and mechanical properties of several MIM-processed beta and/or near beat titanium alloys, including Ti-15V-3Al-3Sn-3Cr, Ti-24Nb-4Sn-8Zr, Ti-10Nb, Ti-16Nb and Ti-22Nb (all in wt.%).

Tensile samples of Ti-15V-3Al-3Sn-3Cr were fabricated by MIM using pre-alloyed gas-atomised powder (< 45 µm, 0.105 wt.% O). After solvent debinding and thermal debiding, the samples were sintered in vacuum at 1400ºC for 120 min. The sintered density was 95.4 % of theoretical density and the as-sintered samples contained 0.21% O and 0.046% C. The resulting ultimate tensile strength (UTS), yield strength (YS) and tensile elongation were 718 MPa, 689 MPa and 9.3%, respectively. After a subsequent heat treatment at 500ºC for 12 h, the UTS and YS increased to 1245 MPa and 1184 MPa, respectively but the tensile elongation dropped to almost zero (0.4%). A detailed micro-structural study suggests that the loss of tensile ductility was due to the formation of carbides (Fig. 3). Carbide formation was also clearly observed in a MIM-processed Ti-24Nb-4Sn-8Zr alloy in the as-sintered state, corresponding to noticeable declines in tensile ductility. However, no carbide formation was observed in the MIM-processed Ti-6Al-4V under similar conditions.

The distinction has triggered a detailed study of the carbide formation in three MIM-processed Ti-Nb alloys by the authors using commercially pure titanium (CP-Ti) as a point of reference. Table 2 lists the alloy compositions, the carbon content of

Composition, Weight %	N max	C max	H max	Fe	O max	Residual max ea.
Grade 1 PM	0.03	0.08	0.015	0.20 max	0.18	0.1
Grade 2 PM	0.03	0.08	0.015	0.30 max	0.25	0.1
Grade 3 PM	0.05	0.08	0.015	0.30 max	0.35	0.1
Grade 4 PM	0.05	0.08	0.015	0.50 max	0.40	0.1
Grade 5 PM (Ti-6Al-4V)	0.05	0.08	0.015	0.40 max	0.30	0.1
Grade 9 PM (T1-3Al-2.5V)	0.03	0.08	0.015	0.25 max	0.30	0.1
T1-6Al-4V, LI[B]	0.03	0.08	0.0125	0.25 max	0.20	0.1
Ti-6Al-6V-2Sn	0.04	0.1	0.015	0.35-1.0	0.30	0.1

Table 1 Impurity requirements for PM titanium and titanium alloys by ASTM988-13. LI: Low Interstitial

	O	C	N
Ti powder	0.0744	0.00469	0.0375
Nb powder	0.221	0.0152	0.0890
CP-Ti	0.175	0.0503	0.0628
Ti-lONb	0.203	0.0562	0.0678
Ti-16Nb	0.255	0.0600	0.0525
Ti-22Nb	0.225	0.0589	0.0547

Table 2 Impurity levels of starting powders and as-sintered MIM-processed samples [5, 6]

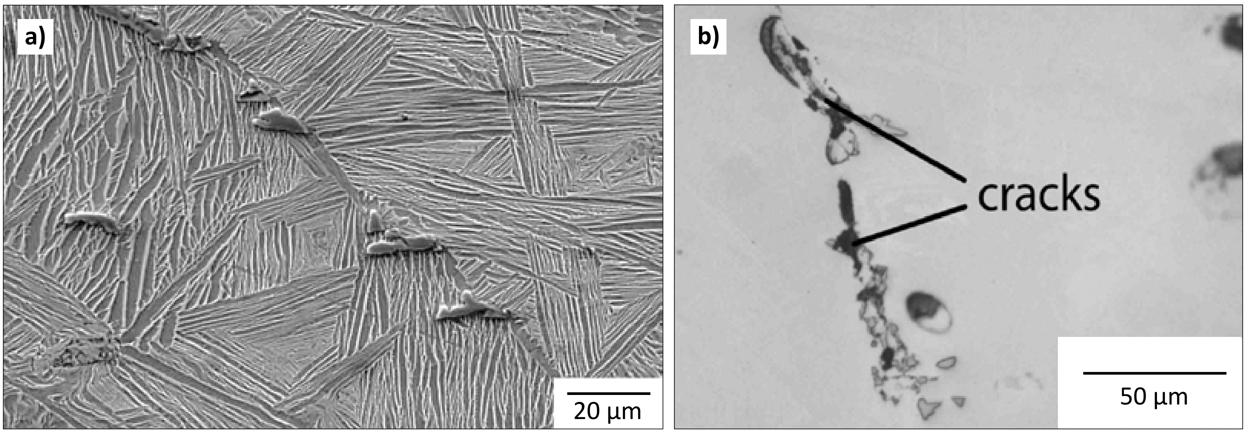


Fig. 4 (a) Grain boundary carbides in MIM-processed Ti-10Nb alloy and (b) cracks observed in fractured tensile samples of as-sintered Ti-10Nb alloy parallel to the tensile direction [5, 6]

the starting powders and the carbon content of each MIM-processed alloy.

The carbon content increased by about 450-550 ppm after MIM compared to the carbon content of the staring powders, irrespective of the niobium (Nb) content. Although the increase is about tenfold, the final carbon content in each alloy is still clearly below 800 ppm (Table 2). However, a noticeable presence of titanium carbides was observed in each MIM-processed Ti-Nb alloy, often along the grain boundaries in the microstructure (Fig. 4). In contrast, no carbide formation was observed in the MIM-processed CP-Ti, despite the similar carbon content (see Table 2). This suggests that the carbide formation is related to the introduction of niobium. Thermodynamic calculations using Thermo-Calc revealed that Nb in the range introduced (10-22 wt.%) can significantly reduce the solubility limit of carbon in Ti and in addition, the solubility limit decreases with increasing Nb content [5, 6]. This was confirmed by the experimental observations shown in Fig. 5, although the overall carbon content was essentially the same in each alloy (see Table 2). In order to eliminate the influence of porosity on tensile properties, the MIM-processed Ti-Nb alloy samples were further subjected to Hot Isostatic Pressing (HIP). Fig. 6 displays the tensile mechanical properties of the MIM- and HIP-processed Ti-Nb alloys. The linear drop in tensile elongation corresponds to the nearly linear increase in carbide area fraction shown in Fig. 5. A detailed discussion of the carbide formation in these alloys has been published in the 2014 Summer issue of *Powder Metallurgy Review* [7].

Coincidently Ma Qian and Ming Yan of RMIT University, Australia [8] discussed in detail the formation of titanium carbides in an as-sintered Ti-15Mo (wt.%) alloy. The alloy was fabricated by uniaxial cold compaction of powder mixes of titanium hydride (TiH_2) powder (99.5% purity; 95–106 µm) and elemental Mo powder (99.5% purity; <63 µm) and sintered in vacuum (10^{-3} Pa) at 1350°C for 120 min, followed by furnace cooling to room temperature at 7°C/min. Similar observations were made, namely although the as-sintered Ti-15Mo alloy contained only about 320 ppm of carbon, a clear presence of titanium carbides was observed in its as-sintered microstructure [3, 8]. The fundamental reason was found to be similar - an addition of 15 wt.% Mo to Ti reduces the solubility limit of carbon from 800 ppm to about 60 ppm by Thermo-Calc predictions [3]. This means that even though the starting powder used is essentially carbon free, the pick-up of carbon from a typical MIM process will still be more than sufficient to induce noticeable formation of carbides in such titanium alloys.

In summary, titanium alloys that contain a high level (e.g. ≥10 wt.%) of alloying elements such as Nb and Mo show a very low carbon solubility limit (e.g. ≤100 ppm). On the other hand, MIM-processed titanium alloys can readily pick up about 300-500 ppm of carbon by weight. It is

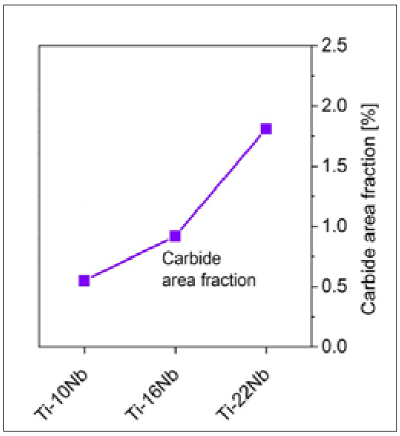


Fig. 5 Carbide area fraction in MIM- and HIP-processed Ti-Nb alloys

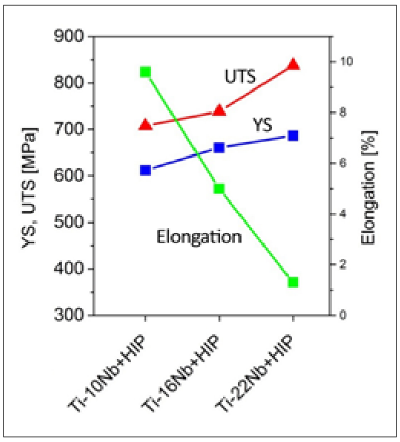


Fig. 6 Tensile mechanical properties of MIM-processed Ti-Nb alloys further consolidated by HIP

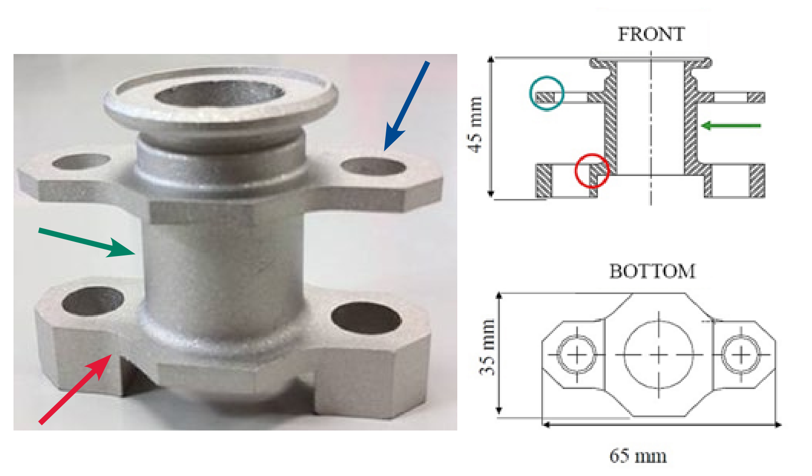


Fig. 7 A titanium part used in fuel manifold of jet engines. The part is commercially fabricated by machining out of a forged blank

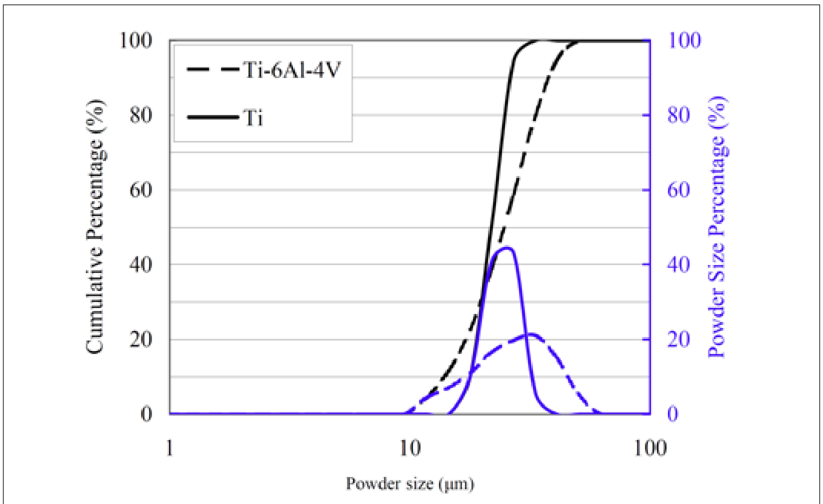


Fig. 8 Powder size distribution of gas atomised CP Ti powder (TILOP-45) and Ti-6Al-4V powder (TILOP64-45), both from Osaka Titanium Tech. Co., Ltd.

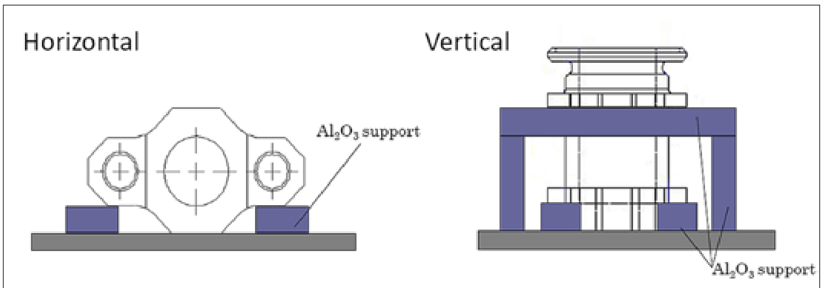


Fig. 9 Placement of the part for thermal debinding

Binder	Melting point (ºC)	Mass (%)
Paraffin Wax (CW)	56-58	69
Carnauba Wax (CW)	68-74	10
Atactic Polypropylene (APP)	110-130	10
Ethyl Vinyl Acetate (EVA)	85-105	10
Di-n-butyl phthalate (DBP)	-35	1

Table 3 The binder system used for the MIM of Ti and Ti-6Al-4V

therefore important to avoid carbide formation in such MIM-processed titanium alloys in order to ensure good ductility. This could be more challenging than the control of oxygen due to the easy pick-up of carbon from the MIM process. The use of a low-carbon or carbon-free binder appears to be the only solution to the fabrication of such titanium alloys by MIM. The development of such a binder will continue to be a challenge for MIM-Ti.

MIM of relatively large titanium parts

Most MIM parts are small in terms of part dimensions (< 50 mm); wall thickness (< 5 mm) and weight (< 50 g). Production of larger-sized MIM parts faces a number of challenges including distortion and defect formation (crack, slump, blister etc.). In addition, the production cycle may increase substantially due to the increased time required for both binder removal and sintering. However, MIM of large-sized Ti parts with acceptable dimensional tolerances and mechanical properties is of constant interest due to the high cost and difficulties of manufacturing them by conventional means.

Development of large sized Ti alloy components for aerospace applications by MIM

Prof Hideshi Miura of Kyushu University, Japan [9] gave an update on his group's effort in developing large-sized titanium alloy components by MIM. An earlier study of the topic was presented at the inaugural Titanium Powder Processing, Consolidation and Metallurgy Conference, hosted by The University of Queensland, Australia in December 2011, entitled "Evaluation and analysis of distortion of complex shaped Ti-6Al-4V compacts by metal injection moulding" [10].

The part selected is shown in Fig. 7, used in the fuel manifold of jet engines, which is commercially machined out of a forged blank. The finished part measures 65 mm × 35 mm × 45 mm and weighs about 50 g when made in Ti-6Al-4V. The shape of the part has some challenging features such as the cylindrical surface (green arrow), overhanging area (blue arrow), and sharp corner (red arrow) while being larger than typical MIM-Ti parts.

Unlike the previous study [10], the part was injection moulded using both gas atomised CP Ti powder (TILOP-45) and prealloyed Ti-6Al-4V powder (TILOP64-45), both from Osaka Titanium Tech. Co., Ltd., in order to better understand the distortion of the MIM Ti-6Al-4V part. Fig. 7 shows the powder size distribution of each powder. A multicomponent binder system was used (Table 3). The powder and binder were mixed and kneaded at 150°C for 60 min. The powder loading was 65 vol.%. The feedstock was injection moulded and the binder was removed through solvent debinding (in n-heptane at 58°C for 4 hours; debinding ratio: ~55%) followed by thermal debinding (heated at 600°C at 1°C/min and kept at 600°C for 1 hour).

Distortion was found to be a major issue for the fabrication of the selected part by MIM and it started to develop from the thermal debinding process. To understand the distortion behaviour the parts were placed in two positions, horizontal and vertical, supported by alumina (Fig. 9). Sintering was carried out in a vacuum (10^{-2} Pa) furnace (VHLgr20/20/20, Shimadzu Mectem, Inc.) at 1250°C for 120 min. Similarly, two sintering set-ups were considered (Fig. 10).

The dimensions of the part were measured using a 3D Coordinate Measuring Machine (LEGEX 776, Mitutoyo Corporation), which performs non-contact measurements using a line laser probe scanning system (scanning error: 12 μm). The level of deflection of the part can be obtained from the measurement results, which are compared with the 3D CAD data (the point of reference) to evaluate the deviation (see Fig. 11). The positive value represents the deflection outward from the reference surface, while the negative value represents the distortion inward from the surface. Two types of distortion are evaluated for each part, out of roundness and deflection.

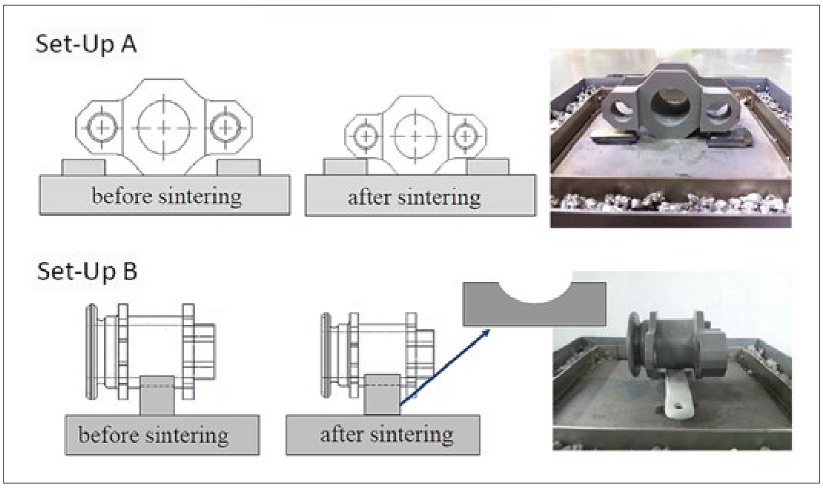


Fig. 10 Placement of the part for vacuum sintering (1250°C for 120 min, 10^{-2} Pa)

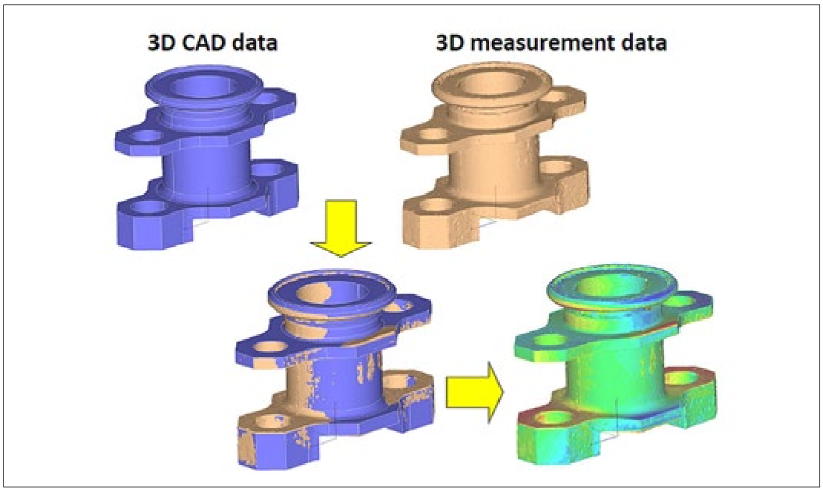


Fig. 11 Data processing for the determination of distortion

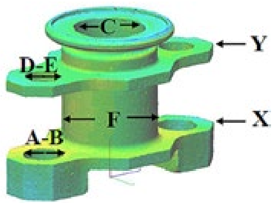
Table 4 summarizes the results of distortion measured at various positions of the fabricated Ti-6Al-4V part under the specified MIM processing conditions. Although these are only some preliminary results, it is clear that distortion is an important issue in the fabrication of relatively large MIM-Ti parts.

Fig. 12 compares the distortion between the same MIM-Ti parts made using gas atomised CP Ti powder and prealloyed Ti-6Al-4V powder. The Ti-6Al-4V part displayed a much greater degree of distortion than the CP-Ti part under the same conditions. Since the mean particle size of the Ti-6Al-4V powder is only slightly larger than the CP-Ti powder, the difference in powder size was considered to be negligible. The major difference noted was the powder size distribution (see Fig. 8); the CP-Ti powder has a narrower powder size distribution than the Ti-6Al-4V powder.

A detailed experimental study was then performed to understand the various factors that affect the part distortion in order to attain satisfactory dimensional control. The following observations are notable.

- Distortion occurs during the earlier stages of thermal debinding when all binder nearly melts and continues to develop until 300°C. After that, the distortion remains essentially constant until the end of the thermal debinding process. Hence, control of the distortion during the early stages of thermal debinding is critical to improving the shape retention of a complex MIM-Ti part.

Feedstock 10% APP 10% EVA	Debinding vertical set-up	Sintering set-up B



	Green compact distortion (mm)	As-sintered distortion (mm)	Percentage of as-sintered distortion (%)	ISO 2768-2 Medium tolerances (mm)	MIM standard (%)
A-B	0.08	0.190	±0.95	0.2	±0.3
C	0.08	0.186	±0.50	0.2	±0.3
D-E	0.09	0.153	±0.90	0.2	±0.3
F	0.11	0.186	±0.40	0.2	±0.3
X	0.105	0.215		0.2	
Y	0.062	0.135		0.2	

Table 4 Effect of debinding and sintering set-up on the distortion of the MIM-Ti-6Al-4V part

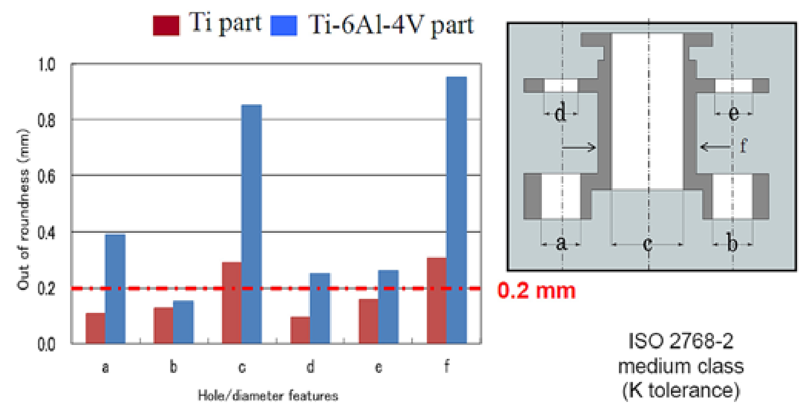


Fig. 12 Comparison of distortion between the MIM-processed parts made using gas atomised CP Ti powder and prealloyed Ti-6Al-4V powder. The latter shows an unexpected greater degree of distortion

- In general, distortion decreases with increasing powder loading. However, powder size distribution plays an important role in the determination of the optimum powder loading. In this regard, the angle of repose may be used as a supplementary parameter to assist in the selection. A high angle of repose implies high interparticle friction and is therefore expected to favour shape retention by enhancing the resistance to distortion during thermal debinding.
- The use of a faster heating rate prior to reaching the decomposition temperature of the binder during thermal debinding can reduce the distortion of the part.

Based on the experimental findings and the new understanding developed, it was found that the use of 67% powder loading in conjunction with the use of a fast thermal debinding rate resulted in acceptable dimensional tolerances for the MIM Ti-6Al-4V parts shown in Fig. 7.

In summary, net-shape fabrication of relatively large and complex titanium parts by MIM is challenging but it is still achievable. The success requires a good understanding of the influence of a wide variety of factors on the distortion and defect formation during each step of the MIM process.

MIM of titanium parts from titanium hydride (TiH_2) powder

Processing of dense and porous titanium parts by Powder Injection Moulding of titanium hydride

Prof E. Carreño-Morelli of the University of Applied Sciences and Arts Western Switzerland gave a comprehensive update on his group's study of dense and porous titanium parts made by MIM [11]. Recent studies of the group on the MIM of TiH_2 prior to the conference can be found in [12, 13, 14].

TiH_2 powder offers several attractive advantages over titanium metal powder in the context of conventional Powder Metallurgy, including the attainment of higher sintered densities and lower oxygen content. In addition, TiH_2 powder can be readily pulverized into fine particulates. Also, TiH_2 powder may be less reactive than titanium metal powder of the same size (easier powder handling) when exposed to air but evidence is still needed to support such a claim. The motivation of developing MIM-TiH_2 according to the speaker was, however, driven by the affordable price of the TiH_2 powder compared to the high price of gas atomised titanium powder. For example, fine (Dv50=20.3 μm) low oxygen (0.07 wt%) TiH_2 powder can be purchased on the market at about 75 EUR/kg (100 kg batch) or 60 EUR/kg (1 metric ton batch). For similar gas atomised titanium powder the price will need to be doubled.

Angular TiH_2 powder provided by AG Materials, Taiwan, was used. The powder contained 0.07 wt.% O, 0.014 wt.% N, and 0.013 wt.% C. The hydrogen content was estimated to be close to 4 wt.%. The particle size distribution was composed of Dv10=11.8μm, Dv50=20.3 μm, and Dv90=34.9 μm. The feedstock consisted of 60 vol.% TiH_2 and 40 vol.% binder (55 wt% paraffin wax, 35 wt.% low density polyethylene, and 10 wt% stearic acid). Compounding was performed in a sigma blade mixer (Fig. 13) at 140°C for 240 min under argon. Polymer-powder

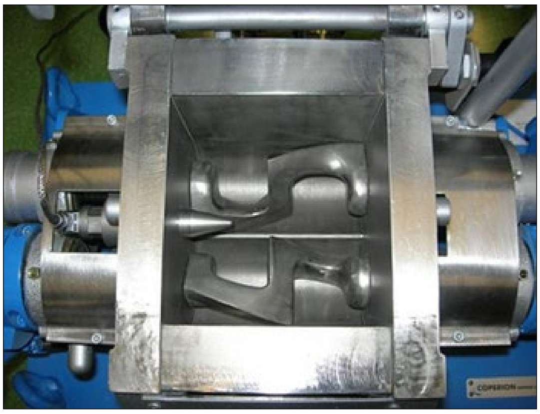


Fig. 13 The sigma blade mixer used for compounding the TiH_2 powder with binder (performed at 140°C for 240 min under argon)

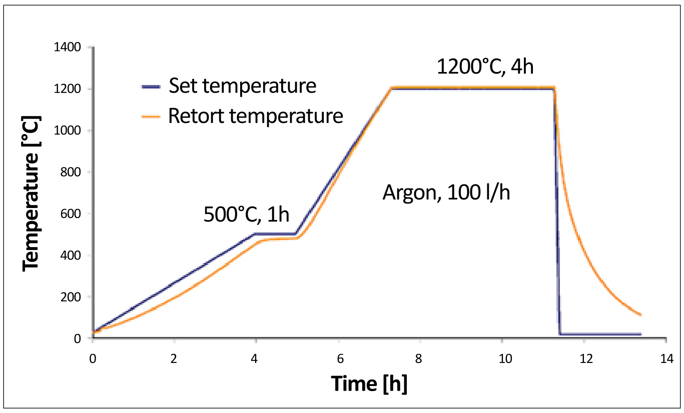


Fig. 14 Thermal debinding, dehydriding and sintering of injection moulded TiH_2 samples

granules were produced by crushing the compounded mixture via slow shearing after it had cooled down to a low temperature. An Arburg 221K 350-100 machine was used for injection moulding. Dog-bone tensile test specimens (60 mm in length) and experimental watch bracelet segments were moulded. Solvent debinding was carried out in heptane at 50°C for 20 h which removed 98% of the paraffin wax and stearic acid. Thermal debinding, dehydriding and sintering (see Fig. 14) were all performed in a Nabertherm VHT8-16MO MIM furnace (which uses molybdenum heating elements) under argon at the pressure of 1 bar and a flow rate of 100 litres/hour. Samples were placed in a debinding retort and zirconia-coated alumina pieces were used as sintering supports.

The as-sintered samples reached 97.1% of theoretical density with an average grain size of about 90 µm compared to a much finer powder size. Table 5 lists the impurity levels and the resulting tensile mechanical properties in relation to CP-Ti Grade 4.

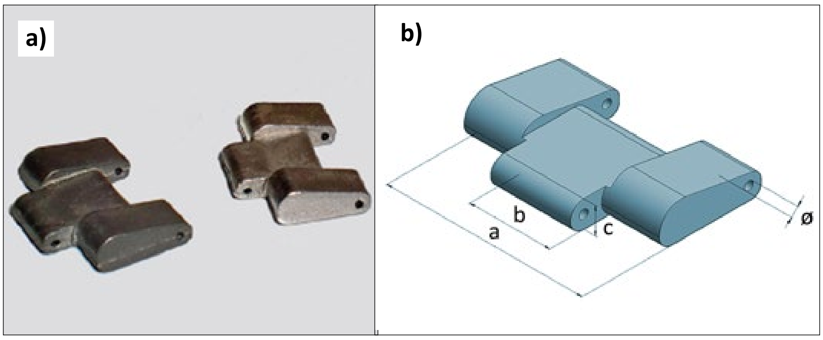


Fig. 15 (a) Experimental watch bracelet segments fabricated from TiH_2 powder by MIM and dimensions used to minor variations

The experimental watch bracelet segments fabricated show good shape preservation, reproducibility and mechanical properties. A detailed assessment was made of 63 experimental watch bracelet segments fabricated by MIM-TiH_2 in terms of weight and dimensional changes (Fig. 15). The following experimental results were obtained:

- Variation in weight of green parts < 0.4%
- Variation in weight of sintered parts < 0.4%
- Linear shrinkage ~ 20% ((expected to be 22%: 16% from binder removal and 6 % dehydriding)
- Hole diameter ø reduced from 0.98 mm to 0.78 mm after sintering
- Scatter in dimensions a, b ~ 0.4 %, and
- Scatter in dimension c ~ 0.5%

'The motivation of developing MIM-TiH_2 was driven by the affordable price of the TiH_2 powder compared to the high price of gas atomised titanium powder'

The impurity levels of carbon, nitrogen and hydrogen in the MIM-TiH_2 parts meet the specifications of CP-Ti Grade 4. The substantial increase in oxygen content from 0.07 wt.% to 0.305 wt.% arose mainly from the argon atmosphere used during sintering which can be mitigated via vacuum sintering or the use of high purity argon. Some contamination from the oxide ceramics used as sintering supports is possible. However, in the case study reported, the increased oxygen content offered desired strengths (higher than those of CP-Ti Grade 4, Table 5) while permitting good tensile elongation (15%, Table 5). According to the speaker, the major issue for

	O [wt.%]	N [wt.%]	C [wt.%]	H [wt.%]	density [%]	YS [MPa]	UTS [MPa]	elongation [%]
TiH_2 powder (D_{V50}~20μm)	0.07	0.14	0.013	4.0	-	-	-	-
MIM-Ti (1200°C 4h)	0.30	0.027	0.065	0.013	97.1	519	666	15
Ti grade 4	0.4	0.05	0.08	0.015	100	480	550	15

Table 5 Interstitial content and tensile mechanical properties of as-sintered MIM-Ti samples from TiH_2 powder

the commercialisation of MIM-TiH_2 is just that it is a relatively new concept. As such, several aspects still need to be studied and optimised, such as feedstock compounding methods for good homogeneity, high shrinkage and dimensional reproducibility (after debinding and dehydriding) and tool wear (when compared to the MIM of titanium metal powder). In summary, TiH_2 powder holds promise as a cost effective option for the fabrication of MIM-Ti parts.

Author

Dr Ma Qian
Professor of Advanced Manufacturing and Materials
School of Aerospace, Mechanical and Manufacturing Engineering
RMIT University (Royal Melbourne Institute of Technology)
GPO Box 2476 ,
Melbourne VIC 3001
Australia

Tel: +61 3 9925 4491
Email: ma.qian@rmit.edu.au

References

[1] H. Miura, Presentation at PM Titanium 2011 in Brisbane Australia (4-7 December 2011). See also H. Miura, The influence of density and oxygen content on the mechanical properties of injection molded Ti-6Al-4V alloys, in Advances in Powder Metallurgy & Particulate Materials – 2010, Metal Powder Industries Federation (MPIF), 2010, 46-53.

[2] T. Ebel, O. M. Ferri, W. Limberg, M. Oehring, F. Pyczak, F.-P. Schimansky, Metal injection moulding of titanium and titanium-aluminides, *Key Engineering Materials* 2012, Vol. 520, 153-160.

[3] M. Yan, M. Qian, C. Kong, M. Dargusch, Impacts of trace carbon on the microstructure of as-sintered biomedical Ti-15Mo alloy and reassessment of the maximum carbon limit, *Acta Biomaterialia*, 2014, vol. 10, 1014-1023.

[4] T. Ebel, D. Zhao, F. Kafkas, "MIM Processing of Titanium Beta Alloys", Presentation at The 2013 International Titanium Powder Processing, Consolidation and Metallurgy Conference (PM Titanium 2013), 2-4 December 2013, Hamilton, New Zealand.

[5] T. Ebel, D. Zhao, F. Kafkas, "MIM Processing of Titanium Beta Alloys", Presentation at The 2013 International Titanium Powder Processing, Consolidation and Metallurgy Conference (PM Titanium 2013), 2-4 December 2013, Hamilton, New Zealand.

[6] T. Ebel, D. Zhao, F. Kafkas, "MIM Processing of Titanium Beta Alloys", *Key Engineering Materials 2014* (in press).

[7] M. Qian, "PM Titanium 2013: Impurities in PM titanium and titanium alloys, porous titanium and applications, and additive manufacturing of titanium in New Zealand", *Powder Metallurgy Review*, 2014, Summer Issue, 53-60.

[8] M. Qian, M. Yan, "Understanding the effect of impurities on the microstructural development of powder metallurgy titanium and titanium alloys", Presentation at The 2013 International Titanium Powder Processing, Consolidation and Metallurgy Conference (PM Titanium 2013), 2-4 December 2013, Hamilton, New Zealand.

[9] H. Miura, "Development of Large Sized Ti Alloy Components for Aerospace Application by Advanced Powder Processing – MIM", Presentation at The 2013 International Titanium Powder Processing, Consolidation and Metallurgy Conference (PM Titanium 2013), 2-4 December 2013, Hamilton, New Zealand.

[10] S. Virdhian, T. Osada, H. G. Kang, F. Tsumori, H. Miura, "Evaluation and analysis of distortion of complex shaped Ti-6Al-4V compacts by metal injection moulding", *Key Engineering Materials*, 2012, vol. 520, 187-194.

[11] E. Carreño-Morelli, "Processing of dense and porous titanium parts by powder injection moulding of titanium hydride", Presentation at The 2013 International Titanium Powder Processing, Consolidation and Metallurgy Conference (PM Titanium 2013), 2-4 December 2013, Hamilton, New Zealand.

[12] E. Carreño-Morelli, M. Rodriguez-Arbaizar, H. Girard, H. Hamdan, J.-E. Bidaux, "Net-shape titanium Grade 4 parts processed from titanium hydride powders", *European Cells and Materials* Vol. 22. Suppl. 4, 2011 (page 33).

[13] E. Carreño-Morelli, W. Krstev, B. Romeira, M. Rodriguez-Arbaizar, H. Girard, J.-E. Bidaux, S. Zachmann, "Titanium parts by powder injection moulding of TiH_2-based feedstocks", *Powder Injection Moulding International*, 2010, vol. 4, No. 3, 60-63.

[14] E. Carreno-Morelli, J.-E. Bidaux, M. Rodrı´guez-Arbaizar, H. Girard and H. Hamdan, "Production of titanium grade 4 components by powder injection moulding of titanium hydride", *Powder Metallurgy*, 2014, vol. 57, 89-92.

Aluminium MIM: New advanced powders and feedstocks achieve higher densities

Whist conventional Powder Metallurgy aluminium parts are today processed in high volumes for established end-user industries, aluminium has not yet become established as an accepted material for MIM. There is, however, growing interest in combining the unique properties of aluminium with the ability of MIM to process large volumes of highly complex components. In this paper Jessu Joys, Rhonda Kasler and Clive Ramsey, United States Metal Powders, Inc., report on the testing of a new commercially available MIM feedstock based on a specially developed fine inert gas atomised aluminium powder.

Several studies have been conducted in the field of aluminium Metal Injection Moulding (MIM) in recent years identifying the advantages of MIM aluminium parts. The interest in such parts has always existed due to the unique physical properties of aluminium and the cost advantage achieved in producing a lightweight part with excellent strength. As MIM technology has gained wider acceptance in recent decades, several research papers and a number of patents have been published emphasising the continued quest to commercialise aluminium MIM technology. However the total number of aluminium MIM parts produced remains limited, regardless of the many application opportunities to make high strength aluminium MIM parts.

The paper published by Liu, Kent and Schaffer in 2009 reported an aluminium nitride (AlN) reinforced 6061 alloyed powder composition for Metal Injection Moulding and processing the parts in a sintering furnace surrounded by magnesium blocks to capture the oxygen [1]. Aluminium based powder grades are not new to the Powder Metallurgy (PM) industry and millions of pressed and sintered aluminium automobile parts have been produced for more than two decades, particularly by part producers in US. Just like the difficulties aluminium PM technology experienced in its infancy, aluminium MIM is also going through similar challenges in terms of optimising the raw materials and processing steps to make it an attractive material of choice.

Metal Injection Moulding is a proven technology with the major processing steps consisting of selecting a fine metal powder tailored for MIM and mixing it with a binder to create the feedstock, followed by injection moulding this feedstock to

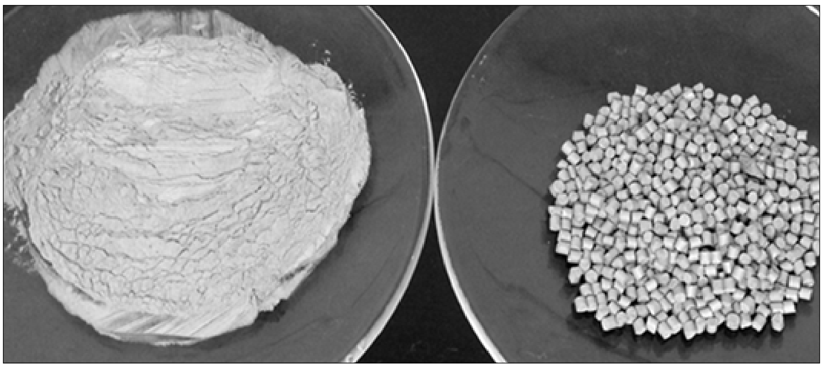


Fig. 1 Left - MIM 6061 aluminium alloy powder from Ampal, Inc.; Right - aluminium feedstock manufactured by Ryer Inc., using 6061 aluminium powder

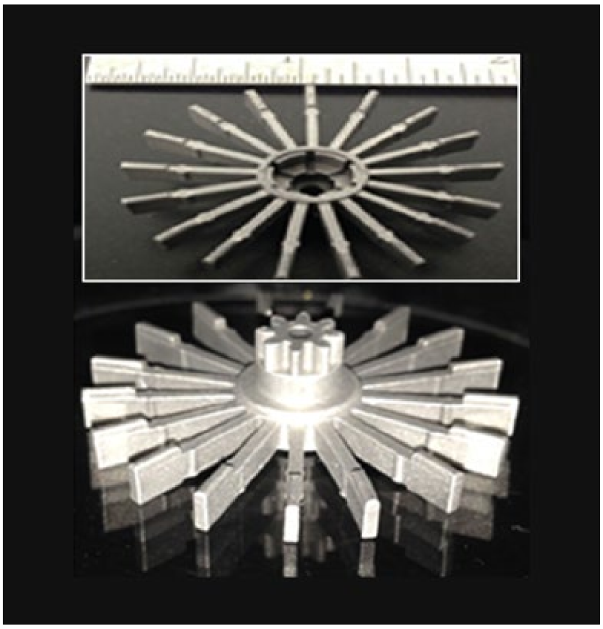


Fig. 2 Aluminium MIM sample part manufactured by Ryer Inc. using the aluminium 6061 feedstock

form a part with a three dimensional shape. The binder is then removed by various techniques to produce the finished part with the required geometry via the sintering process. Materials such as stainless steels have gained popularity thanks to these powders being optimised for the MIM process and accompanying standards were defined along with the processing steps. This has not yet happened for aluminium but a field tested feedstock is now available based on a newly developed ultra-fine aluminium alloy powder and a proprietary wax based binder system developed by Ryer, Inc., based in Temecula, California, USA. Fig. 1 shows the ultra-fine aluminium alloy powder MIM 6061 and the wax based feedstock. A sintered aluminium sample part with a 98.6% theoretical density is shown in Fig. 2.

Advantages of selecting aluminium MIM as a process to produce parts

The list of advantages of aluminium and aluminium injection moulded parts is extensive; however, the only aluminium MIM part that has been repeatedly mentioned in publications is the heat sink. The higher thermal conductivity and greater flexibility in design over extrusion and die-casting are the main reasons to select aluminium MIM technology to make heat sinks [2].

The price of aluminium is also about one third of that of copper based on volume and other common alloyed metal powder grades currently used in the MIM industry. Some of the reasons why aluminium MIM has not gained popularity are its lower strength properties, difficulty in sintering, and until now the lack of availability of feedstock that a part maker can process easily. The size of a typical MIM part is 5 – 100 g and there are several intricate parts that can be manufactured for the electronic and medical industries using aluminium MIM technology. A case study published by Parmatech Corporation [3] discussed replacing a plastic articulation gear that failed due to insufficient strength. The plastic part was temporarily replaced with a machined aluminium part and then permanently replaced with 17-4 stainless grade. There are a lot of great potential opportunities for aluminium MIM to replace parts in this category but it requires part producers to have more experience with processing aluminium MIM parts.

Investment casting and die-casting are two major competitive processes to aluminium MIM. Investment casting is a very competitive process compared to aluminium MIM but the moulds cannot be reused and because of this it is very difficult to make large numbers of parts. High volume complex parts can be produced using die casting but smaller parts with thin walls, along with the difficulties in minimising and/or eliminating porosity, are key disadvantages of this process. Press

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, µm	12 – 18	12 – 18	12 – 18
d90, µm	34 Max.	34 Max.	34 Max.
Surface area (BET), m^2/g:	0.4 Max.	0.4 Max.	0.6 Max.

Table 1 The chemistry and other measured properties of the selected powder grades

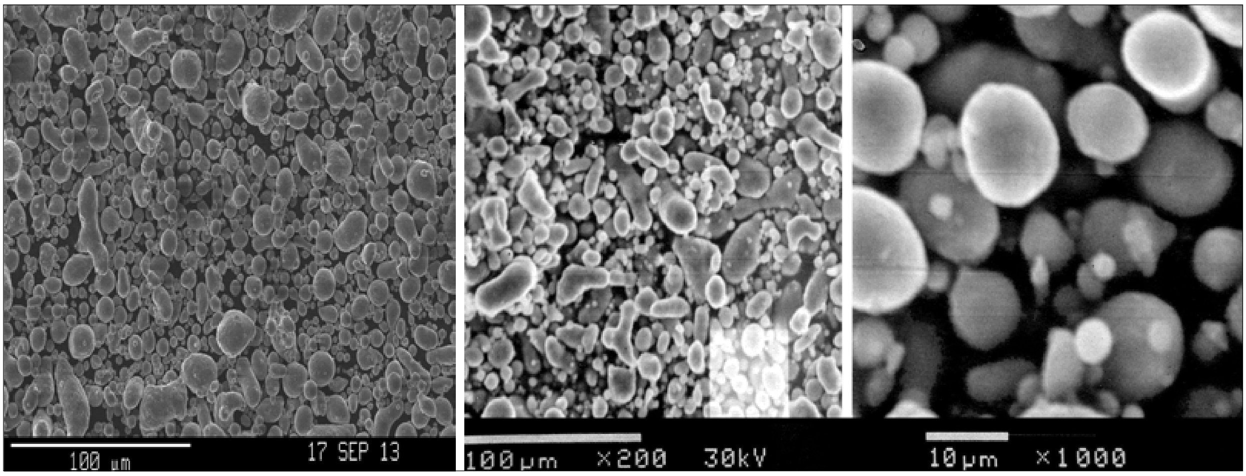


Fig. 3 SEM images of MIM 6061 (left) and MIM 2024 (centre and right) powder grades

and sintered Powder Metallurgy is a good option but it is very difficult to make parts with highly complex geometries.

Surface layers on aluminium powders

The major challenge in the processing of aluminium or aluminium based powder is the surface oxide layer coating with a thickness of approximately 4 nm. This oxide layer needs to be reduced to attain good interparticle contact during sintering. Several methods have been discussed in the past and incorporating a small amount of magnesium in the aluminium was one of the solutions to reduce the oxide coating [4]. This reaction is explained by the equation as:

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

Some hydrocarbons and hydroxides can be present on the surface in which the hydroxide can be absorbed from the atmosphere with high moisture content and humidity. One of the most popular methods of making aluminium powder is via the atomisation process and the surface oxide coating will be there regardless of the type of atomisation, whether it is air or inert gas atomisation. The surface oxide coating depends on the type of gas that is used and air atomised powder will have a thicker oxide coating compared to inert gas atomised powder.

Powder selection

In order to develop specialty grades for aluminium MIM a thorough study was done focusing on the morphology, particle size distribution and chemical composition of the popular wrought alloyed aluminium grades widely known as 2024, 6061 and 7075 alloys. The 2024 alloy has good mechanical properties at elevated temperatures and better resistance to crack propagation. The 6061 alloy is one of the most popular wrought alloyed grades with known properties such as good elongation, extrudability, weldability, machinability, thermal conductivity, electrical conductivity and anti-corrosion properties. The 7075 alloy has excellent mechanical properties via heat treatment and has good corrosion resistance.

All the powder grades evaluated were inert gas atomised and the selected particle shape was spheroidal, as shown in Fig. 3. Particle size distribution is an important factor and the recent trend in the MIM industry is to use finer powder grades with an average particle size of 15 µm or below. Available finer alloyed powder grades with an average particle size (d50) of 10 µm to 20 µm have been reviewed and powder grades with an average particle size of 15 µm were selected as the best option. As the aluminium powder size decreases, the specific surface area increases and the oxide and oxygen content increases. In all three powder grades the aluminium oxide content was kept below 0.5% to improve sintering. The three different grades of powders were specially formulated to aid the sintering process but, as with any process, some parameters may require adjustment.

'After reviewing the safety concerns in handling fine aluminium powder a commercially available feedstock may be the preferred choice for part makers'

The chemistry and other measured properties of these powder grades are shown in Table 1. The "Total others" percentage in Table 1 contains proprietary range of other elements. In the MIM industry it is common for part manufacturers to blend their own in-house proprietary feedstock. After reviewing the safety concerns in handling fine aluminium powder, however, a commercially available feedstock may be the

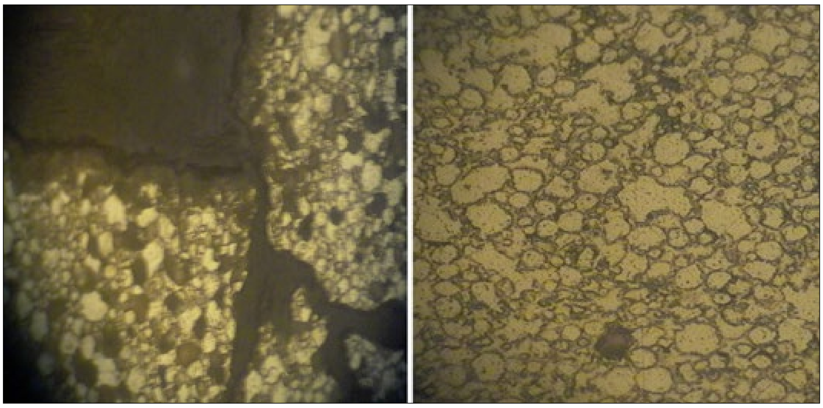


Fig 4. Metallographic images of parts sintered at 630°C and 640°C-650°C

preferred choice for part makers. Several companies are evaluating the new aluminium feedstock and we can expect several aluminium MIM parts in the near future.

Processing of MIM 6061 aluminium alloyed powder

There are several types of binders available on the market today, including water, wax and polymer based binders. A set of parts was prepared using the water based binder but the mechanical properties of the sintered parts were much lower than expected and the microstructural analysis identified poor sintering as the cause. The next binder chosen was a wax based binder and Fig. 1 (Ryer Inc.) shows the commercially prepared feedstock. These proprietary binders can be debound by solvent, Supercritical Fluid Extraction (SFE) or thermal debinding [5]. In the thermal debinding process the binder vaporises and it is also considered as a relatively easy debinding technique.

It has been shown in a study of the liquid phase sintering of aluminium alloys that a nitrogen atmosphere is essential and a dew point of -60°C or better is recommended [6]. The demonstration parts were sintered in a MIM furnace with a 100% nitrogen atmosphere and a dew point of -55°C. In aluminium PM, sintering conditions are closely monitored and optimised as the part goes through a growth phase first before shrinking and stabilising as it spends a fixed amount of time at the correct sintering temperature [4]. Binder removal in aluminium Powder Metallurgy involves the removal of ethylene bistearamide (EBS) or stearates at a lower temperature of 430°C – 510°C under nitrogen atmosphere before sintering. The removal of binders and sintering of aluminium MIM parts is similar to this but the sintering process is much longer and the time it takes to process the parts will be about 8 – 10 hours. The primary binder in this aluminium feedstock burns out in the range of 250 to 300°C and the secondary binder will burn-out in the range of 450°C to 500°C.

'It has been shown in a study of the liquid phase sintering of aluminium alloys that a nitrogen atmosphere is essential and a dew point of -60°C or better is recommended'

A set of experimental sample parts was prepared by Ryer Inc. using a feedstock with a green density of 2.0 g/cm^3. The solvent debinding method was chosen to remove the binder. This first set of brown parts were then sintered at 630°C and the microstructural analysis showed poor sintering with a large number of pores and some cracks. The weight of the sample part was about 20 g with an overall outer diameter of about 3.8 cm. The parts were sintered on alumina plates as graphite plates are not recommended since the parts may react with the material [7]. Several trials were done at different temperatures and the processing conditions were optimised to get good sintered properties.

In the next stage of the study a set of tensile bars was moulded, solvent debound and sintered in a furnace with the temperature ranging from 250°C to 650°C. The sintering temperature range was 640°C to 650°C and the overall processing time was around 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

	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 2 Comparison of tensile properties of MIM 6061 and the wrought alloy 6061

the temperature is not carefully controlled. Fig. 2 shows a sample part sintered at the optimised sintering conditions using the wax based feedstock with aluminium powder grade MIM 6061.

The sintered density of the test bars was 2.66g/cm^3, which is about 98.6% of theoretical density. The tensile properties were tested and the average value of ultimate tensile strength (UTS) was around 200 MPa and the Rockwell hardness value was around 93 (B Scale). Fig. 4 shows the sectional microstructure of the part sintered at 630°C and the part sintered at the optimised temperature range of 640°C to 650°C. The parts sintered at optimised conditions show less porosity and good sintering (Fig. 4). The tensile bars were heat treated (T6) at 510°C for 30 minutes and water quenched to ambient temperature before being solution treated for 185°C for 8 hours. The comparison of tensile properties of MIM 6061 and the wrought alloy 6061 properties is summarised in Table 2.

Conclusion

This study demonstrates that the successful combination of optimised aluminium alloy powders and the wax based feedstock based on a proprietary binder can overcome the difficulties in the aluminium MIM process.

- The sintered density of the Metal Injection Moulded 6061 aluminium alloy sample parts was very close to the theoretical density.
- The "as sintered" ultimate tensile strength (UTS) value of the MIM 6061 was very close to wrought alloy 6061-T4 value.
- The 6061-T6 heat treated UTS value was also close to the wrought alloy 6061-T6 value.

Several MIM part producers around the world are evaluating the new aluminium alloy powders.

Contact

Jessu Joys
Vice President of Technology
United States Metal Powders, Inc.
408 U.S. Highway Route 202
Flemington, NJ 08822
USA
Tel: +1 908 782 5454
Email: j.joys@usbronzepowders.com

References

[1] Z.Y. Liu, D. Kent, G.B. Schaffer, *Material Science and Engineering A* 513-514 (2009) pp352-356

[2] L.K.Tan, J.L. Johnson, "Metal Injection Moulding of Heat Sinks", *Electronics Cooling*, November 2004.

[3] G.Goto, Metal and plastic molding – a happy relationship, *Metal Powder Report*, Vol.68, March-April 2013, pp28-31

[4] G.B. Schaffer, T.B. Sercombe, and R.N. Lumley. "Liquid Phase Sintering of Aluminium Alloys", *Materials Chemistry and Physics 67* (2001), pp85-91

[5] R.M. German, A. Bose, Injection Moulding of Metals and Ceramics, Metal Powder Industries Federation (MPIF), Princeton, 1997.

[6] G.B. Schaffer, B.J. Hall, S.J. Bonner, S.H. Huo and T.B. Sercombe, "Effect of the Atmosphere and the Role of Pore Filling on the Sintering of Aluminium", *Acta Materialia Volume 54* (2006), pp131-138,

[7] L. Tan, C.T. Yeo, "Forming Complex Shaped Aluminium Components", Advanced Materials Technologies, Pte Ltd., EP 1344593 A2 (2003)

[8] R.J. Petcavich, X. Yang, "Powder and binder systems for use in metal and ceramic powder injection molding", US5977230 A (1999)

Events Guide

2014

PM2014 World Congress
May 18–22
Orlando, Florida, USA
www.mpif.org

Additive Manufacturing with Powder Metallurgy
May 18–20
Orlando, FL, USA
www.mpif.org

HIP 2014, 11th International HIP Conference
June 9 -13
Stockholm, Sweden
www.hip14.se

7th Powder Metallurgy Conference and Exhibition, TPM7
June 24 – 28
Ankara, Turkey
www.turkishpm.org

Sintering 2014
August 24-28
Dresden, Germany
www.sintering2014.com

Euro PM2014
September 21-24,
Salzburg, Austria
www.epma.com

2015

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

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

Advertising

To discuss advertising in PIM International contact: Jon Craxford, Advertising Sales Director

Tel: +44 207 1939 749
jon@inovar-communications.com

Advertisers' Index

3D Material Technologies (ARC Group)	2
Advanced Metalworking Practices, LLC	18
Ametek - Reading Alloys	33
AP&C	23
Arburg GmbH & Co. KG	Outside back cover
AT&M	27
BASF SE	14
Carpenter Powder Products	7
Centorr Vacuum Industries, Inc	21
CM Furnaces, Inc	16
Cremer Thermoprozessanlagen GmbH	5
Elnik Systems	19
eMBe Products & Services GmbH	22
Epson Atmix	9
Erasteel	20
Erowa	25
Euro PM2014 (EPMA)	66
FCT Anlagenbau GmbH	36
Formatec Ceramics	4
Gero GmbH	13
Greenlong Machinery	26
Hardex	32
Ipsen Inc	6
Jiangxi Yuean Superfine Metal Co Ltd	17
Kerafol GmbH	28
Kinetics Climax Inc	31
LÖMI GmbH	8
MIM2015 Conference (MPIF)	Inside back cover
Novamet Specialty Products Corp	12
Parmaco	29
Phoenix Scientific Industries Ltd	35
PolyMIM	24
Powder Metallurgy Review	46
Sandvik Osprey Ltd	11
TAV S.p.A.	10
TempTAB	42
TD Molybdenum & Tungsten Manufacturing LLC	34
Teibow Co., Ltd	28
Tisoma	34
United States Metal Powders, Inc	Inside front cover
USD Powder GmbH	15
Winkworth	30
Wittmann Battenfeld GmbH	41

METAL INJECTION MOLDING ASSOCIATION **MIMA**

Call for Presentations

MIM2015

International Conference on Injection Molding of Metals, Ceramics and Carbides

FEBRUARY 23–25 • SHERATON TAMPA RIVERWALK
TAMPA, FL

Abstract Submission Deadline: September 30, 2014

Call for Presentations for MIM2015

Innovation in different segments of powder injection molding (PIM) is responsible for the rapid growth of this field. The PIM industry (MIM—metal injection molding; CIM—ceramic injection molding; and CCIM—cemented carbide injection molding) has estimated sales of over $1.5 billion and could possibly double in a span of five years.

The objective of the conference is to explore the innovations and latest accomplishments in the areas of part design, tooling, molding, debinding, and sintering of PIM parts. The conference will also focus on the developments in PIM processing of different materials including metals and alloys, ceramics, and hardmaterials.

This specialized conference is sponsored by the Metal Injection Molding Association, a trade association of the Metal Powder Industries Federation, and its affiliate APMI International. The conference is targeted at product designers, engineers, consumers, manufacturers, researchers, educators, and students. All individuals with an interest in the application of powder injection molding will be encouraged to attend.

DEADLINE FOR ABSTRACT SUBMISSION IS SEPTEMBER 30, 2014

MIM2015 CONFERENCE (February 23–25)

A two-day event featuring presentations and a keynote luncheon

- *Dimensional Accuracy and Consistancy*
- *Designing MIM Parts and Materials for Performance and Value*
- *Part Selection—Best Practices*
- *Leading Process Trends*
- *Tabletop Exhibition & Networking Reception with Representatives from Many of the Leading Companies in the Field*

...and Much More!

Optional One-Day Powder Injection Molding Tutorial Precedes Conference (February 23)

Taught by Randall M. German, FAPMI, world-renowned PIM expert

An ideal way to acquire a solid grounding in powder injection molding technology in a short period of time

- Introduction to the manufacturing process
- Definition of what is a viable PIM or MIM component
- Materials selection and expectations
- Review of the economic advantages of the process

This conference is sponsored by the **Metal Injection Molding Association**, a trade association of the **Metal Powder Industries Federation**

Visit mimaweb.org or mpif.org to submit an abstract