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FOR THE METAL, CERAMIC AND CARBIDE INJECTION MOULDING INDUSTRIES

POWDER INJECTION MOULDING INTERNATIONAL

in this issue

Advances in PIM biomaterials
Profile: Mercury Centre
MIM2012 review

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POWDER INJECTION MOULDING INTERNATIONAL

For the metal, ceramic and carbide injection moulding industries

PIM's niche technologies set to deliver increased industry growth

Whilst PIM's mainstream applications continue to enjoy strong and sustained growth worldwide, it is easy to overlook the enormous potential that PIM's "niche" technologies hold for future industry growth.

Developments in MicroPIM have been reviewed in recent issues of *PIM International*, with this being an area of our technology that is certainly expected to provide unprecedented growth in the coming years. However, as this latest issue demonstrates, special PIM technologies for biomedical applications also offer equally exciting prospects for growth and innovation.

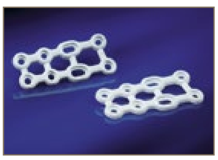
In his review, "Advances in PIM biomaterials: Materials, design, processing and biofunctionality" (page 31), Dr. Frank Petzoldt highlights the specific advantages that PIM processing of biomedical products now offers, as well as detailing the large number of current and potential applications that will inevitably transform patient care as well as deliver growth for PIM in lucrative new markets.

There was also much to be positive about at MIMA's MIM2012 conference in San Diego, March 19-21. Primarily an industry-oriented event, this year's presentations once again reflected the evolution of the technology, with innovations in materials and processing continuously widening the range of products that can be produced by PIM. Read our event review starting on page 43.

We also report on the opening of the Mercury Centre, a new research laboratory in the UK dedicated to both PIM and Additive Manufacturing (page 37).

Our technical papers in this issue cover the influence of surface aspects and properties of MIM titanium alloys for medical applications (page 57), the evaluation of a MIM micro-component (page 62) and the evaluation of simultaneous Micro Powder Injection Compression Moulding (MicroPICM) (page 67).

Nick Williams
Managing Director and Editor



Cover image
Injection moulded trauma plate made from PLA composite material (Courtesy Fraunhofer IFAM, Germany)

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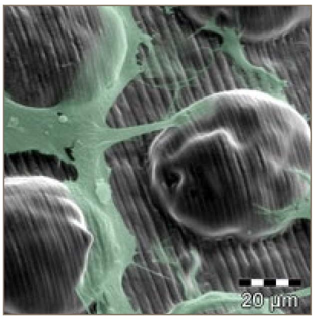

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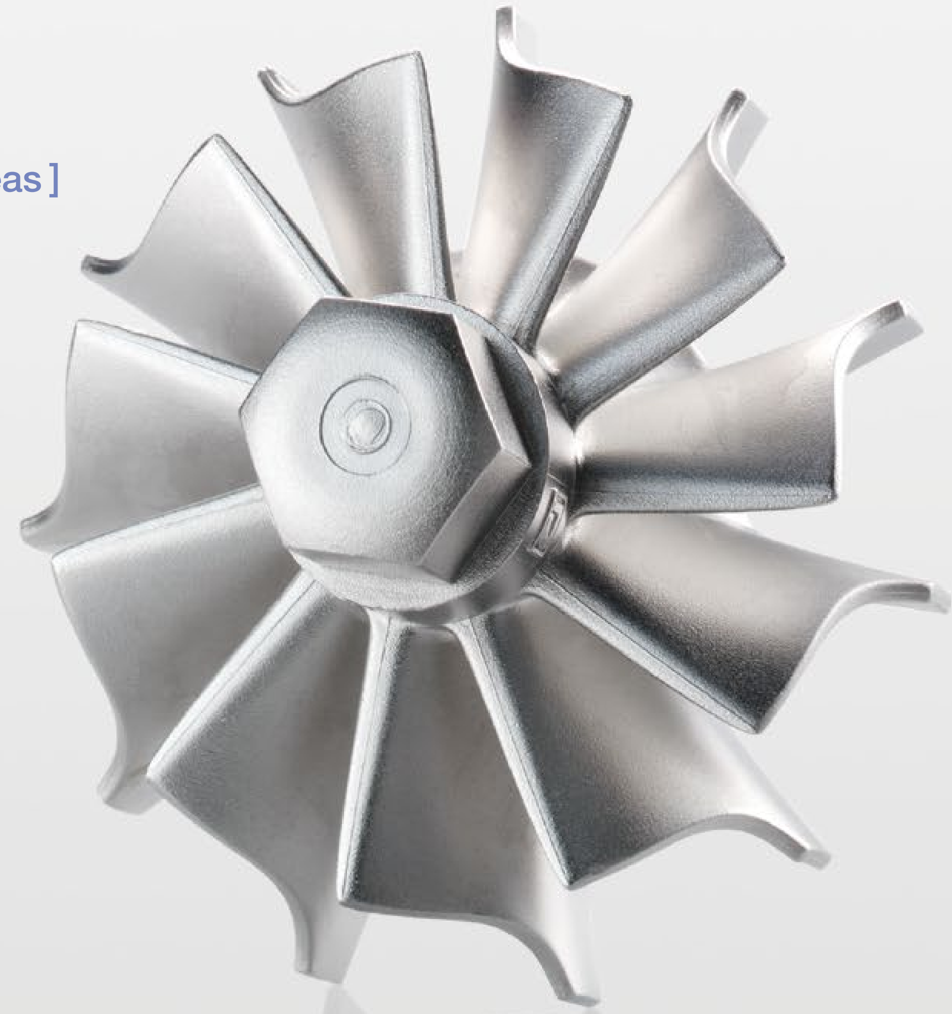


Industry News

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

ARC Wireless to acquire AFT and Quadrant Metals Technologies, aims to become a world leader in MIM

The board of directors of ARC Wireless Solutions, Inc. (ARC) announced on April 12 the signing of definitive agreements to purchase Advanced Forming Technology, Inc., (AFT) and Quadrant Metals Technologies, LLC (QMT). QMT is a holding company that owns a majority interest in several manufacturing businesses including US MIM producer FloMet LLC.

Through the combination of FloMet and AFT, ARC states that it will create a world leader in MIM, describing the technology as "innovative and fast-growing." Ted Deinard, Interim Chief Executive Officer of ARC, commented, "While we will continue to be focused on growing our wireless business, we are excited about the opportunity to transform ARC into a larger platform that should enable us to serve our current customers better and to enhance shareholder value."

"We are grateful to welcome the new additions to ARC's platform and enthusiastic about creating the world leader in MIM. The combination of FloMet and AFT is a significant milestone in the MIM industry and we are excited about what we can build with the stronger ARC platform in the future."

Jason Young, Chairman of the ARC Board of Directors added, "After a number of years evaluating potential transactions for ARC, we are pleased that we have now entered into definitive agreements with businesses that will transform ARC into a more robust platform with meaningful cash flow. We look forward to the synergies that a larger organisation will provide to our businesses, their customers, and all of our shareholders."

Advanced Forming Technology, Inc. is an ISO-certified manufacturer of MIM parts for the automotive, aerospace, medical, firearms and consumer markets. AFT operates both out of its 113 acre worldwide headquarters campus in Longmont, Colorado and its 10 acre campus in Retsag, Hungary. Throughout the past 24 years, it was stated, AFT's technical expertise has enabled it to establish a strong customer base with multiple multi-national Fortune 500 firms. AFT will divest itself of its Thixoforming division prior to the closing.

FloMet LLC, located in Deland, Florida, is regarded as one of the pioneers and leading innovators in MIM with more than 20 years of experience.

ARC Wireless

ARC, through its operating subsidiaries ARC Wireless LLC and ARC Wireless Ltd. (collectively "ARC Wireless"), focuses on wireless broadband technology. ARC will maintain its commitment to growing the wireless broadband internet business, however, the company states that it will now have the benefit of a larger manufacturing platform to provide further support to grow its business and continue to streamline costs.

The transaction is expected to be completed in the second quarter of 2012, subject to regulatory and shareholder approval. Highlights of the acquisitions include the following:

- ARC to acquire AFT, including its assets and operations in Hungary, for $43 million, approximately 1.0x Book Value, in a mix of cash and a convertible promissory note.
- ARC to issue 7,857,898 shares valued at $4.00 per share, a 36% premium to ARC's closing price as of April 12, 2012, to acquire QMT in a non-cash transaction.
- Transaction values equity of QMT at $31.4 million, a significant discount to the low end of a range determined by an independent valuation and advisory services provider.
- Pro-forma projected Net Sales for twelve months ending June 30, 2012: $66 million.
- Historical EBITDA margins at QMT have been approximately 15-19%, which ARC would expect to achieve or improve on company-wide over time, upon integration and growth of its business.

www.arcwireless.net

Oechsler explores opportunities for Ceramic Injection Moulding in China

Oechsler AG of Ansbach, Germany reports that its China production base in Taichang achieved 160% sales growth in 2011 to reach Yuan 700 million ($111 million), states a report in *Plastics News* (May 4, 2012).

Oechsler established its China subsidiary in 2004 and started plastic injection moulding operations in 2005 with about 50 employees in rented manufacturing space. It now has a workforce of more than 1,000 operating in a new 193,000 ft^2 facility. In addition to plastic moulding, the Taichang plant has also started mass production of glass-fibre reinforced injection moulded composites and is developing ceramic injection moulded components.

Fig. 1 CIM zirconia control surrounds used on the BMW 7 series iDrive, as published in PIM International, Vol. 3 No. 2

Vincent Chan, Managing Director of Oechsler Plastic Products Co. Ltd. claims that the company is the first in China to have fully applied the glass fibre reinforced injection moulding technology for a variety of applications. He said that the fibre-reinforced composites are stronger than traditional plastics, hard but not brittle and have been used to make parts including cell phone casings as thin as 0.2 mm, such as the back cover of Blackberry smart phones.

Mr Chan also highlighted ceramic injection moulding as a growth technology in China for electronic and automotive applications, and that Oechsler has started to work with BMW's China operation. Oechsler AG already produces a number of CIM zirconia components for use in BMW cars made in Germany. "We are considering expanding our CIM capacity in China following a market study," Chan stated. The company is said to be working with customers to develop more applications and is conducting initial testing.

Fig. 2 A CIM zirconia component used on the BMW 7 series automatic gear lever, as published in "Oechsler AG proves its competence in ceramic injection moulding with new BMW applications", PIM International, Vol. 3 No. 2 June 2009, pages 31-35

www.oechsler.com

Dou Yee Technologies Pte Ltd announces its expansion into the North American market

Dou Yee Technologies Pte Ltd, headquartered in Singapore, has announced its expansion into the North American market and the appointment of its US based management team to spearhead growth and drive market share. Based at its new North American marketing and sales offices in Daytona Beach, Florida, the company has appointed Brian T. Dodge as the company's Director of Marketing and Sales for North America.

Dodge joins Dou Yee Technologies with over 35 years of experience in the metals industry, predominantly PM. The company states that with a proven track record of success in this arena, Dodge has held a number of senior management positions with such companies as Metal Powder Products Company, FloMet LLC, and most recently as President of Custom Manufacturing Services, a North American based applications, design, and materials consultancy.

"Brian brings insight, expertise, and enthusiasm to Dou Yee Technologies and has the ability to build and deliver greatly on our ambitious plans for the North American market including all of the US, plus Canada and Mexico," said K H Low, Senior Director, Sales & Marketing, for Dou Yee Technologies Pte Ltd. "We aim to redefine the ways by which leading companies and design engineers approach the sourcing of custom engineered MIM components. Brian will help us develop and replicate the market traction, commercial momentum, and customer results that we've already achieved in other parts of the world."

Dou Yee Technologies states that it will redefine how companies fulfil their MIM requirements by introducing a new sourcing model that will yield a local sales and support presence in North America, plus the precision and accuracy that has become the hallmark of Asian engineering, coupled with rapid production capabilities, lower production and raw material costs, and ease of component delivery throughout the Asian manufacturing zone, or any other part of the world.

"Given that we are already revolutionising the MIM process for some of North America's most iconic manufacturers and brands, we view this expansion as the next logical step in both our growth strategy and our ability to deliver world class service to our growing customer base," explained Low. "Our mission is to work with North American design engineers, managements, and manufacturing companies to help them source their MIM components more effectively, smarter, faster, and ultimately more successfully than has previously been possible."

Dou Yee Technologies Pte Ltd, a member of Dou Yee International, offers MIM, CIM and Plastic Injection Moulding and has been serving its customers in both local and overseas markets for more than 15 years. It has a plant of over 70,000 ft^2 that includes R&D labs and tool design facilities.

www.douyeetech.com
www.dytmim.com

Surface roughened zirconia implants successfully made by Powder Injection Moulding

The results of research at the Dental Research Institute and School of Dentistry in Seoul, Korea, have shown that osseointegration of powder injection moulded (PIM) zirconia implants is promising, and that using roughened mould etching technology can successfully produce rough surfaces on the zirconia implants.

The results were published in *Clinical Oral Implants Research* April 4, 2012, pp 1-6. The PIM zirconia implants were evaluated in rabbit tibiae with some 20 rabbits receiving three types of external hex implants with identical geometry on the tibiae: (1) machined titanium implants, (2) PIM zirconia implants without mould etching, and (3) PIM zirconia implants with mould etching.

Removal torque tests and histomorphometric analyses were used to test the characteristics of the three types of implants. For example, it was found that the roughness of PIM zirconia implants was higher than that of machined titanium implants.

The PIM zirconia implants exhibited significantly higher bone–implant contact and removal torque values were better than the machined titanium implants ($P < 0.001$). The PIM zirconia implants produced using the roughened mould also showed significantly higher removal torque values than the PIM zirconia implants produced without using the roughened mould ($P < 0.001$) ■

Spyderco's Metal Injection Moulded "bi-fold" knife

Spyderco of Golden, Colorado, USA, is using metal injection moulding to produce a flat-saber ground blade from 440C stainless steel in its innovative Bi-Fold knife (Fig. 1). The design of the knife centres around a Fred Perrin inspired index finger hole containing a trigger, which when pressed releases and exposes the 32 mm long blade. With the index finger in the hole the knife is retained in the hand in a ready-to-cut position. By pressing the trigger the blade can again be swung back into the handle. A separate locking mechanism plus backup lock inside keeps it closed.

The MIM 440C blade has weight saving cut-outs. Because of the 'spring action' of the blade the Bi-Fold is considered a 'restricted item' under the US's Federal Switchblade Law, and both buyers and sellers are subject to state and federal laws applying to purchasing such restricted items.

www.spyderco.com ■

Fig. 1 Spyderco's Bi-Fold knife with MIM blade shown in the open and closed positions

Certech to consolidate CIM core production in Wilkes-Barre

MTC Certech, which has been a wholly owned division of Morgan Technical Ceramics since 2008, has announced plans to consolidate its ceramic injection moulded components operations into its 63,000 ft^2 facility in Hanover Township, Wilkes-Barre, PA, USA. The consolidation will add 80 new jobs and retain 185 positions. Certech will also purchase new manufacturing equipment.

"The Certech facility has one of the most efficient and experienced teams in North America," said Mike Kuzdzal, Vice-President and General Manager of Certech North America. "As we continue to look for opportunities to improve our customer service levels and offer the best technical and most competitive products to the marketplace, it was a logical decision for us to move work into and create jobs for this site. The Pennsylvania government agencies we worked with to make this happen were extremely helpful and also focused on the growth of this facility." Certech Inc. received a $346,000 funding offer from the Department of Community and Economic Development, including $160,000 in job creation tax credits, $36,000 in job training assistance and a $150,000 Pennsylvania First grant.

"We are thrilled by Certech's decision to expand its Hanover Industrial Estates facility," said Larry Newman, Vice-President of the Greater Wilkes-Barre Chamber of Business & Industry. "It is very good news, not just because this project brings so many new quality jobs to the Wilkes-Barre area, but also because of what Certech's investment says about Pennsylvania's ongoing competitiveness as a manufacturing location."

Certech manufactures complex injection moulded ceramic components for the investment casting industry, primarily for turbine engine blades and vanes used in aircraft and power generation. The company employs a proprietary low-pressure injection moulding process and a proprietary sintering process specifically designed to achieve high volumes with short lead-times.

www.mtccertech.com

MPIF short course offers introduction to PM and MIM

The Metal Powder Industries Federation (MPIF) has announced dates and published the full programme for its popular 'Basic PM Short Course'.

The intensive three day course will be held at Penn Stater Conference Center Hotel, State College, Pennsylvania, USA, from 23-25 July 2012. It offers an introduction to powder metallurgy from powder production to component design and testing.

Randall M. German, San Diego State University, will present an introduction to Metal Injection Moulding, covering MIM applications and properties, as well as comparing and contrasting the technology with traditional PM.

The course is designed for anyone who is either new to the powder metallurgy industry or looking to broaden their knowledge of the technology. It will be co-chaired by Myron I. Jaffe, PM Consultant, and Harb S. Nayar, President, TAT Technologies, Inc.

www.mpif.org

Canada's Maetta Sciences receives CDN $6.5 million investment to develop MIM process for medical and aerospace applications

The Caisse de dépôt et placement du Québec and the Fonds de solidarité FTQ announced a $6.5 million investment in Maetta Sciences in April 2012. Maetta is a Boucherville-based company specialising in medical implants and instruments, as well as parts for the aerospace industry. Each of the organisations invested $3.25 million, bringing the total investment in Maetta to $6.75 million. This was the Fonds de solidarité's first investment in Maetta.

"The Caisse has been a partner of Maetta Sciences since 2006 and has seen its technology evolve to meet the needs of new market niches, including in the medical sector, which offers extremely attractive growth opportunities," said the Caisse's Normand Provost, Executive Vice-President, Private Equity. "We believe the company has everything it takes to succeed: a strong management team, cutting-edge technology that allows it to offer specialised products at competitive prices and a compelling development plan."

"The Fonds de solidarité is happy to back Maetta's growth," added Gaétan Morin, Executive Vice-President, Corporate Development and Investments, at the Fonds de solidarité FTQ. "Maetta has carved itself out a niche as a supplier in the aerospace and medical equipment sectors. Its developed expertise and innovation bode well for the future of this company and its workers. The exceptional growth potential of a major industrial company in Québec more than justifies its addition to our new economy portfolio."

"For us, this is the beginning of a new phase that will be driven by strong growth," affirmed Maetta president and CEO Yvan Beaudoin. "Last year, we successfully qualified our technology with several key accounts in the medical and aeronautic sectors. Today we have a solid order backlog and requests for new projects keep coming in. One of the things we will be able to do as a result of this investment is move to a larger facility, better adapted to our needs."

Maetta collaborates in the design and manufactures final shape complex parts that provide improved functionality and significant cost reduction to its customers via its proprietary metal injection moulding process. Maetta states that its unique metal injection technology, combined with its sophisticated quality system, offers a distinctive proposition to industries such as medical and aerospace, challenged by small production volumes of complex shape parts and stringent quality requirements.

www.maetta.ca

Submitting News

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

PIM diamond-copper composites for electronic packages

Researchers at Weifang University in Weifang, China, have successfully used a combination of powder injection moulding (PIM) and copper pressure infiltration to produce diamond-copper composites with a high volume fraction of diamond powder.

The diamond-copper composites have high thermal conductivity, low coefficient of thermal expansion (CTE) and are intended for the third generation thermal management materials in applications such as electronic packaging. According to a paper presented at the 2011 International Conference on Electrical and Control Engineering (ICECE 2011) held in Yichang, China, September 16-18, the authors Chi Yuan and Jian Wang found that in optimal conditions they could produce high thermal conductivity packaging with a 62% loading of diamond powder. The powder injection moulded diamond preform was infiltrated with copper at 1450°C and at a pressure of 30 MPa with holding time of 25 minutes to give a final density of 99.7%. The thermal conductivity was reported to be 530W/(m-K), and the coefficient of thermal expansion (CTE) ranged from 5.5 ppm/K to 7 ppm/K in the temperature range from 50 to 400°C. These properties are said to meet the demands of electronic packaging materials.

PIM SiCp/Al composite packaging materials

Another group of Chinese researchers at the State Key Laboratory for Advanced Metals and Materials at the University of Science and Technology Beijing, recently reported on the use of powder injection moulding to produce near-net-shape packages using SiC/Al composites. Here PIM was also used to produce the SiC performs with a 63 vol% SiC powder loading. The PIM performs were pre-sintered and then infiltrated with aluminium by pressure/pressureless (~75 MPa) infiltration at 1000-1200°C.

According to a paper published in *Progress in Natural Sciences: Materials International* ('Review of metal matrix composites with high thermal conductivity for thermal management applications' by Xuan-hui QU, Lin ZHANG, Mao WU, and Shu-bin REN, Vol. 21, June 2011, pp 189-197; available online 21 March 2012) the feedstock for the PIM process is produced by mixing SiC powder and the binder in the double planetary mixer in the temperature range of 135-160°C. The preforms are injected moulded at a pressure of 60–80 MPa, and the moulded preforms are subjected to debinding and pre-sintering.

Fig. 1 (a) shows a SiC preform fabricated by PIM. Figs. 1 (b), (c) and (d) indicate SiC_p/Al, SiC_p/Cu and diamond/Cu composites respectively, fabricated by the combination of powder injection moulding and pressureless infiltration. The relative density of the SiC/Al package was reported to be over 99% with average CTE values lower than 7×10^{-6} K^{-1} between 25°C and 100°C, and thermal conductivity of over 190 W/(m•K). This is significantly lower than the vCTE and TC values found for diamond-copper composite packaging materials. ■

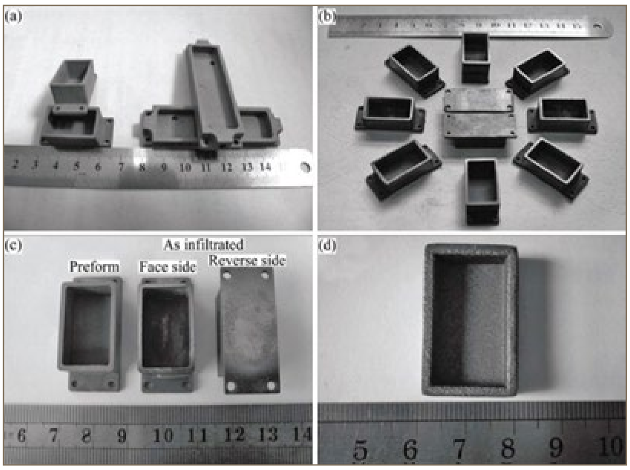


Fig. 1 Various kinds of net-shape metal matrix preform and corresponding composites: (a) SiC perform ; (b) Infiltrated SiC_p/Al; (c) Infiltrated SiC_p/Cu; (d) Infiltrated diamond/Cu

Element22 builds on Tijet's expertise to develop the market for MIM titanium products

In the Autumn of 2011 TiJet Medizintechnik GmbH, based in Kiel, Germany, was acquired by Matthias Scharvogel and the company was subsequently renamed Element22 GmbH. Scharvogel told *PIM International*, "This new name already reveals where our emphasis lies - developing and manufacturing parts out of titanium, the 22nd element in the periodic table, and its alloys. Our long-term experience and eager engineering and management team form a sound basis to enable an expansion into a wider range of end-user industries."

Reflecting this change, the company has expanded its activities from purely medical applications and it is now collaborating with additional partners to develop and manufacture products for the aerospace and space industries, as well as in the consumer goods industry.

The primary production process used at Element22 is Metal Injection Moulding (MIM). Scharvogel stated, "What makes Element22's technology unique is our own customised titanium feedstock. This is manufactured in-house according to a special formula and all our production processes are dedicated and optimised to the use of this feedstock. The goal of our technology is to produce the highest quality components at cost competitive prices."

The company's technology is based on many years of development in co-operation with key research institutions. Based on work at Fraunhofer IFAM, Bremen, Germany, and HZG Helmholtz-Zentrum Geesthacht, Germany, the company was able to produce complex components from a titanium alloy which, for the first time, retained the excellent mechanical characteristics of the basic material used. Motivated by these results a complete production line for medical

A MIM titanium derailleur component for bicycles

A MIM titanium aerospace fastener

This MIM titanium housing is for the consumer market

A thin walled MIM titanium housing for the medical sector

MIM components made from titanium was setup in Kiel, in the second half-year of 2004 and from 2005 the production of Ti-MIM parts commenced.

In April 2011 the ASTM F 2885 "Standard Specification for Metal Injection Molded Titanium-6Aluminum-4Vanadium Components for Surgical Implant Applications" was published. This standard sets the benchmark for the quality of implantable titanium components.

"Element22 is one of only a few companies worldwide that is able to meet the stringent requirements of this standard. As an active member of the ASTM committee, we have been strongly involved in creating this standard. The publication of a comparable standard for the use of metal injection moulded unalloyed titanium components for surgical applications is planned for end of 2012," commented Scharvogel.

The mechanical properties of the MIM parts produced by Element22 are similar to wrought titanium and the properties can be adjusted depending on the application. "Metal Injection Moulding has several key advantages compared to traditional production technologies that make this process of great interest to new markets, opening up a world of innovation possibilities," stated Scharvogel. "It is suited to the precision net shape manufacturing of complex parts in serial production quantities. In doing so, titanium's main characteristics, such as high strength, high corrosion resistance and low density, are commercially usable to enable lightweight design and thereby offer considerable energy savings. The MIM of titanium can, therefore, be considered a green technology that will help to save resources."

In addition, Element22 offers titanium components made by Super Plastic Forming (SPF). SPF is based on the use of a hot shielding gas to form a sheet metal into a cavity. Element22 is using this technology for the production of Titanium-6Aluminum-4Vanadium shells for pacemakers and neurostimulators.

In the future the company plans to apply its technologies to other metals and their alloys and implement new powder metallurgy based processes in order to further strengthen the use of these new green technologies.

Element22 GmbH has a certified quality management system according to the international standard EN ISO 13485.

www.element22.de ■

Polymer Technologies Inc. achieves SAE AS9100C certification

Polymer Technologies, Inc. (PTI), based in Clifton, New Jersey, USA, has announced the successful completion of its certification audit to AS9100 Revision C. Representatives from the independent, third party registrar SAI Global conducted a four-day audit of PTI's quality management system. At the conclusion, there were zero reported findings and the result was the certification of PTI's organisation as being compliant with the strict requirements of this most recent version of the Aerospace Standard.

AS9100 is the international management system standard for the Aircraft, Space and Defence (AS&D) industry. The standard provides manufacturing suppliers with a comprehensive quality system for providing safe and reliable products. AS9100 is managed by the International Aerospace Quality Group (IAQG) and based upon ISO 9001. The latest Quality Management System, Revision C, is a designation offered only to organisations that design, develop and produce aviation, space and defence products while demonstrating strict adherence to quality, reliability and safety standards. It is endorsed by all major Aerospace regulators including the Federal Aviation Administration (FAA) and the U.S. Department of Defense (DoD).

"AS9100C Certification is a rigorous auditing system that validates our organisation's effective quality management system while providing a measurement for critical cost and time-to-market factors," said PTI President Neal Goldenberg. "Achieving this certification with zero findings demonstrates our commitment to excellence."

This newest Revision C builds upon the basic tenets of the previous revision B in such areas a continuous improvement, control of non-conforming product and management responsibility. Revision C now also increases focus on program and supply chain management, as well as, vendor and subcontractor performance. Additionally, the new version requires increased visibility on many types of risks that could affect program timelines and/or part quality.

"We invested in this effort to add value to our customers and to further establish our reputation as a leading supplier of custom plastic injection, metal injection (MIM) and ceramic injection moulding (CIM) services," added Goldenberg. "We take very seriously the parts we produce for the aerospace industry, many of which are flight-critical on man-rated engines."

Examples of PTI's aerospace parts made via powder injection moulding include a Hastelloy-X component for the combustion section of a jet engine and an Inconel part for an exhaust subsystem. Additionally research and development is currently underway to replace complex metal parts with ceramic components made via CIM from zirconia and alumina.

"Switching to ceramic will greatly enhance thermal properties allowing for longer exposure at higher temperatures, at which other metal alloys could not continuously function. Also, owing to ceramics' inherent hardness, significantly increased wear resistance offers longer life to parts that experience high levels of wear," Goldenberg stated. "The net-shaped technology of our CIM operation allows us to offer these components for a fraction of the price which machined parts would cost."

www.polymertek.com

ISO schedules new PM and MIM standards

The International Standards Organisation (ISO) Technical Committee 119 covers all aspects of Powder Metallurgy with its secretariat based at SIS in Stockholm, Sweden. The Chairman of ISO TC 119 is Dr Jan Tengzelius of Höganäs AB, Sweden. The secretariat recently issued its second newsletter (May 2012) which outlined new or updated PM standards being prepared, and included details of the next plenary meeting of TC119 which will be held in Tokyo October 11-12 to coincide with the 2012 PM World Congress in Yokohama.

The newsletter reported that a final draft (FDIS) for the new updated standard ISO 5755: ' Sintered metal materials – Specifications', has been sent out for voting and the new standard will be ready for publishing by end of 2012. The standard includes about 150 different materials including low- and high-alloyed steels as well as copper-based materials. The included materials are presented at three different density levels and typically also with different contents of carbon. Chairman of the working group for this Standard is Dr Brian James.

Dr James is also responsible for the group developing the first ISO standard for MIM materials and the final draft of ISO/FDIS 22068: 6' Sintered metal injection moulded materials — Specifications' has been sent out for voting by the members. The standard includes about 50 different materials including low-alloyed steels, stainless steels, soft magnetic materials and titanium. The density is defined as less than 5% of residual porosity. The MIM standard is expected to be ready for publishing by the end of this year.

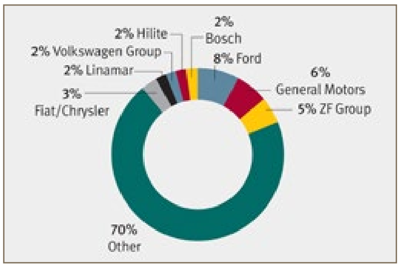
The newsletter further reported that two new ISO standards have been published for: 'Determination of cleanliness of PM parts' (ISO 28279:2011), and 'Abrasion test for Hard Metals' (ISO 28080:2011). Also a new working group has been established by a group of Swedish companies to establish a national Swedish standard for 'Hot Isostatic Pressing'. The first focus of the group will be to agree on a test method and equipment for preparing samples and testing for argon content in the HIPed material.

www.sis.se

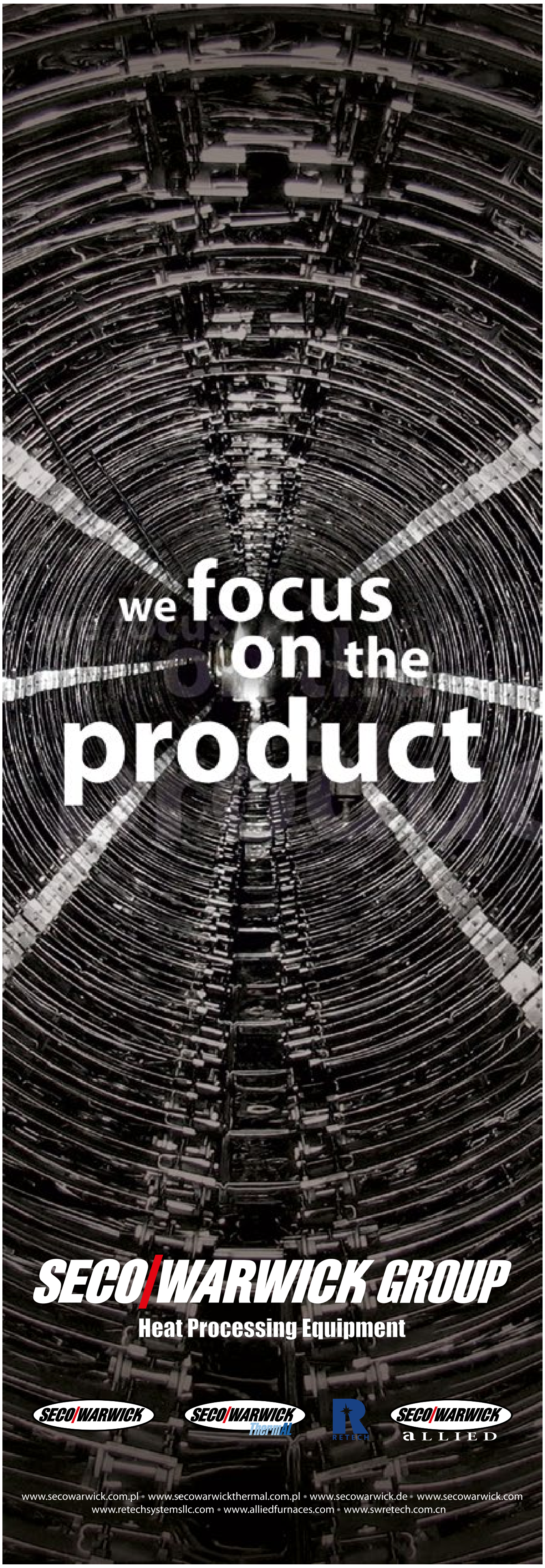
GKN starts 2012 with Q1 sales up 17% in first quarter

GKN Plc, UK, has continued to make good progress with sales for the three months ended 31 March 2012 totalling £1,742 million, a 17% increase over the comparable period in 2011, or an 8% increase on an underlying basis. GKN Powder Metallurgy division's first quarter 2012 sales increased 9% to £236 million, benefiting from good growth in North American automotive production and new programme launches across the division, stated the company. Trading profit was £22 million with the trading margin improving to 9.3%. The division includes a major MIM operation in Bad Langensalza, Germany.

www.gkn.com



GKN 2011 PM sales by customer



CIM zirconia dental implants seen as alternative to alumina and titanium

Problems with previous ceramic implant materials such as aluminium oxide led to initial reservations in the dental world about the use of zirconia. Now these reservations are being overturned by Maxon Dental, the dental business of Maxon Motor GmbH in Marburg, Germany, with its ceramic injection moulded (CIM) high performance yttrium-stabilised zirconia dental implants, branded OMNIS. These CIM zirconia implants are said to have two to three times greater rigidity than aluminium oxide, and are said to have better biocompatibility than titanium implants, which can, it is stated, give rise to chronic inflammation in some patients.

Dr. Norbert Grafe and Dr. Birgit Lehnis state in a Maxon Dental report that the specially designed surface structure of the CIM zirconia implant materials is said to guarantee rapid and secure osseointegration (Fig. 1), which matches that of etched titanium implants. They state that Maxon Dental uses ceramic injection moulding to produce the OMNIS implants because of the complex shape, high sintered density and unique surface structure that can be achieved by the CIM process. The company uses a fine zirconia powder (0.3 µm) containing 5 vol. % of yttrium oxide, which is blended with a thermoplastic binder and granulated to produce the injection moulding feedstock.

The authors of the report state that the zirconia used for the one-piece OMNIS implant exists in three different phases. At room temperature, the monocline phase is normally stable; when warmed, the monocline phase changes into the tetragonal phase; if the temperature rises further, this becomes the cubic phase. The tetragonal phase demonstrates favourable values for implantology in terms of rigidity and fracture toughness. A few more percent Y_2O_3 is added to keep the tetragonal phase stable at room temperature. Fine ceramic powder is mixed with a thermoplastic binder system to form a material that can be injection moulded. This compound can be processed as freely as with plastic injection moulding. The compound is poured into the injection moulding equipment and injected into a tool at high pressure, producing the implant's green body.

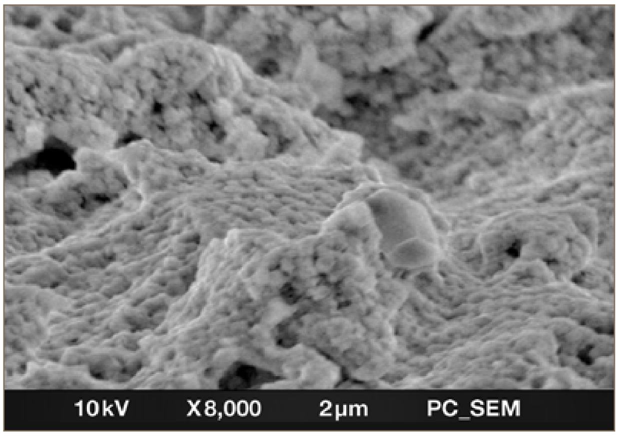


Fig. 1 The specially developed surface structure developed by Maxon Dental on the CIM zirconia implant guarantees optimum osseointegration and matches that of etched titanium implants

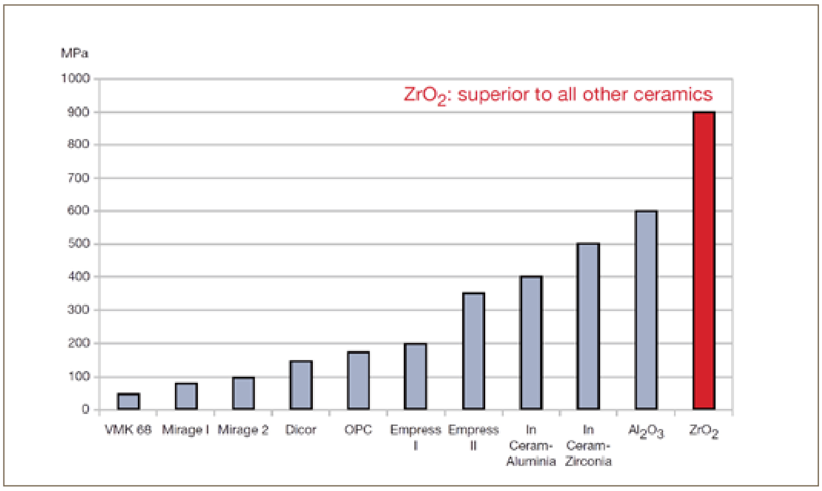


Fig. 2 Zirconia ceramics are more flexible than Al_2O_3 in conjunction with a lower elasticity modulus (Al_2O_3 350 x 10^3 N/mm², ZrO_2 200 x 10^3 N/mm²) (Courtesy Maxon Dental)

After high pressure injection moulding, the green parts undergo debinding at 120°C in a protective atmosphere, and are finally sintered at 1500°C to reach a density of ~6.05 g/cm³. The sintered implant material does not require a post-hot isostatic pressing operation. Properties include: hardness ~1350 HV, bending strength of 800 – 1200 n/mm², elastic modulus 2 x 105 N/mm², and a co-efficient of thermal expansion of 10 x 10^{-6} K^{-1}. The report from Maxon Dental includes a detailed description of how a patient was successfully treated with a ceramic injection moulded OMNIS implant.

www.maxondental.de

New 15th edition "International PM Directory" includes PIM producers and suppliers

The new 15th Edition *International Powder Metallurgy Directory* (IPMD) 2012-13 has now been published. As well as featuring a fully updated PM industry directory section, this 648 page reference publication includes more than 190 pages of PM and PIM market and technology information.

The IPMD has been a unique and essential source of information on the global PM industry since it was first published in 1977. This latest edition contains details of more than 4800 companies involved in both PM and PIM, including PIM parts makers, feedstock producers and PIM equipment suppliers. The IPMD is published by Inovar Communications Ltd and is an A4, softcover, 648 printed pages book, ISBN 978-0-9558223-2-2.

www.ipmd.net

Carbon nanotubes/copper powder feedstock studied for high performance heat sinks

The trend towards ever more powerful smart electronic chips, which attain high temperatures during operation, has seen increasing attempts at developing more effective, thermally conducting materials for heat sinks and ways to produce the highly complex shapes needed. Powder injection moulding (PIM) has been seen as a key manufacturing route for defect-free heat sinks made from metal matrix composite materials having high thermal conductivity and a low coefficient of thermal expansion.

The incorporation of carbon nanotubes into PIM feedstock has also been seen as a novel approach to aid the development of high performance heat sinks for the electronics industry, and research has been carried out at the Dept. of Mechanical Engineering, University of Technology Petronas, in Malaysia, to optimise the flow behaviour of multi-walled carbon nanotubes (CNTs) reinforced copper matrix feedstock for PIM. The researchers involved (A.S. Muhsan, F. Ahmad, M.R. Raza and N.M. Mohamed) recently published the results of their research in the *International Journal of Applied Physics and Mathematics*, Vol. 1 No. 3 November 2011, 199-202.

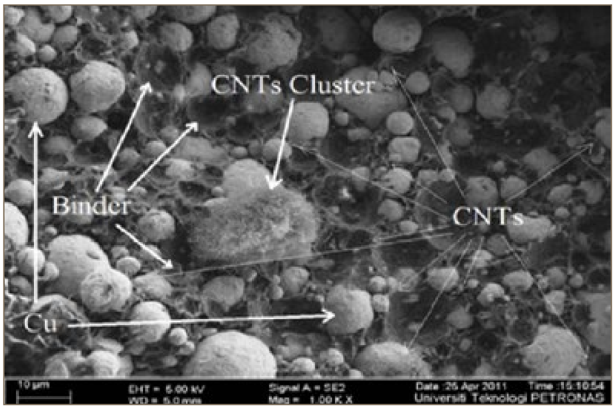


Fig. 1 Scanning electronic microscopy image of Cu/CNTs feedstock. (From paper: 'Flow Behaviour of Cu/CNTs Feedstocks for Powder Injection Molding' by A. L. Muhsan, etal. International Journal of Applied Physics and Mathematics, Vol. 1 No. 3 November 2011, 199-202)

In order to identify the most suitable binder with minimum viscosity, and to achieve higher loading of solids for the Cu/CNTs PIM feedstock, the researchers used a rheometer, (Shimadzu flow tester CFT-500D), with a capillary die of 1 mm diameter and length of 10 mm. Binder granules were filled into the rheometer barrel, heated to 160°C and slight pressure was applied to the rheometer ram and held for 5-10 minutes to attain equilibrium temperature throughout the materials. The materials were extruded through the capillary die and the time taken was recorded. Volumetric flow of melt was calculated for shear rate and the corresponding shear stress was calculated to determine the viscosity of the binder. The viscosity of binder was measured over a shear rate of approximately 2000 s^{-1}.

The researchers studied three binder formulations and selected a binder formula based on 70% paraffin wax, 25% HDPE, and 5% stearic acid (designated B3) to be most effective due to its lower viscosity, and this binder was used to introduce fine gas atomised copper powder with a particle size distribution of >22 µm. Four different powder loadings were tested – 55, 57, 59 and 61 vol%. For preparation of copper/ MWCTNs feedstock, copper powder and CNTs were dry blended in a ball mill for 20-30 minutes, followed by compounding the mixture at 140°C. This ensured a uniform dispersion of CNTs and copper powder in the binder, and mixtures were solidified and granulated to > 5 mm feedstock for powder injection moulding.

They found that by adding a further 5% paraffin wax to the B3 binder formula and with a reduction in HDPE the viscosity level was reduced to ca. 17 Pa.s, which was considered suitable for incorporation of copper powder and CNTs. A 59 vol % copper powder loading in the feedstock was found to be most suitable for substitution of CNTs in Cu feedstock. The results showed that copper powder composite mixtures containing up to 10 vol% multi-walled carbon nanotubes (MWCNTs) had a viscosity low enough to be successfully powder injection moulded to produce defect-free test samples. ■

Submitting News

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

Technical Programme published for PM2012 Yokohama

The Technical Programme for the PM2012 PM World Congress & Exhibition, to be held at the Pacifico Yokohama Convention Centre, Japan, October 14-18, has been published.

The congress will be opened with a special session devoted to recent trends in competing manufacturing technologies such as casting, forging, and fine blanking. This will be followed by a four-day technical programme containing close to 500 technical papers in oral and poster sessions.

All aspects of PM materials and processing will be covered, including MIM. The technical programme will also contain Special Seminars organised by the Japan Powder Metallurgy Association (JPMA), a series of case studies on environment and energy saving, and the presentation of the JPMA awards.

There will also be a special session on the PIM trends in North America, Europe and a number of Asian countries.

The Asian Powder Metallurgy Association (APMA) has also announced that the PM2012 exhibition is close to selling out and that more than 75 exhibitors have already booked space.

PIM International will be exhibiting at PM2012, we look forward to seeing you there!

www.pm2012.jp

Full details on the Technical Programme and congress registration are available online.

MIMA releases new promotional video

PM and MIM: Touching Your Life, a new video showcasing the capabilities of metal injection moulding (MIM) has been released by the Metal Injection Molding Association (MIMA) of the Metal Powder Industries Federation (MPIF). The new video is available for purchase in DVD format from MPIF or can be viewed online on the MPIF and MIMA websites.

The 15-minute programme, aimed at potential end users who may not be familiar with PM and MIM, is built on the theme, "Every day, in some way, PM and MIM touch your life." It is divided into two parts, initially introducing the viewer to PM, then specifically to the MIM process, providing design engineers with all the facts needed to understand why, if they're designing an intricate metal part, they should think of MIM from the start.

As well as being targeted towards end-users, MIMA states that it is also an effective training tool for employees of MIM and PM manufacturers.

www.mimaweb.org

Wittmann Battenfeld India celebrates 5th Anniversary

Wittmann Battenfeld India Pvt. Ltd. is celebrating its five year anniversary at its premises in Chennai in 2012. Wittmann India renamed itself Wittmann Battenfeld India Pvt. Ltd to better reflect the broadened sales and service support after Wittmann's acquisition of Battenfeld in April 2008.

Since its founding, the Indian company has enjoyed uninterrupted growth. This is not only reflected in its market share, but also in the growth of its team, which has now surpassed 35 employees.

Wittmann Battenfeld India provides customised automation solutions, and is a leader in development of linear robots. Another leadership role for the company is in the field of powder injection moulding with specially adapted injection moulding machines of the Battenfeld HM series. A large number of Wittmann Battenfeld machines are used by India's largest MIM producer, Indo-US MIM Tec Pvt Ltd., based in Bangalore.

www.wittmann-group.com

The team of Wittmann Battenfeld India (Photo Courtesy Wittmann Battenfeld)

PIM route to complex glass-carbon components investiagted

A research project designated 'GlasPIM', financially supported by the German Federal Mininstry of Economics and Technology, has been underway since August 2011 to develop technology for producing electrically conductive sintered glass-carbon resistor components using powder injection moulding (PIM).

The German Ceramic Expert Group based at the Fraunhofer IKTS Research Centre in Dresden, reports that the aim of the GlasPIM project is to study the specific resistance of sintered glass-carbon materials, and the influence of various parameters involved in obtaining complex shaped components with the desirable microstructures and properties using PIM.

The project will also evaluate the economic aspects of producing highly complex shaped glass components previously not possible by this manufacturing technique, and the production using PIM, not only of electrically conductive components, but also transparent glass components having high geometrical complexity and edge sharpness.

Partners in the GlasPIM project include the Fraunhofer IKTS Research Centre, ceramic feedstock producer Inmatec Technologie GmbH (Rheinbach), and CIM producer Kläger Spritzguss GmbH. Further information is available from Dr. Tassilo Moritz, Expertenkreis Keramikspritzguss, email: info@keramikspritzguss.eu

www.keramikspritzguss.eu

The rapid production of MIM prototype components

Michael Bischoff of OBE Ohnmacht & Baumgärtner GmbH, Ispringen, Germany, presented a case study at a seminar during the 'Suppliers Convention' at the 2012 Hannover Fair (April 23), which looked at the use of different methods used by his company for producing MIM prototype components. He stated that a small number of complex shape MIM prototypes could be produced in around two to three days, and that if higher quantities of prototypes were required (100 to 500) then these could be produced in two to three weeks.

Bischoff explained that for a small number, for example five, prototype parts OBE first produces a 'neutral' moulded part in the green state, which he stated should not be bigger in volume than a 'walnut'. The green part is then milled to the required shape using CAD data, followed by sintering with controlled shrinkage of the machined part. All MIM materials, including titanium, can be easily machined in the green state, he said, and the future injection point can even be milled into the prototype. In this way a small number of parts can be generated within two to three days from the realisation of the 2D or 3D CAD drawing. The resulting sintered prototypes can be used for mechanical property tests, and for functional, optical and haptic checks, thereby eliminating any design and production problems in serial production.

It was stated that if 100% simulation of MIM component production is required for say 100 to 500 prototype parts, then OBE uses a low-cost aluminium tool/injection mould insert which can be produced within two to three weeks also from CAD drawings. These tool inserts can be used for moulding the same feedstock as would be specified in the mass produced MIM part, and the prototypes can be produced at considerably less cost and in a faster time than if expensive mass production tooling first had to be manufactured.

www.obe.de

Fig. 1 OBE Ohnmacht & Baumgärtner GmbH can produce prototype MIM parts by green machining and sintering within two to three days.

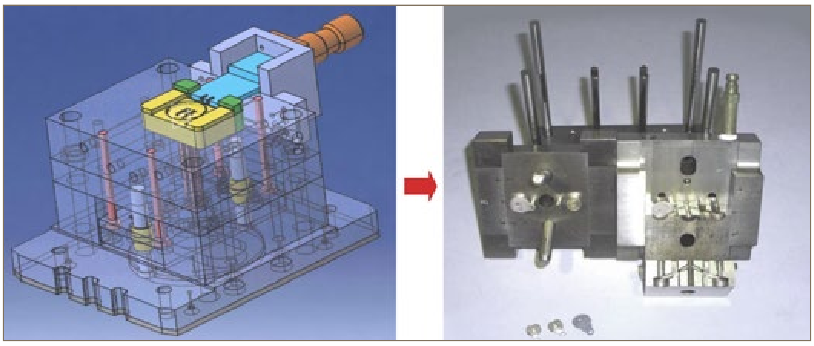


Fig. 2 Aluminium tooling and inserts are used to produce larger volumes (100 to 500) of MIM prototypes.

Submitting News

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New sinter-hardening alloy developed for high strength Metal Injection Moulded parts

Sinter-hardening ferrous alloys have been widely used for a number of years for the production of press and sintered Powder Metallurgy parts with ultimate tensile strength (UTS) around 1200 MPa and hardness values of 40 HRC at a sintered density of 7.2 g/cm^3. However, elongation at this density level is relatively poor at <1%. Some ten materials standards have been developed by the Metal Powder Industries Federation (MPIF) for these sinter hardened alloys using mostly prealloyed steel powders, but new alloys are needed to achieve even higher strength, hardness and ductility.

An additional issue is dimensional control, which even at cooling rates of >30°C/min in the sintering furnace it is still sufficiently rapid to cause deformation and can limit dimensional control of the sintered parts. In metal injection moulding this potential lack of dimensional control can be even more critical because of the highly complex shapes of most of the MIM parts produced, and as yet no sinter-hardening MIM alloys appear to have been patented or registered in MPIF Standards.

Kuen-Shyang Hwang and Chen Hsu at the National Taiwan University in Taipei, together with colleagues from the industry in Taiwan, initiated a research programme five years ago to design a new MIM alloy that can be sinter hardened using standard cooling schedules (<30°C/min), without the need for rapid cooling such as gas quenching. They also set themselves a goal to obtain material properties comparable with those of heat treated MIM-4140 and MIM-4605, the latter having the highest strength according to the MPIF MIM standard. After quenching and tempering MIM-4605 has a UTS of 1655 MPa, a hardness of 48 HRC, and elongation of 2%.

The results of their research were published in the January/February 2012 issue of the *International Journal of Powder Metallurgy*. The researchers reported that a new MIM alloy was developed containing Fe-6Ni-0.8Mo-0.8Cr-0.4C and designated Fe-6 w/o Ni, together with Fe-2Ni-0.5Mo-0.4V (designated Fe-2Ni w/o Ni), which is a modification of MPIF MIM 4605 and which served as a benchmark for comparison of the research results.

The MIM alloy was produced from BASF carbonyl iron powder (3.8 micron) and the mixture of Fe, Ni, Mo and Fe-Cr elemental powders was kneaded with 7 w/o wax based binder and the resulting feedstock injection moulded. After solvent and thermal debinding, the moulded parts were sintered at 1330°C in vacuum and then furnace cooled to 900°C followed by fan cooling. The average cooling rate over the range of 600°C to 500°C was 25°C/min. Both new alloys were tempered at 200°C for 2 hrs.

The authors reported that the use of fine powders and high temperature sintering resulted in a density of 7.63 g/cm^3 (97.1% pore free density) in both the Fe-6 w/o Ni and Fe-2 w/o Ni materials with resulting ultra high strength and high ductility. In fact the mechanical properties are superior to those cited in MPIF standards for heat

Alloy	Heat Treatment	Hardness (HRC)	Ultimate Strength MPa (psi x 10^3)	Yield Strength MPa (psi x 10^3)	Elongation (%)	Impact Energy J (ft.•lbf)
Fe-6 w/o Ni	As-Sintered	54	2,100 (304)	1,370 (199)	4.4	26* (19)
	Tempered	50	1,900 (275)	1,480 (214)	7.6	55* (40)
Fe-2 w/o Ni	As-Sintered	96 HRB	730 (106)	460 (66)	10.0	33* (24)
	Quenched & Tempered	44	1,700 (246)	1,510 (219)	3.0	57* (42)
18Ni (250) Maraging Steel	Solutioned & Aged	48	1,800 (261)	1,700 (246)	8	37 (27)
4340	Quenche & Tempered	53	1,980 (287)	1,860 (270)	11	20 (15)
300M (4340+1.6 w/o Si)	Quenched & Tempered	54	2;140 (310)	1,650 (239)	7	22 (16)
8640	Quenched & Tempered	55	1,810 (262)	1,670 (242)	8	12 (9)
MIM-4605	Quenched & Tempered	48	1,655 (240)	1,480 (214)	2	55* (41)
MIM-4140	Quenched & Tempered	46	1,650 (239)	1,240 (180)	5	75* (55)
FLC-4805 (7.2g/cm^3)	Sintered & Tempered	39	1,280 (186)	-	<1	20* (15)

*unnotched specimen

Table 1 Mechanical properties of fan-cooled Fe-6 w/o Ni, Fe-2 w/o Ni and wrought ultra high strength steels (from paper "Ultrahigh strength Sinter Hardening MIM Alloy Steels' by K-S Hwang, et al, published in International Journal of Powder Metallurgy, Vol 48, No 1, 2012, 35-43)

treated MIM-4605 and press and sinter-hardened FLC-4805, and were found to be comparable with those of ultra-high strength wrought steels (see Table 1). The UTS of the new sinter-hardened and tempered Fe-6 w/o Ni MIM alloy was found to be 1900 MPA, with a hardness at 50 HRC and elongation of 7.6%. This gives the material the advantage of not requiring quenching and tempering, unlike wrought 4360 and 8640 alloy steels.

The researchers also found that in terms of dimensional control the new sinter hardening alloy powder provided significant improvements in dimensional control in MIM parts production. Using production parts, the sintered and tempered Fe-6 w/o Ni specimens with a wall thickness of 15 mm showed a standard deviation of 0.007 mm compared with 0.021 mm in the quench-and-tempered Fe-2 w/o Ni parts. Flatness distortion was also reduced in the new alloy.

www.ntu.edu.tw

Focus on Powder Injection Moulding at PM-12 India

A special session on Powder Injection Moulding was held during PM-12 International Conference & Exhibition on New Vistas in Particulate Materials Technology, Mumbai, India, 2-4 February, 2012. The event was organised by the Powder Metallurgy Association of India (PMAI) and attracted more than 200 international delegates. Professor Ramamohan Tallapragada provides an overview of the session.

Prof. Parag Bhargava, IIT Bombay, presented a review paper on **Powder injection moulding principals and processes**. Important considerations in the selection of raw materials, and, development and characterisation of feedstock were reviewed, and various possible defects that are likely to be encountered in injection moulding explained. Several debinding techniques and characterisation of sintered components were also discussed.

The research work of his group on the metal injection moulding of an electrolytic iron powder based feedstock was presented as a separate paper. In this paper, electrolytic iron powders were used with stearic acid as a surfactant and two types of binder systems, water soluble (PEG, PE-wax and PMMA) and solvent (n-hexane) soluble (paraffin wax, HDPE). A workable paste like feedstock was obtained using a solvent soluble binder system and sintered components are produced. However, the low density and ductility obtained after sintering are attributed to segregation of the binder, leading to void formation during prior debinding and also due to some oxide formation. It was also found that a paste like feedstock is difficult to obtain with a water based binder system.

The **Processing of Catamold® Feedstock** was discussed by Prashant G. Joshi, BASF India. The system, it was stated, has been serving as a benchmark for the processing of metals and ceramics by injection moulding thanks to its technical and economic advantages. Key technical features were discussed and applications in the automotive, electronic and medical industries illustrated.

Michalel Godin, Mate Consulting Ltd, China, in his presentation on **Powder Injection Moulding- New Developments in Metals and Ceramics** reported that PIM in China reached estimated sales of $55million in 2011, as compared to total Asian sales of $500million. The PIM markets in China and India, it was stated, are still rather small although there are multiple PIM startups entering the market every year. At present, stated Godin, there are 73 PIM producers in China and four in India. Much larger markets for MIM are found in Japan, Taiwan and Singapore.

Most commonly used materials in PIM are 17-4PH, 316L and Fe Ni alloys (Fig. 1). PIM in China is strongly focused on consumer, computer and communication components (CCC) and only a few companies in China manufacture medical and automotive components, which are very similar to those produced by Japanese, European and US PIM companies (Fig. 2). The reason, it was stated, is that the required international ISO and TS standards take a long preparation time. Almost all PIM companies in China and India manufacture their own feedstock. While Chinese companies primarily use Chinese equipment, it was stated, Indian companies use equipment made overseas.

The PIM industry in India is largely dominated by one company, Indo-US MIM Tec Pvt Ltd, with a current production capacity of approximately 700 tons of PIM parts per year. It was stated that 95% of the product is exported. It was pointed out that MIM grade metal powders are not produced in India. Besides Indo-US MIM Tec Pvt Ltd., there are another three much smaller PIM producers in India, with many more startups to be seen over the next few years.

Prof. P. P. Date of IIT Bombay presented his research group's work on **Analysis of Solvent debinding process in Powder Injection Moulding using improvised mass transfer models**. The solvent debinding process has so far been modelled based upon Fick's law of diffusion, which uses a simplified and idealised representation to represent the real phenomena in solvent debinding, which in reality includes many additional complexities like presence of a stagnant film, penetration, surface renewal, etc. There is a need to critically evaluate all the phenomena occurring and then

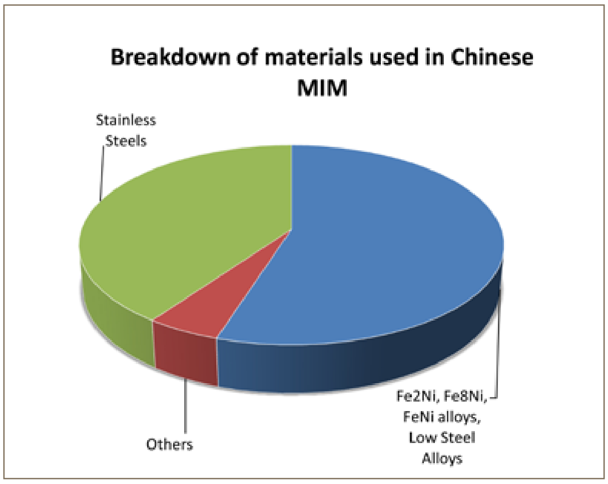

Fig. 1 Breakdown of MIM materials used in Chinese MIM, as presented by MATE Consulting Ltd., China

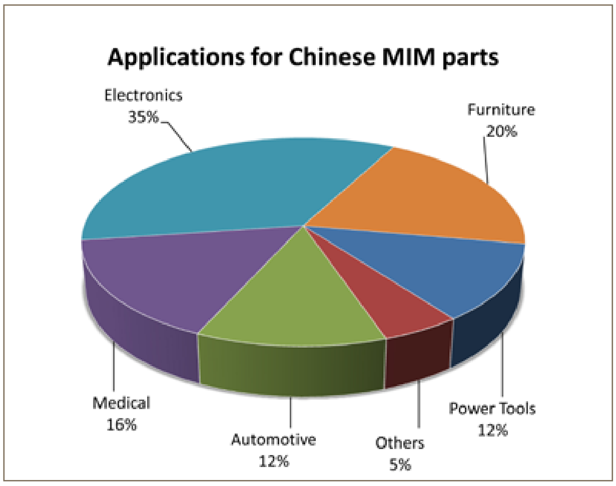

Fig. 2 Applications for Chinese MIM parts as presented by MATE Consulting Ltd., China

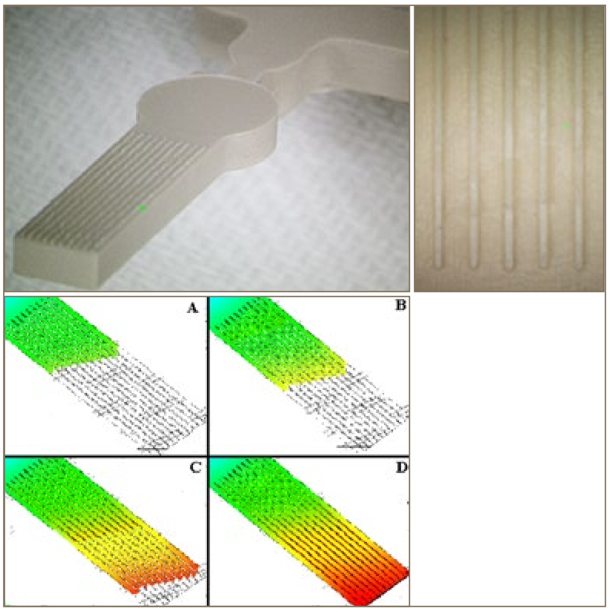

Fig. 3 Top left and right, CIM alumina micro channel arrays (MCAs) used for experiments. Bottom, progressive filling of micro channels using Catamold AO-F from Moldflow simulations

apply a suitable model for it.

According to Prof. Date the phenomena are analogous to the ones being applied to drug dissolution models in the pharmaceutical field. Hence an attempt is being made to study the applicability of these models to the solvent debinding method and the results of the experiments are evaluated through these models for validation. The most suitable models found provide results that are significantly close to the experimental findings as apposed to the Fick's law based model.

Sachin Laddha of Battelle Science & Technology India Pvt. Ltd., Pune, presented his research work on the fabrication of **PIM of Ceramic Micro arrays For Aggressive Environments**. The problems of material homogeneity at the macro scale (short shot) and microscopic (binder/ powder separation) levels during the fabrication of micro channel arrays (MCAs) from ceramic particles by PIM were emphasised. A new study protocol was outlined, which can be used as a development tool for nano particle processing for PIM. The author envisaged that experimental understanding of material homogeneity issues and models for micro system design will significantly contribute to the technological foundation and future development of PIM for micro scale applications (Fig. 3). ■

Erratum

The publishers would like to correct a missing image acknowledgment in the article "Hot Isostatic Pressing of PIM Parts: Material Properties and Increased Productivity", as published in *Powder Injection Moulding International*, Vol. 6 No. 1 March 2012, pages 61-63.

Fig. 6, "Typical 17-4 PH stainless steel MIM component; un-etched microstructure shows isolated porosity as sintered (left) that has been eliminated after HIP processing (right), (original magnification 100x)" should read "Courtesy Bodycote".

Advances in PIM biomaterials: Materials, design, processing and biofunctionality

Medical products have a large number of critical requirements. Today's state of the art in PIM technology already meets many of these, however not all the requirements of biomedical applications can currently be met by PIM solutions. In this article, Dr. Frank Petzoldt, Deputy Director of the Fraunhofer IFAM institute in Bremen, Germany, considers what developments are needed for PIM to be able to offer further added value in medical applications. From new design features to special surface structures that enhance biofunctionality, there are numerous challenges and opportunities ahead for the industry.

Medical technologies are becoming ever more important because of the year on year increases in average lifetimes. This has opened up a huge market for medical devices that is served by a wide variety of industries. There are many well-known international companies producing surgical instruments and medical equipment, as well as implants. In all of these segments complex metallic and ceramic components are of great interest.

A large number of such components manufactured by PIM technology are already being used in medical applications. These are supplied to medical companies by PIM manufacturers who can provide a wide range of innovative and economically attractive solutions. This is, therefore, a growing market that offers significant opportunities for companies along the whole PIM supply chain. For example, there are opportunities to create new business starting with specially tailored powder or feedstock, stringent PIM process control and ending with special surface treatments.

The outlook for PIM in medical applications shows a continuously growing market. Today, the most prominent application is the mass production of dental brackets by PIM. Additionally, the market for components for disposable medical instruments is becoming ever more valuable. Here there are excellent prospects for high volume production. Non-disposable instruments also present opportunities, but with the added challenge of having to fulfil other requirements, such as corrosion resistance in special environments and the ability to withstand numerous sterilisation cycles.

Hurdles such as reliability tests and legal issues, especially for components that are in long-term contact with the human body, have to be overcome to enable the broader application of PIM components as implants. This is a great challenge for PIM component manufacturers and it will require a better acceptance of PIM by medical device manufacturers as a reliable process for high quality components with functional and economical advantages.

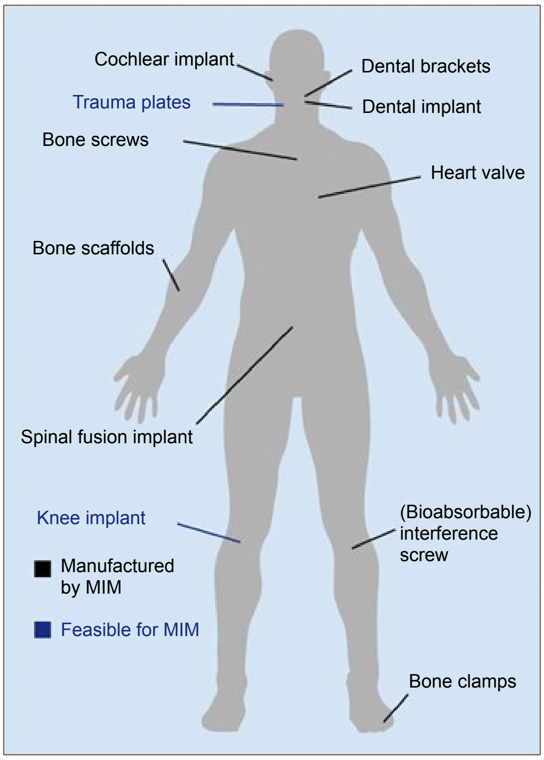

Fig. 1 Components for medical use manufactured by MIM

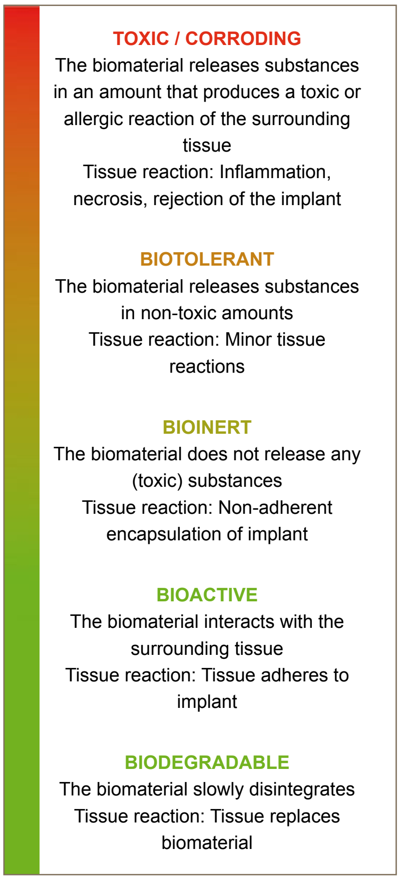

Fig. 2 Grades of biocompatibility

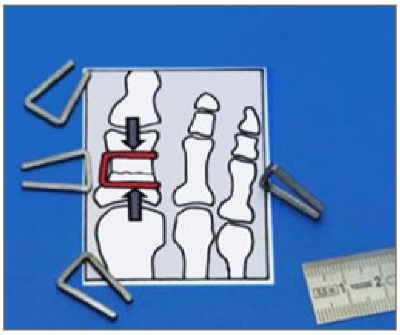

Fig. 3 Bone clamp for setting fractures in small bones (toes), injection moulded from NiTi shape memory alloy (© Forschungszentrum Jülich, Germany)

Existing solutions and new challenges

There are specific critical requirements that need to be met by a producer of PIM medical products. Firstly, the medical industry's strict quality requirements have to be fulfilled. This includes a quality system being compliant with ISO 13485, a quality standard for the production of medical devices. Surgical instruments such as endoscopic components, scalpel handles and instrument bodies are today produced by an increasing number of MIM manufacturers.

Implants that have to be in contact with the human body for some time are categorised into three general classes depending on the duration of contact. Very strict rules have to be fulfilled, especially for the Class 3 long-term implant components. For application in the human body, each product requires a conformity assessment that has to be delivered by the component manufacturer.

With this in mind, it is no surprise that the majority of today's PIM components used in medical applications are Class 1 components such as dental brackets. Only very few applications of MIM Class 2 components, such as implanted bone fixation parts, are already used by medical doctors. Due to the long time to market for Class 3 parts, it is a major challenge for a PIM producer to get access to such applications and to create a sustainable business. There are, nevertheless, a growing number of metallic components used as "spare parts" for humans. Fig. 1 shows how MIM parts are already helping to "re-invent a human". Going through the list of applications, by far the most important MIM parts in terms of business are dental brackets, but complex systems such as cochlear implants are helping deaf people to hear again thanks to high precision MIM components that offer both technical performance and economic benefits.

Trauma plates, dental implants and bone screws are further examples of medical applications where MIM offers a competitive solution. When considering bone scaffolds, it is important to recognise that there is no alternative technology that can provide a feasible solution other than powder technology.

Materials

When discussing potential materials for PIM medical applications it is important to understand the specific requirements. In Fig. 2 different grades of biocompatibility are explained. Typically the material for the majority of PIM parts in medical applications has to be at least bio-inert. Efforts to create bioactive surfaces by using PIM technology will be discussed later in this article. A major challenge and opportunity for the future is the development of a biodegradable material combined with a suitable shaping process, which will hopefully be PIM.

Today the list of metallic and ceramic materials for medical applications is not very long, however, commercially available powders and feedstocks already cover many requirements. The most common materials for surgical instruments and orthodontic applications are stainless steels such as 17-4PH, 420 or 316L, all of which combine good corrosion resistance and mechanical properties.

Special Ni-free stainless steel grades are also very interesting materials for components that are in close contact with the skin, as well as for implants. The reason for this is to avoid the risk of contact-allergenic reactions with nickel. Such Ni-free materials, for example BASF's Panacea feedstock, are also used to produce consumer goods and jewellery.

Two ceramic materials (aluminium oxide and zirconium oxide feedstocks) are also currently used for dental implants and dental brackets, as well as other medical components produced by CIM. The white colour or translucent nature of these components is a major benefit in comparison to Ti or CoCr alloys for applications where there is an aesthetic consideration.

There are other materials of interest for PIM which offer unique properties. So called shape memory alloys change their shape to a predefined structure at a certain temperature, for example at body temperature. To broaden potential applications of MIM components the processing of pre-alloyed NiTi powder with a phase transformation temperature of 37°C by µMIM has been evaluated. This means that by cooling the component during surgery to below 37°C the shape can be completely different compared to the shape above the transition temperature. The bone clamps for setting fractures in a toe, shown in Fig. 3, are made from the shape memory alloy NiTi. The clamp helps to stabilise a fracture in the toe by making use of the shape memory effect, creating a mechanical stress in the desired way.

Further processing can involve plasma ion immersion treatment of the surface to slow down or prevent nickel from diffusing into the body [1, 2].

One of the most important materials in medical applications is a CoCr alloy. Today fine gas atomised CoCr powder is available for PIM and also Additive Manufacturing by Selective Laser Melting (SLM).

Titanium and Ti-alloys are very interesting materials for many medical

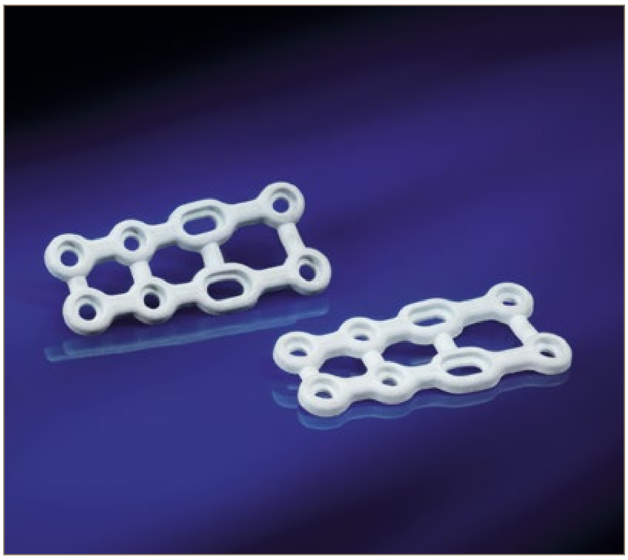

Fig. 4 Injection moulded trauma plate made from PLA composite material

Fig. 5 The smallest human bone (stapes) replicated by μMIM. Materials are stainless steel or titanium (in cooperation with Krämer-Engineering, Rendsburg, Germany)

devices due to their light weight and valuable mechanical properties. MIM of titanium and its alloys is therefore set to become ever more attractive, despite the fact that the market share for Ti in MIM is currently just 1%. The mechanical properties of the sintered parts have been significantly improved in recent years and impurity pick-up has been minimised thanks to sophisticated processing.

The availability of fine powders with a spherical particle shape and low impurity levels is a prerequisite for the success of titanium MIM. The price of these powders still restricts the application of titanium and its alloys to small components or high-end speciality products. Furthermore, it is important to guarantee a reproducible process chain focussing on impurity control, as well as titanium grades that can be processed in series production equipment.

The proven advantages of the MIM of titanium, specifically precision in combination with good mechanical properties, have been demonstrated in a number of medical components including artificial heart valve rings and trauma plates. The MIM of titanium and its alloys is on a growth track thanks to success stories that are helping to increase confidence in PIM technology and its introduction in safety critical applications [1-3]. The standardisation of MIM Ti is an important step towards the broader acceptance of the process as a reliable production technology.

It is also possible to tailor the pore-structure of sintered Ti parts. The parts can be used for filter applications, but also as structural components depending on the porosity level. Bone scaffolds can be produced by PIM, as well as by additive layer manufacturing technologies like Selective Laser Melting (SLM) or Electron Beam Melting (EBM), both of which are interesting alternative production methods for individual shapes and small series customised products.

During the European Powder Metallurgy Association's (EPMA) EuroPM 2006 Conference in Ghent, Belgium, a Special Interest Seminar focusing on the MIM of Titanium was organised and during this year's EuroPM Conference in September in Basel, Switzerland, the progress in MIM of Ti and Ti alloys over the last six years will be reviewed.

'The proven advantages of the MIM of titanium, specifically precision in combination with good mechanical properties, have been demonstrated in a number of medical components'

Fig. 4 shows trauma plates as they can be produced by PIM. The special material that was developed is a polylactic acid (PLA) composite material. PLA is a biodegradable polymer. The composite selected for the investigations by Fraunhofer IFAM has a composition of 70% Hydroxilapatite (HA) and 30% PLA. This blended composite, which was produced using a unique process, was mixed with a water-soluble binder based on polyethylene glycol and polyethylene oxide. Such a feedstock can be processed on a conventional moulding machine.

A future scenario is the possibility to repair any bone defect through the use of degradable materials. This means, for example, that a bone screw could be made by PIM from a composite material which takes the full load directly after surgery and then degrades at the same rate as the bone defect recovers. This innovative concept is under investigation within a Fraunhofer internal project combining the skills of different institutes. The first positive results have been the definition of different suitable composite feedstocks and the chance to create a desired shape by injection moulding. It is obvious that this research and development will take years until its real application in the human body. Assuming a successful development this could be the next significant breakthrough for PIM in medical applications.

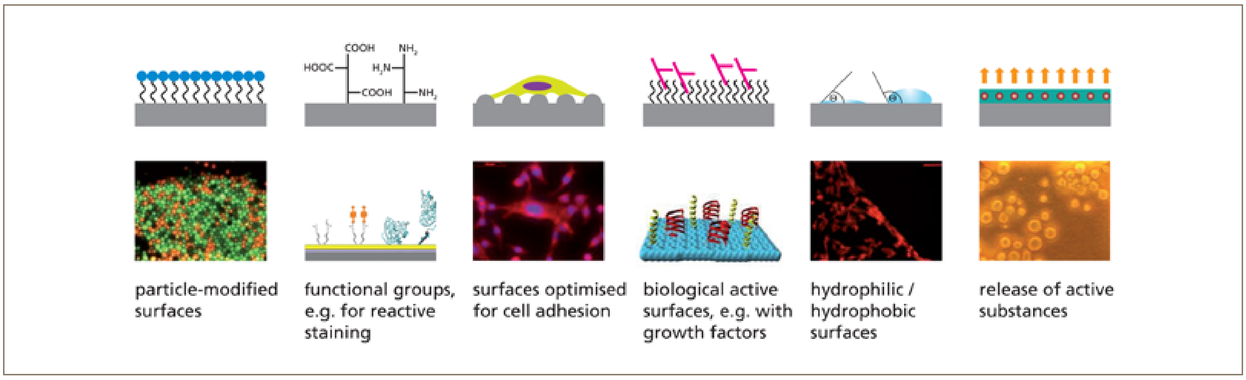

Fig. 6 Variety of possible surface modifications

Processing and design

The whole process, from powder to the sintered component, is very important because any pick-up of impurities has to be avoided. Therefore precautions during the whole production chain have to be made. A clean production environment, with a specific cleanroom class, may in some production steps (such as packaging) be as important as control of sintering atmospheres. It is clear that it is necessary to have full control of processing conditions to achieve and provide the highest quality parts. Quality control, as well as documentation, has to be approved for medical products in a very stringent way.

The freedom of design that PIM offers is an important argument for choosing this manufacturing process in competition with other shaping technologies such as machining, casting or sheet metal forming. For parts that make use of porosity, there is simply no option other than powder technology. If structures are extremely fine, or the pores have to be designed at a certain size, then PIM is without a doubt the most suitable manufacturing process.

Compared to the standard PIM process widely used in industry, some specific requirements have to be considered for μPIM. These include powder particle size, which is significantly reduced compared to standard PIM, and binder composition, which needs to be adjusted for a safe ejection of small structures. Because of these variations, debinding and sintering processes have to be adapted accordingly.

'The freedom of design that PIM offers is an important argument for choosing this manufacturing process'

Fig. 5 shows the reproduction of the smallest human bone as an example of a μMIM component. There were some significant challenges to reproduce this bone. In a project carried out in co-operation with Krämer Engineering, Rendsburg, Germany, a mould for the replication of the smallest human bone in the ear (stapes) was designed and manufactured [3]. The goal of this project was to demonstrate the potential of μMIM production, specifically relating to the precision and reproducibility of the process. While investigating process reproducibility for the injection moulded and sintered parts, only slight variations in weight and dimensions were found. The variation in weight of the moulded and sintered parts is approximately 1.5% at a total weight of only 5 mg. After optimising all process parameters along the production chain, from feedstock adjustments to moulding and sintering parameters, a sinter density of 95% was reached.

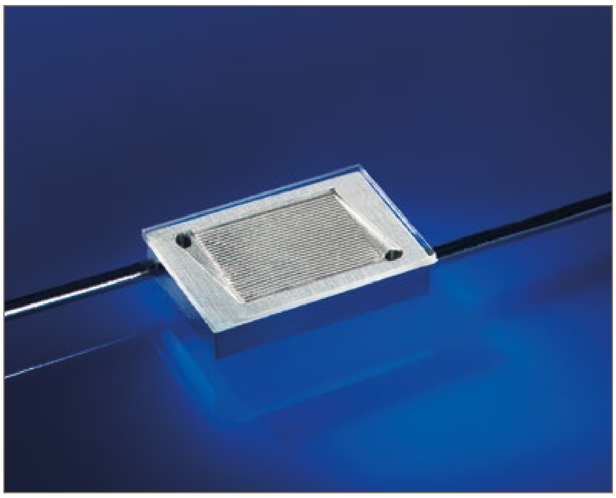

Fig. 7 Micro reactor with photocatalytic coating, channel width 250 μm

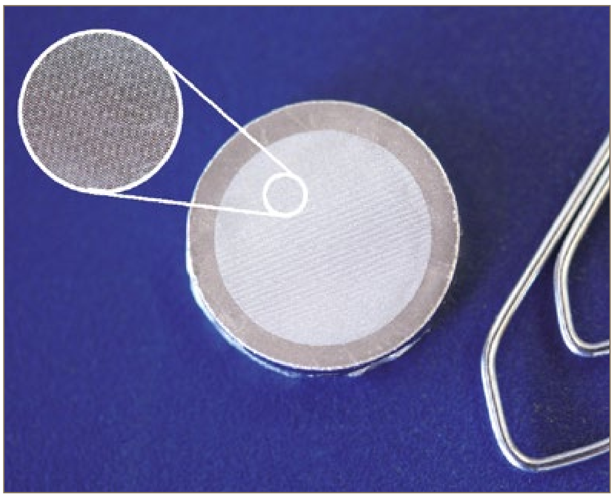

Fig. 8 Surface functionalisation by metal injection moulding with special nanosized powders

Biofunctionality

The biological response of a surface can be enhanced in different ways. The goal is always to achieve an intensive bioactive material interaction with the surrounding tissue.

Fig. 6 shows the different ways to achieve such biofunctionality. Firstly, it is possible to modify a surface with particles bonded by adhesion. In a similar way, functional groups can be chemically bonded onto the surface to enhance the interaction with human cells. Influencing surface roughness is also a well-known route to influence cell growth. If real cell-growth management can be achieved in the future it will be important to understand the basic mechanisms of the interaction of different types of cells with different surfaces. Additionally bioactive substances with growth factors can enhance the integration of an implant. This means the development of coatings, which could for example release active substances, is a path to follow for improved biofunctionality.

Secondary production steps such as grit-blasting and acid-etching are currently used to modify the surface. In the future it will be more and more important to create bioactive implants directly. Thereby the risk of de-lamination of functional coatings can be avoided. The question is how PIM components can contribute to these upcoming needs for future biomedical applications. The answer is that there are good opportunities to participate in this trend with solutions by PIM technology. Of key importance is the fact that designed surface structures for optimised cell adhesion can be directly manufactured by PIM without any additional secondary processing operation.

If this advantage can be combined with a good choice of a base material, PIM technology should have a great competitive advantage. Additionally the option to make use of some of the mentioned functional coatings is a key to success. Intelligent solutions for future implants can be designed this way.

For permanent bone implants a stable connection with the surrounding bone tissue is essential for the implant to be capable of replacing the full function of the bone. A material with mechanical properties like bone, and that directly stimulates bone cells to adhere to and form new bone at the implant surface, would be the optimal implant material. Titanium has been chosen as it is seen as the best choice for bone implants thanks to its ability to react in a positive way with human cells. The reactivity of titanium surfaces is positive for the biological integration, but is a challenging problem when moulding and sintering titanium parts as it rapidly picks up impurities such as oxygen, carbon and nitrogen.

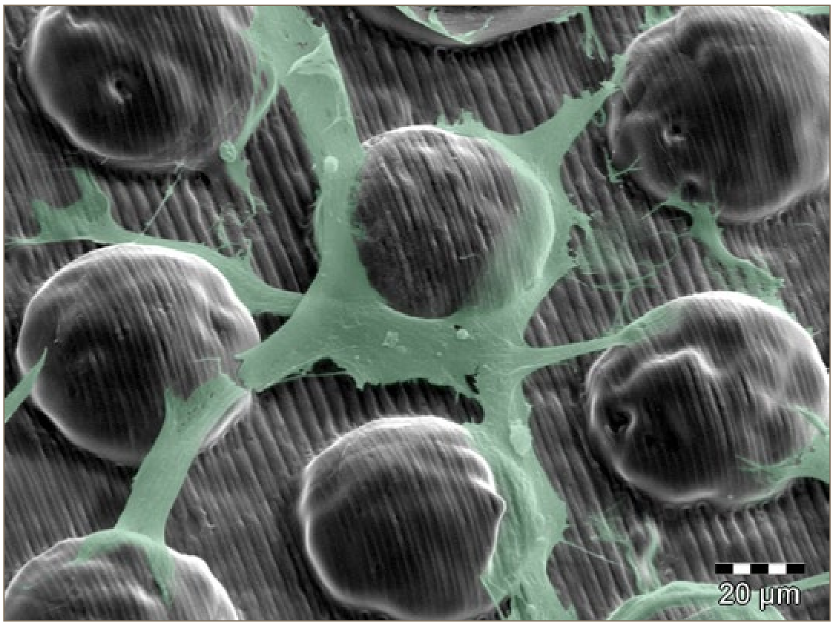

Fig. 9 Cell adhesion on a microstructured surface for cell growth management, e.g. on implants

> *'Of key importance is the fact that designed surface structures for optimised cell adhesion can be directly manufactured by PIM without any additional secondary processing operation'*

A first step to show the positive influence of microstructures is to control the reproducible production of micro structured surfaces by PIM. An example is a micro reactor with a channel width of 250 µm.

Fig. 7 shows such a microfluidic reactor coated with an active photocatalytic layer of titanium dioxide for the treatment of liquids in biotechnology. The possibility to control the surface structures by an appropriate choice of powder, and the chance to reproduce structures in a size range of less than 100 µm, are unique features of PIM and offer great potential for future applications in cell growth management [4].

The surface structures of implants that are in contact with human cells can be optimised for improved growth behaviour. The PIM process offers unique possibilities to combine the freedom of geometrical complexity and the chance to tailor the surface structure in a desired way, influencing cell growth. Consequently the development of a low cost processing technique for the production of regular micro patterned surfaces is an opportunity for PIM [5, 6].

It is known that regular micro patterns on surfaces can significantly enhance the integration of implants into the body. Therefore micro structured surfaces with hemispheres of 50 µm in diameter and with a 20 µm interspacing were created using µMIM. Test structures as shown in Fig. 8 were produced. Surface topography patterning using the μMIM process, together with micrometer-scale hemisphere structures (Fig. 9), will be taken forward towards the one-step production of bioactive orthopaedic titanium implants.

There are definitely challenges in handling and processing extremely fine Ti powder. The first cell culture experiments that were performed by EMPA Materials Science and Technology, Switzerland, gave hints that sub-structuring on a surface with regular micro patterns has a positive effect on the growth of bone cells on an implant material and suggest that the presence of the hemispheres significantly influences adult human stromal cell adhesion and functionality.

Summary

There is a clear demand for the large scale production of small complex components, for example for implants or components for surgical instruments. It has been shown in recent years that a number of standard metallic materials, as well as some ceramic materials, can be processed by PIM. All of them are proven to be suitable for medical applications. Special bio-inert or even bioactive materials can also be processed by PIM. New biodegradable composite materials have a great perspective for future implants.

A reproducible part quality can be obtained for both the production of micro parts and larger components with well defined micro patterns. As shown by micro-structuring of stainless steel surfaces, modifications of the materials and processing conditions can lead to promising novel surface properties which can enhance bioactivity, making PIM a promising technology for novel medical applications.

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A new centre for PIM research in the UK: Sheffield's Mercury Centre opens for business

The City of Sheffield, in the north of England, has a long tradition of expertise in metalworking that dates back to its dominant position as a centre for steel production in the 19th century. This tradition is set to continue with the recent opening of the University of Sheffield's new Additive Manufacturing Suite, part of the University's Mercury Centre for Innovative Materials and Manufacturing. Dr David Whittaker attended the opening ceremony on April 19 2012 for *Powder Injection Moulding International* and reviews recent work undertaken relating to PIM and Additive Manufacturing.

The University of Sheffield's Mercury Centre was established through a grant of around £5 million from the European Regional Development Fund (ERDF), matched by a similar investment by the University of Sheffield itself. The centre, part of the University's Department of Materials Science and Engineering, offers a range of advanced manufacturing and analysis capabilities, ranging from the predictive modelling of products and processes through to the manufacture of complex components and full characterisation of structures and properties.

The manufacturing services are based on a full range of near net shape powder based technologies, allowing clients to manufacture components from novel materials with increased functionality. The centre is aimed at providing industry with access to the latest technologies and its team is dedicated to developing "fit for purpose" solutions to specific product or process needs. The Additive Manufacturing Suite houses the centre's impressive array of advanced processing equipment, the majority of which is dedicated to the manufacture of products from powder feedstocks.

The event's proceedings began with a series of presentations, the first of which comprised some words of welcome from one of the centre's joint Directors, Professor Mark Rainforth, who is also head of the Department of Materials Science and Engineering.

Next came presentations from two local companies who have already benefited from working with the centre. Firstly, Edward Draper, from the UK's JRI Orthopaedics, provided a perspective on his company's views on "innovation in practice". JRI Orthopaedics is an SME (Small or Medium Sized Enterprise) that is competing in the medical devices sector. This sector, it was stated, is dominated by a small number of major multinational companies and combines the apparently contradictory attributes of being conservative and highly regulated but at the same time having fast-moving demands for new clinical applications.

Fig. 1 Professor Mark Rainforth, Mercury Centre's joint Director, welcomed visitors

Fig. 2 Guests in the atrium of the Faculty of Engineering

Fig. 3 Edward Draper, JRI Orthopaedics, presented his company's views on "Innovation in Practice"

Fig. 4 Professor Iain Todd, the Centre's other joint Director, provided an overview of the Centre's activities and facilities

In this environment, it is essential for a small "player" to be able to "stay ahead of the game" in new product development in order to maintain its viability. JRI has enlisted the assistance of a number of UK academic centres of excellence in pursuing innovative developments. In assessing the potential benefits of applying Additive Manufacturing (AM) technologies in the manufacture of its products, Draper stated that the Mercury Centre has been the company's chosen partner, stating that JRI has received invaluable benefit from the partnership.

Following this presentation, Kartik Rao of Metalysis Ltd., a second locally based SME, described his company's areas of collaboration with the Mercury Centre. Metalysis was spun out of the University of Cambridge with a view to scaling-up and commercialising the University's patented FFC process for metal powder production. The process relies on electrolytic de-oxidation to strip the oxygen ions away from a porous electrode produced by pressing and sintering a metal oxide feedstock. The oxygen ions are then passed through a molten $CaCl_2$ electrolyte to a graphite electrode to form CO_2 or CO. The focus of Metalysis's activities has been on the production of titanium (commercial purity titanium and titanium alloys) and tantalum powders by this process. The Mercury Centre's role in the collaboration is in exploring a range of downstream technologies for the consolidation of Metalysis's titanium powder materials.

'Todd's group, which formed the initial nucleus of the Centre's research interests, has a long established reputation in Metal Injection Moulding (MIM) developments.'

The series of presentations was concluded by Professor Iain Todd, the centre's other joint Director, who provided an overview of the centre's activities and facilities. This was followed immediately by a whistle-stop tour of these facilities (literally a whistle-stop tour as a whistle was blown to co-ordinate the movements of groups of attendees from one station to the next).

Metal Injection Moulding

Professor Todd's group, which formed the initial nucleus of the centre's research interests, has a long established reputation in Metal Injection Moulding (MIM) developments.

The group is probably best known for its work on interstitial control in CP-Ti and Ti-6Al-4V MIM products, with this work having already featured in past issues of *Powder Injection Moulding International* (e.g. December 2010, pp. 56-62; March 2012, pp. 56-57). Increasing interstitials in wrought titanium alloys, especially oxygen, result in an increase in yield strength, tensile strength, hardness and fatigue resistance at a given stress level, but have a detrimental effect on ductility. Nitrogen has the most potent effect, but it is oxygen that causes most concern, because of its high solubility in titanium.

In the development of MIM titanium for high performance applications, this has led to two areas of concern:

- The need for careful control of the many potential sources of interstitial contamination in the MIM process – in the starting powder, in the decomposable substances in the binder and the potential pick-up from the atmosphere in the debinding and sintering processes.
- The relative lack of understanding of the relationship between interstitial levels and mechanical properties in MIM titanium parts has led to a situation where, to penetrate such markets, the MIM sector is being forced to aim at the same limits as have been established for wrought or cast titanium.

Work reported by the Mercury Centre group has addressed both of these areas of concern and has involved:

- The adoption of a binder system, comprising a major fraction (87 wt%) of water soluble polyethylene glycol (PEG), a minor fraction (11 wt%) of a back-bone binder polymethyl-methacrylate (PMMA) and a surfactant addition (2 wt%) of stearic acid (SA). Handling of the materials has been carried

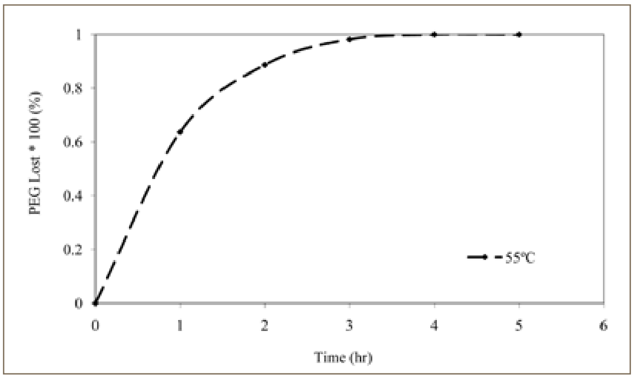

Fig. 5 Amount of PEG removed from the moulding versus the leaching time at 55°C

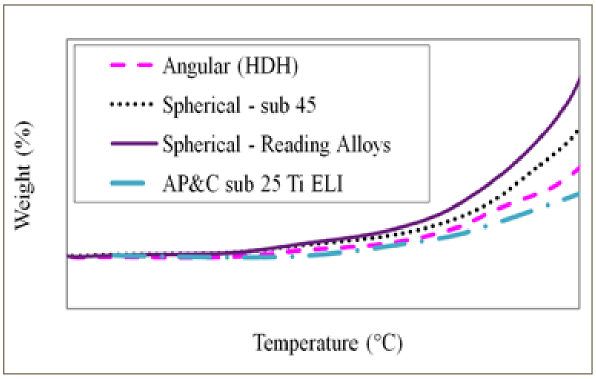

Fig. 6 TGA analysis showing powder oxidation rates. Powder was heated from 50°C at 10°C/min in air at 20.0 ml/min

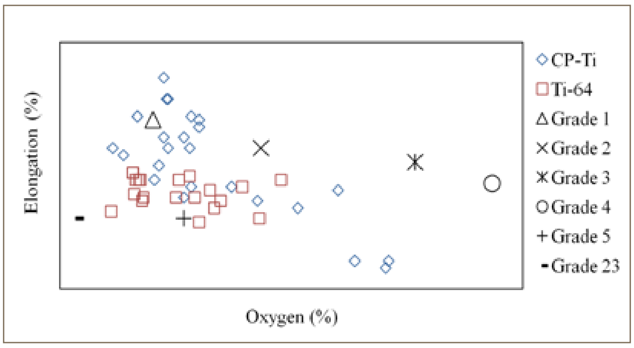

Fig. 7 Effect of oxygen on CP-Ti and Ti-64 elongation

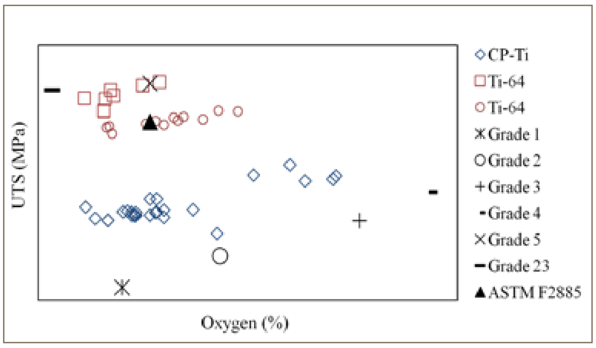

Fig. 8 Effect of oxygen on CP-Ti and Ti-64 UTS

out in an inert argon atmosphere to make feedstocks with powder loadings of 66 and 69 volume%.

- Removal of the PEG binder constituent by solvent extraction. Fig. 5 demonstrates that complete removal of PEG was achieved in warm water at 55°C after 5 hours.
- Thermal debinding of the back-bone PMMA constituent. Thermo-gravimetric analysis (TGA) results, shown in Fig. 6, have indicated that oxidation dramatically increases above 400°C, but that, below that temperature, oxidation is not significant, even in air. These results have demonstrated that thermal debinding should be carried out at a temperature below 400°C, but that, at higher temperatures, sintering atmosphere control is important.
- Sintering in an argon atmosphere with a retort flow rate of 10 litres/min. Sintering temperature selection is an item of compromise. To minimise interstitial contamination, sintering temperature should be as low as possible, but, to achieve the required densification, higher sintering temperatures (e.g. 1300°C) and longer sintering times (2 hours) are needed.

Using optimum processing conditions, it has been determined that oxygen pick-up in MIM could be limited to around 0.06 wt% for sub-25 µm Ti-6Al-4V ELI, but to as little as 0.03 wt% for sub-45 µm Ti-6Al-4V and CP-Ti. The influence of oxygen content on as-sintered mechanical properties is shown in Figs. 7 and 8. Fig. 7 shows the influence on the elongation levels of CP-Ti and Ti-6Al-4V. There was a wide range of elongation levels in the lower oxygen interstitial range, but the expected reduction of elongation with increasing oxygen content can be observed in the higher oxygen range for CP-Ti. Ti-6Al-4V elongation levels appear not to reduce dramatically with increasing oxygen level and there is some scatter in the data.

Fig. 8 shows that the tensile strengths of both the CP-Ti and Ti-6Al-4V MIM samples increase with increasing interstitial oxygen content,

Fig. 9 Alfred Sidambe answers questions regarding the Arburg Allrounder 320C injection moulding machine

Fig. 10 Fatos Derguti, Manufacturing Fellow at University of Sheffield, discusses the range of Additive Manufacturing technologies now available within the Mercury Centre

but that the level of tensile strength of CP-Ti is high in comparison to the titanium grades 1 to 4.

CP-Ti MIM parts containing low interstitials but with high tensile strengths have been successfully produced and sufficiently strong Ti-6Al-4V MIM parts, meeting the requirements of ASTM F2885-11, can be manufactured with low interstitial levels. The MIM titanium work has been aimed largely at the aerospace and biomedical sectors. Work on other material types has also spanned these two application sectors.

Work has been reported (*Materials Letters*, Volume 70, 2012, pp. 142-145) on the development of porous NiTi (shape memory alloy) products for biomedical implant applications. The processed material had a porosity level of 39-45% and an average pore size of 100-120 µm (Fig. 11). A suitable sintering temperature window to achieve the desired structure has been defined. A sintering temperature above 1050°C is required to allow sufficient inter-diffusion to create essentially the NiTi phase and avoid phases such as $NiTi_2$ and Ni_3Ti with poor mechanical properties, while sintering above 1250°C reduces the amount and size of the porosity.

The centre has also supported Rolls-Royce plc's activities in developing a MIM-based route for Inconel 718 superalloy aero-engine compressor stator vanes, as previously reported in *Powder Injection Moulding International* (September 2011, page 24) (Fig. 12). The conventional route for this application is a 7-stage forging process, whereas the MIM product requires only a single post-sintering forging stage followed by finishing processes.

The experimental equipment supporting these MIM projects was viewed during the tour:

- A Hauschild Engineering laboratory scale, centrifugal Speedmixer
- A twin-screw extruder for the granulation/pelletisation of the mixed feedstock
- An Arburg Allrounder 320C moulding machine
- Batch debinding and sintering furnaces.

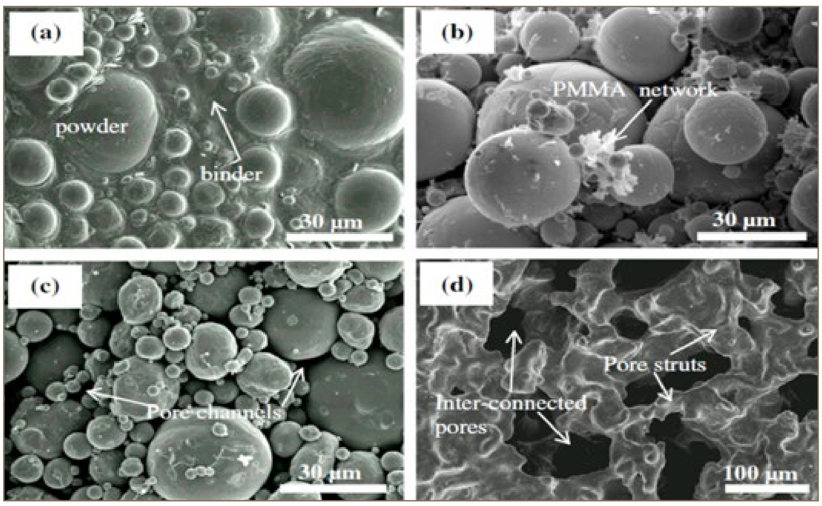

Fig. 11 SEM images showing microstructural changes during processing: (a) as-moulded, (b) as-leached, (c) as-thermal debound and (d) as-sintered. (from Materials Letters, 70, 2012, pp. 142-145)

Additive Manufacturing

The group's initial forays into Additive Manufacturing (AM) technologies were to explore their potential for the rapid, lower-cost manufacture of MIM tooling.

"My interest in Additive Layer Manufacturing (ALM) grew from a desire to develop better quality, more efficient toolmaking for Metal Injection Moulding. I found using ALM opened up exciting new design possibilities such as incorporating sophisticated, conformal cooling channels that couldn't be produced using traditional techniques," stated Professor Todd.

An EOS laser melting machine was used to build a standard insert based on the Hasco quick removal insert. The material used was stainless steel. Fig. 13 shows the insert after die manufacture of a tensile specimen on the left, and a sample of the blank on the right. Fig. 14 shows the facets of the moving and fixed half inserts. The surface finish shown is as the part came out of the EOS machine. A further polishing step is needed to bring the final surface finish of the die cavity to levels used for injection moulding.

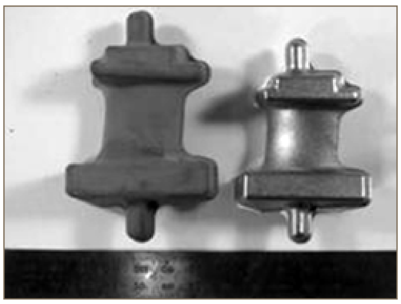

Fig. 12 Superalloy aero engine compressor stator vanes before and after sintering (Courtesy Rolls Royce, UK)

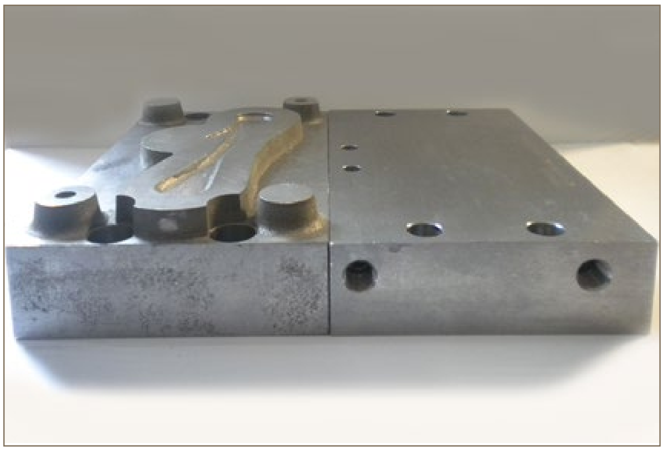

Fig. 13 Insert after die manufacture of a tensile specimen on the left, and a sample of the blank, right

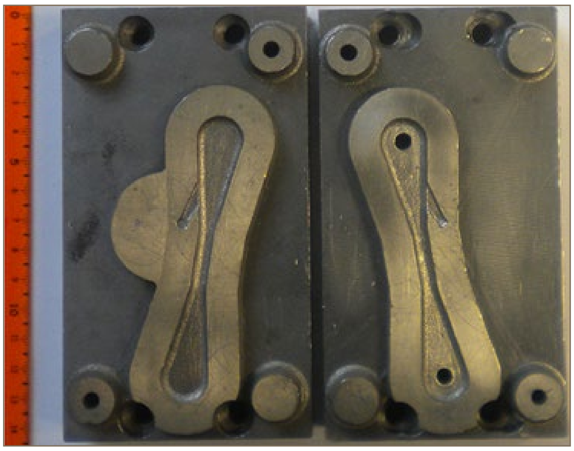

Fig. 14 Facets of the moving and fixed half inserts. The surface finish is shown as it comes out of the EOS machine

The manufacture of conformal cooling channels via AM has also been Investigated by the Mercury Centre group. These can be introduced easily and can follow the contours of a cavity to increase/control heat transfer to improve productivity. Today, when the centre fields enquiries for development work about additive tool making, they pass them on to one of the UK commercial AM bureaux, with whom they maintain close relationships.

The centre's AM interests have now developed away from tooling into series production applications. Additive Manufacturing processes join materials, usually layer upon layer, to make objects from 3D model data. Synonyms include Additive Fabrication, Additive Processes, Additive Techniques, Additive Layer Manufacturing, Layer Manufacturing and Freeform Fabrication.

Given that these processes are aimed at building components with 3-dimensional geometrical complexity, it might be anticipated that there could be a degree of competition with MIM. In fact, the application sectors which have interests in both forming technologies, principally aerospace and biomedical, generally view them as being complementary rather than competing.

AM products cover a wider size range than MIM. These range from the very small (where there could be an overlap with MIM) to larger parts limited only by the volume of the build chamber in the processing equipment. A principal benefit of AM technologies is they obviate the need for tooling. The economic benefit of eliminating amortised tooling costs are highest at low production volumes, so any area of potential competition would be restricted to MIM's lower volume range.

AM is able to offer a degree of geometrical complexity that even MIM cannot provide, for instance, in direct manufacture of complex, internal channels. To a first approximation, any shape, which can be drawn in 3-D modelling software, can be built by AM. There are, however, also limitations to AM. For instance, the building of over-hanging features generally also requires the building of support structures. Also, achievable surface finish is limited by the layer thickness in AM build. For these reasons, AM is a near-net rather than a net-shape forming technology for most practical applications; finishing operations are almost always involved.

The biomedical sector, for instance, would choose to use MIM for the volume manufacture of standard-sized parts (e.g. orthodontic brackets), but AM for bespoke, customised parts (e.g. dental implants).

The tour also involved the viewing of the impressive range of AM technologies now available within the centre. Their longest established pieces of AM equipment are two ARCAM Electron Beam units, but these have been more recently supplemented with a Renishaw Selective Laser Melting unit and an Optomec Aerosol Jet Printing facility. The most recent additions to the centre's experimental facilities, demonstrated on the tour, were:

- A Spark Plasma Sintering (SPS) unit – only the second piece of SPS equipment to be installed in the UK
- A Pro-beam Electron Beam Welder.

In addition to the hardware, the tour also involved a demonstration of some of the centre's process modelling/simulation capabilities. These capabilities have been built on the use of commercial simulation software; in the case of MIM moulding filling simulation, this was Procast software.

Following the tour, attendees had the opportunity for networking and technical discussions over a traditional "pie and pea supper" before the event concluded.

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MIM2012 Review: MIMA's annual conference returns to the heartland of MIM

The MIM2012 International Conference on the Injection Molding of Metals, Ceramics and Carbides took place in San Diego, California, from March 19-21. Organised by the Metal Injection Molding Association (MIMA), a trade association of North America's Metal Powder Industries Federation (MPIF), the event once again attracted more than 130 delegates. Over the following pages *PIM International* presents some event highlights.

The choice of venue for MIMA's annual conference has for many years alternated between North America's east and west coasts. This year's event took place in the southern Californian city of San Diego and once again attracted in excess of 130 attendees. As well as offering some welcome sunshine after a long winter, the area also holds significance as the heartland of the modern commercial development of metal injection moulding during the late 1980's.

An international mix of participants represented all areas of the PIM community, from part producers through to industry suppliers and researchers. Co-chaired by Bruce Dionne, Megamet Solid Metals, Inc., and Toby Tingskog, Sandvik Osprey Ltd., the conference once again proved to be an invaluable forum for networking and the exchange of industry knowledge.

PIM tutorial attracts key MIM users, suppliers and producers

An established feature of MIMA's annual event is the optional pre-conference PIM tutorial. This year's tutorial attracted 31 participants, including key end-users, PIM parts makers and industry suppliers. The tutorial, presented by Prof. Randall M. German, San Diego State University, offered a solid grounding in the technology and its applications.

Conference presentations reflect the continuing evolution of PIM

Two days of conference presentations saw a wide variety of topics covered, from updates on current areas of research to industry-focussed presentations and practical case studies. These were supplemented by a series of short commercial presentations by exhibitors that introduced new developments in PIM equipment and materials. A selection of presentations are reviewed on the following pages, with a highlight being the lunchtime keynote by Joe Zajk, of Ruger & Co., Inc., which offered an end-user's perspective on the use of MIM in firearms applications (see full review on pages 46-48).

Industry remains on a growth track

What was clear from discussions with many of North America's leading PIM parts makers is that they are busier than ever, with reports of high numbers of new tools and growing volumes. With new producers reported to be entering the industry, all indictors suggest that the coming year will see strong growth for the Powder Injection Moulding industry worldwide.

Fig. 1 The MIM2012 tabletop exhibition & networking reception was a big success, featuring 27 companies offering the latest products and commercial capabilities

Aqueous coating for kiln furniture offers advantages for PIM producers

As Animesh Bose reports, a presentation by Mohammad Behi and Alex Lobovsky, United Materials Technologies LLC, Newark, NJ, USA, offered an innovative solution to the challenge of strong yet light ceramic machined setters for sintering complex PIM parts.

An important development in the area of kiln furniture and sintering furnace setters for use in the Powder Injection Moulding (PIM) industry is a novel process known as Naneramic Infusion, developed by United Materials Technologies LLC., Newark, New Jersey, USA.

Generally, sintering furniture made from dense ceramic material accounts for a substantial portion of the overall furnace load. The heavier load results in reduced life of the hot structural components of the furnace. Also, excessive energy is expended in heating up the heavy ceramic furniture during the heating cycle and it also requires longer times to allow the parts to cool, resulting in longer furnace cycle times and gas consumption (if a protective atmosphere is required).

In the case of PIM, it is often preferable to use porous ceramic setters which have been machined into complex shapes. These machined setters are used to support the complex shaped parts and help maintain their shape during the sintering process. The handling difficulties and short lifetime of these relatively fragile and porous ceramic sintering setters negatively impact the process economics.

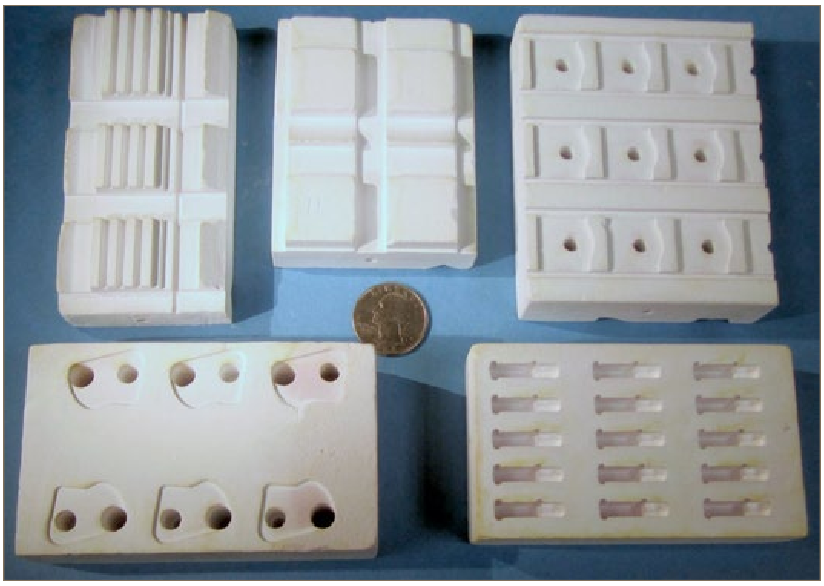

Fig. 1 Porous ceramic sintering setters of complex geometry dip coated to form a dense skin of different materials

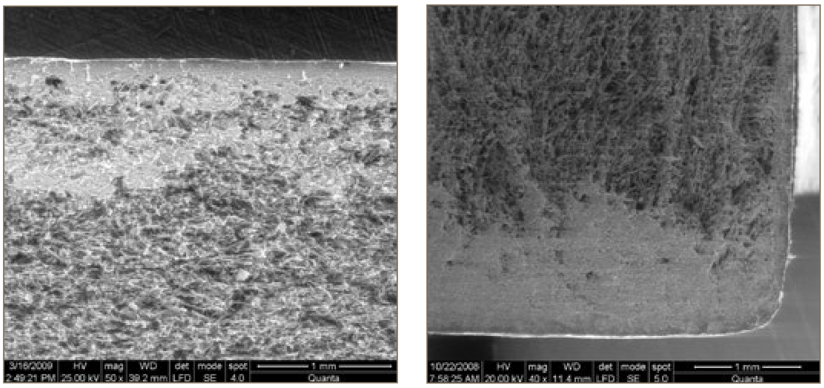

Fig. 2 Coating penetrates the surface creating a crust with a gradient of density

The ideal solution to this problem would be the development of porous, lightweight, high temperature resistant ceramic setters that can have a surface almost as hard and wear resistant as a solid ceramic. This ideal combination has been achieved through the novel process of Naneramic Infusion of sub-micron ceramic particles into porous ceramic structures, such as alumina fibre boards, resulting in improved life and performance of numerous sintering furniture applications for use in temperatures as high as 1600°C.

Fig. 1 shows several different sintering setters having complex geometries that have been coated using the novel technique. Fig. 2 shows a higher magnification picture of the coating showing that the coating penetrates the porous surface resulting in a crust with a density gradient. This hard crust results in a relatively hard and wear resistant surface that prevents dusting and edge crumbling of the setters and extends their useful life.

The ability of the process to coat complex contours is depicted in Fig. 3, which shows two porous alumina blocks joined together with the solid alumina screw, where the ceramic blocks have been coated using UMT low viscosity slurry. Fig. 4 shows the SEM photomicrograph of a thread (contoured portion) in the porous alumina block with the dense coating that reduces the dusting and crumbling of even the fine edges of the thread. This has been demonstrated by examining the coated thread after repeated joining and separating of the two coated plates by the screw. Normally with an uncoated thread, the threads in the hole will tend to erode after just one screwing and unscrewing operation, while the coated thread remained intact even after numerous demonstrations.

Thus, the Naneramic Infused kiln furniture and sintering fixtures for PIM have the strength and feel of the solid ceramics while retaining all the advantages of the inexpensive and lightweight porous parts. According to UMT, it is possible to decrease the setter weights by up to 80%. With their process, UMT can infuse inexpensive porous alumina structures with alumina, zirconia, and even silicon carbide resulting in huge cost savings. The process also has the capability of ceramic infusions with other materials. The infused part has an ideal strength-to-weight ratio "box" design with the rigid shell and

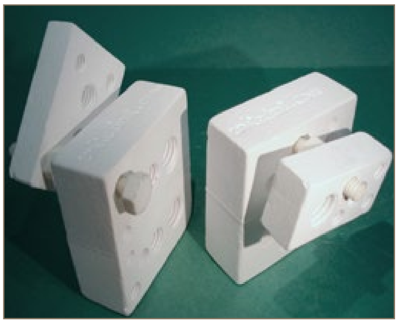

Fig. 3 Porous alumina blocks coated with UMT low viscosity slurry are joined with ceramic screws

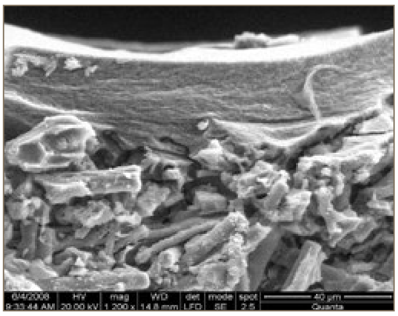

Fig. 4 SEM of the thread (see Fig. 3) in porous alumina protected by the hard coating

lighter core. Setters processed by their novel technology, claims UMT, have been tested by a major MIM gun parts manufacturer for the past three years. During this time period, over a thousand setters have gone through hundreds of sintering cycles with no failures being reported so far. Some of the benefits of the UMT coating process for sintering setters and kiln furnitures are:

- Lower thermal conductivity
- Lightweight setters reduces load on supporting structure
- Lower heat storage results in lower heating cost as well as heating and cooling cycle time reduction
- Improved thermal shock resistance
- Ease of machining: complicated geometric features to accommodate and support MIM parts can be easily machined in porous ceramic.
- Thermal efficiency: the fast response of highly porous sintering fixtures allows for more accurate control and uniform temperature distribution within the furnace.

This process has the potential to provide PIM and PM part producers with an economical solution for sintering setters and kiln furniture.

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Mould it wrong to make it right

A unique aspect of MIMA's annual conference is the number of case-study presentations that look at "real-world" challenges.

Bruce Dionne, General Manager, Megamet Solid Metals Inc., Earth City, MO, USA, presented a case study at MIM2012 that highlighted the common problem of warpage during the sintering of MIM parts. Certain designs are more prone to warpage than others and the industry has developed a number of techniques to manage warpage during sintering, including the use of custom sintering supports. These can however be expensive to fabricate and they reduce overall furnace capacity, undermining the competitiveness of MIM.

In this study Megamet took the approach of deliberately moulding an "out-of-shape" part in anticipation that warpage during sintering would result in the required shape. The test sample was a broken ring with a small ligament tying the broken ends together (Fig.1 left). The sample was sintered suspended on a ceramic rod with the open ends facing down (Fig. 1 right). This method was chosen because it showed the most efficient furnace loading characteristics with more than twice as many pieces per load as the next best method. The goal height was 1.078" (2.73 cm).

Two test cavities were created at pre-emptive warp dimensions. The first was created at 1.06" (2.69 cm) or -0.018" (-0.45 mm) of uniform warp about the centroid holding the volume constant. Dionne reported that the sintered parts sagged to an overall mean height of 1.12" (2.84 cm), over-shooting the mark. A second attempt was made at a pre-emptive warp of 1.02" (2.59 cm) or -0.058" (-1.47 mm). This one fell short in the other direction at 1.06" (2.69 cm) average height.

As there were only two data points, linear interpolation was then chosen to establish the optimum as-moulded dimensions. Dionne noted that more data points would require more mould cavities to be cut and processed, increasing the cost of the analysis accordingly. Shrinkage was left out of the equations for simplicity, however it was stated that this cancels out anyway as it applies to both f and f(x). The next step was to cut a new cavity at the anticipated height and process parts.

The data indicated that two point linear interpolation is effective in the neighbourhood of generally accepted MIM tolerances (~±0.003/1in) and Dionne stated that cost calculations can be run to show the payback for this analysis. The sintering method tested tripled furnace loading and this method of warp correction eliminated the need for secondary straightening operations.

Dionne concluded that creating iterative mould cavities and undertaking analysis to achieve preemptive warp correction was successful on this geometry, allowing Megamet to capitalise on furnace efficiency and remove secondary operations, however it was pointed out that such analysis will become far more complex with increasing complexity of geometry.

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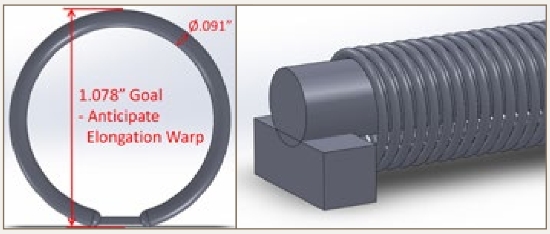

Fig. 1 The test sample (left) and the required sintering support for optimum furnace loading (right)

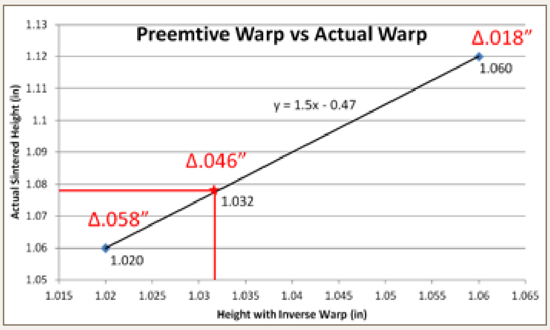

Fig. 2 Linear interpolation was chosen to establish the optimum as-moulded dimensions

MIM2012 Review: Keynote gives insight into the application of MIM in the firearms industry

The firearms industry was one of the earliest high volume adopters of MIM technology, particularly in North America where a thriving consumer market exists in addition to the defence sector. The use of MIM for the production of new components is not, however, a foregone conclusion. As Joseph J. Zajk, Chief Engineer, Pistols at Sturm, Ruger & Co., Inc. explained at the MIM2012 luncheon keynote, a number of factors have to be considered before a manufacturing route is selected.

An ongoing aspect of the MPIF's MIM conference is the much anticipated keynote luncheon at which an end-user shares his or her experience of MIM technology. At this year's event, held in San Diego, March 20-21, Joseph J. Zajk, Chief Engineer, Pistols at Sturm, Ruger & Co., Inc. offered an insight into the application of MIM in the firearms sector and made some suggestions on how the MIM industry needs to improve materials choice and materials performance data.

Component production at Ruger

Sturm, Ruger & Company, Inc., commonly known as Ruger® Firearms, was founded in Southport, Connecticut, USA, in 1949 by William B. Ruger and Alexander Sturm. Today the company is one of the US's leading firearms manufacturers and the company prides itself on producing innovative, rugged, reliable firearms that deliver good value to customers around the world.

The company's first firearm was the Ruger Standard Pistol, manufactured from stampings and machined wrought components. It wasn't until 1953 that the company first used precision investment castings. These were applied in its Single-Six revolver, where the frame and a number of other components were investment cast.

Over the following decades, ongoing enhancements in investment casting technology were achieved and significant expertise was developed covering a variety of materials including titanium. In 2007, all of Ruger's foundry operations were consolidated at Pine Tree Castings in Newport, New Hampshire, USA.

Zajk explained that for over 50 years, the company's famed reliability and value had largely been due to Ruger's expertise in precision investment castings and the process had become the company's technology of choice for producing small, intricate components.

Investment casting is still at the heart of the company's component production capability with pistol barrels, slides, hammers, receivers, frames, bolts, hammer and triggers, to name just a few, all in high-volume production.

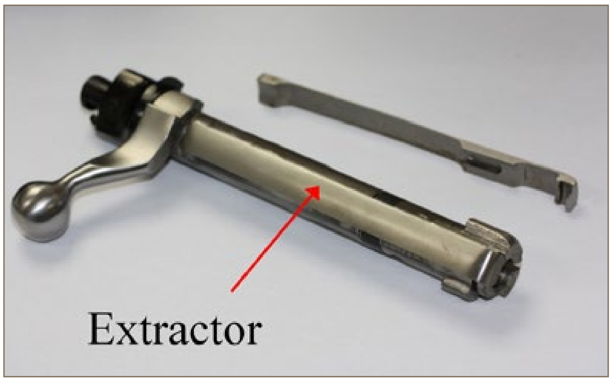

Fig. 1 Extractor for Ruger® M77® Bolt Action Rifle

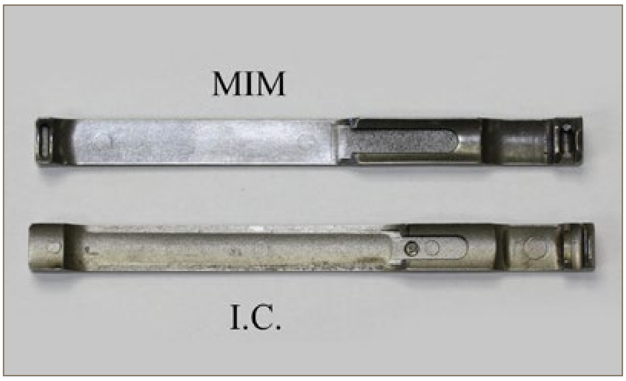

Fig. 2 The replacement MIM extractor part and the original investment cast (IC) component

So why MIM?

The trend towards smaller firearm designs with smaller, more intricate parts made investment casting these components challenging and Ruger turned to MIM to complement its expertise in investment casting.

Zajk commented that William B. Ruger Sr. once said, "The key is complexity of the component you are considering to make an investment casting. If it isn't complex, the casting process is hardly beneficial." The same approach needs to be taken when applying MIM technology, suggested Zajk – if there's no complexity, there's no advantage.

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

A series of case studies was presented that highlighted the advantages and disadvantages of the MIM process for a selection of gun components.

Extractor for Ruger M77 Bolt Action Rifle

The first case study that was presented was for an extractor for a Ruger® M77® rifle. This long life-cycle part had been in production since 1968 and at that time investment casting was by far the best process available. The part was cast as shown in Fig. 1, then machined, split, and heat treated, making machining difficult.

In 1997-1998 the part was converted to MIM. This required a number of small changes to the design, including added coring and altered thicker sections. An advantage, stated Zajk, was that MIM allowed multiple part configurations to be produced through the use of inserted cores.

The conversion resulted in the elimination of all machining, with the only finishing operation being the polishing of the outside (Fig. 2). The cost was about equal to investment casting and machining, stated Zajk, but the advantage was that the process virtually eliminated scrap.

Fig. 3 Ruger's LCR® (Lightweight Compact Revolver), introduced in 2009

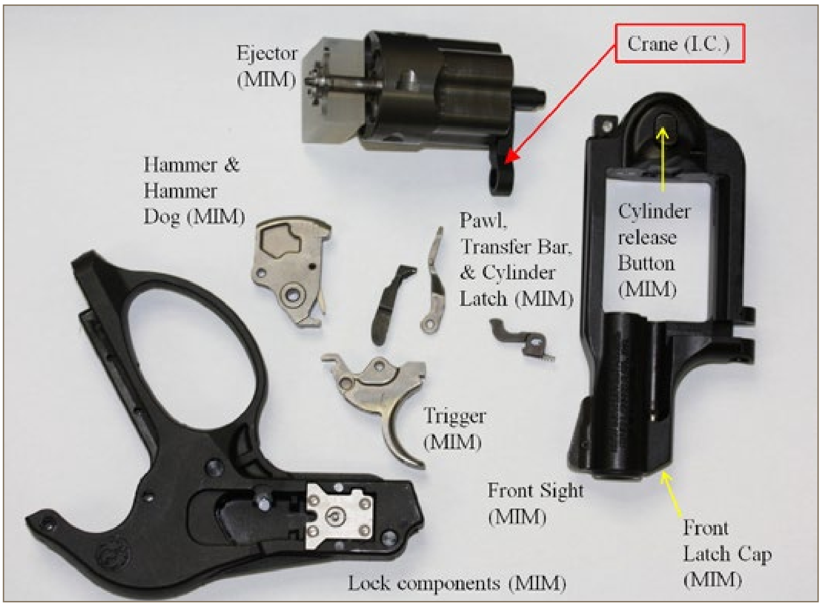

Fig. 4 Many of the components in Ruger's LCR® were specifically designed for MIM production

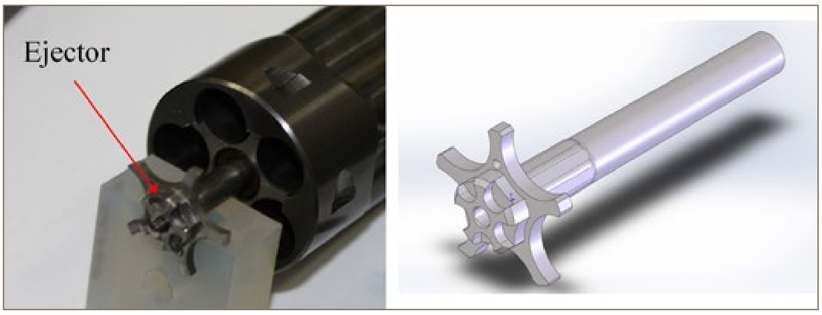

Fig. 5 The star shaped ejector in Ruger's LCR® (left) and a metal injection moulded ejector blank (right)

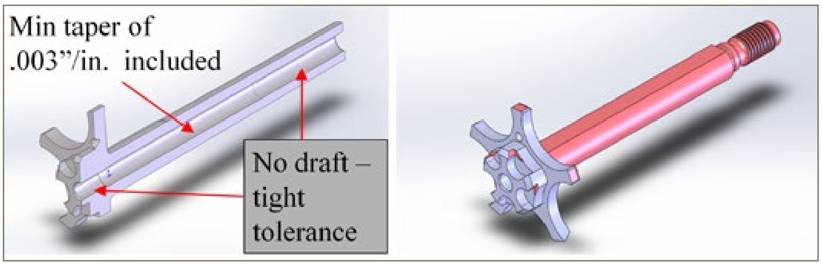

Fig. 6 Illustration of the MIM ejector part showing the tight tolerances required (left) and (right) details of machined areas (pink) versus as-MIM'ed

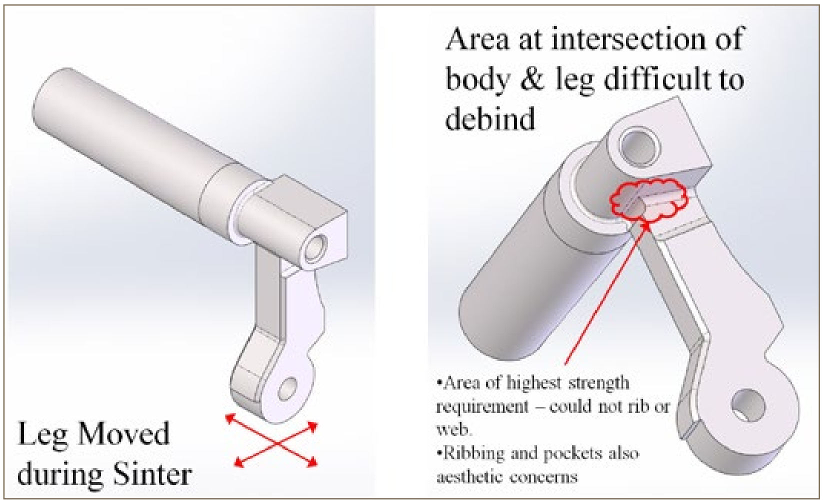

Fig. 7 A failure of MIM in the LCR programme was the crane (or yoke). Design restrictions in this high performance part meant that there was no opportunity to make the necessary adaptations that may have facilitated MIM production

MIM in Ruger's LCR® (Lightweight Compact Revolver)

In 2009, Ruger introduced the LCR® (Lightweight Compact Revolver) (Fig. 3). This was Ruger's first clean-sheet revolver design in over 20 years and presented the company with the opportunity to design for MIM from the outset. Additionally, the revolver's small size and light weight meant that many of the components that the company traditionally investment cast were no longer a good fit for that process. Overall cost was also a concern, as Ruger was entering a highly competitive market. A number of MIM parts found application in the LCR®, as can be seen in Fig. 4

Ejector

One complex part from the LCR® was a star-shaped ejector. A MIM blank was produced that incorporated a deep through hole with a minimum draft. The requirement to gundrill and ream was eliminated and the hole established machining datum. Figs. 5 and 6 show the finished part, with the pink areas being machined and the grey areas as moulded. Zajk stated that in this instance the MIM component required less machining than a casting, offered equivalent material properties and came in at a lower overall cost.

Revolver Crane

Zajk highlighted one MIM failure in the LCR® development programme, a MIM crane (or yoke). Cranes have traditionally been investment cast at Ruger, or more commonly forged at other manufacturers. The main problems were identified as debinding and straightness issues, as well as the need for cored holes. In attempting to address the straightness problem, more material was added to the MIM part in the required areas. Cored holes created issues with holding tolerances on the final machined part, and debind issues left doubts as to part strength (Fig. 7). In the end, stated Zajk, the MIM blank was virtually identical to the cast blank in terms of machining requirements and cost, so there was no compelling reason to use MIM.

Perceptions of MIM technology and outlook

Zajk commented that in its early days, MIM technology had developed some negative associations within the gun community. Unlike other consumer sectors, he stated, gun enthusiasts are more likely to strip down their guns, make close inspection of components, and even perform modifications and adjustments. In the process, any defects or lower material properties ended up being widely discussed within the gun community.

Whilst the perception of MIM technology has dramatically improved, Zajk stated that MIM still lags behind other processes in the key area of materials availability. "As it relates to firearms, there are material gaps in what is currently available in MIM materials relative to investment casting - the industry really needs to fill in some of those gaps."

It was also stated that data on impact toughness of MIM materials was required by the firearms industry, particularly so that engineers can see how impact toughness varies as a function of tempering temperature.

"Some steels exhibit tempering embrittlement at low tempering temperatures," commented Zajk, "There is data available for many wrought alloys that we can use a reference, but some MIM materials like 4605 don't have a wrought equivalent in use anymore, so there's little impact toughness available and, when there is, it's old."

'As it relates to firearms there are material gaps in what is currently available in MIM materials relative to investment casting - the industry really needs to fill in some of those gaps.'

Concluding, Zajk stated that Ruger's perception of MIM technology is that it both complements and overlaps precision investment casting for firearms components. Both are capable of producing complex shapes, however MIM has the advantage of offering more net shape potential, thinner walled sections and deep holes. It is also able to produce smaller components than investment casting, however part geometry ultimately influences whether MIM or investment casting is the best choice.

MIM 2012 Review: Opportunities for the low volume PIM of hardmetal and ceramic wear parts

A presentation by Animesh Bose, Materials Processing, Inc., at the MIM2012 Conference, San Diego, USA, March 19-21 reviewed the production of large sized low volume hardmetal and ceramic wear parts by the PIM process. As Bose explains, by using custom binder systems and low pressure injection moulding, PIM technology has enabled the effective production of parts that would be prohibitively expensive via alternative manufacturing routes.

There is a substantial market for tungsten carbide based hardmetal wear parts, many of which have complex shapes that are reasonably large in size and produced in relatively low volumes. Animesh Bose of Materials Processing Inc., Haltom, Texas, USA, described some of the different technical and economical drivers in manufacturing these hardmetal parts by PIM which, he stated, require a fundamental shift from the conventional PIM process.

Hardmetals, also known as tungsten carbides or cemented carbides, are a class of two-phase composite material consisting of hard tungsten carbide particles cemented together by a metallic binder phase typically consisting of cobalt or a combination of nickel and cobalt, often with other additives to improve functionality such as wear, abrasion, corrosion and heat resistance. Bose stated that hardmetals were one of the earliest powder metallurgy (PM) products and that these ultrahard materials are used as cutting tools, drills, and various wear parts such as wire drawing dies, nozzles, knives and blades for cutting metals, plastics, composites, and stones, mining and oil exploration to name just a few

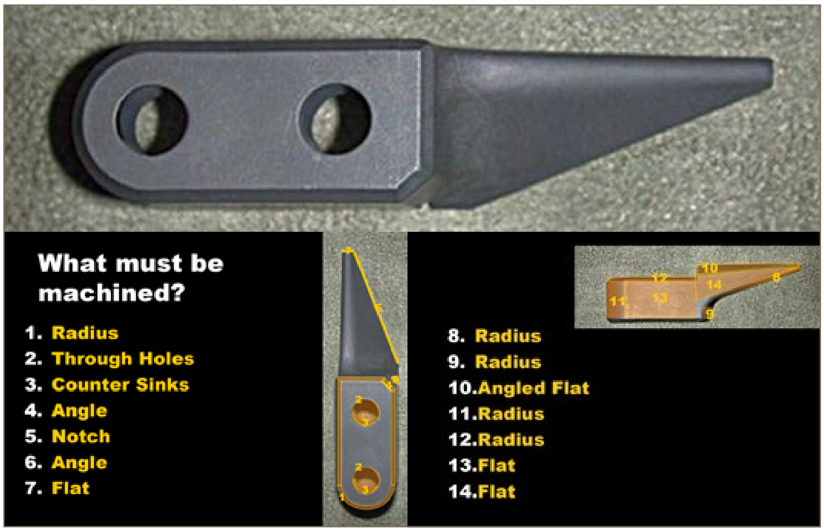

Fig. 1 Pre-forming, green machining and powder injection moulding are the only viable options for producing this hardmetal part. The pre-formed green hardmetal part requires 14 machining steps

applications. Many of these hardmetal components are in serial production using conventional pressing and sintering techniques, with a limited number of parts, such as complex shaped cutting tools and drills with internal cooling channels, made by powder injection moulding (PIM) or extrusion.

Hardmetal wear parts typically tend to be larger in size than cutting tools. Though wear parts such as nozzles can have a weight range from a few grams to around few hundred grams, many wear parts can weigh over 1 kg and the number of parts required is often quite low, from 100 to 1,000 parts a year, stated Bose. Such low volume wear parts are obtained by pre-forming a green billet using cold isostatic pressing, die compaction, or extrusion, followed by green

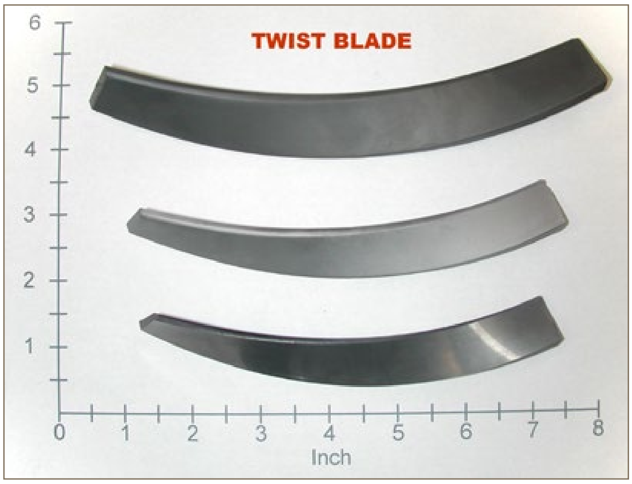

Fig. 2 Powder injection moulded hardmetal twist blade having 35 degree helix

Fig. 3 A PIM part with a rifling pattern in the ID

machining to the required shape and then dewaxing and sintering. An example of a hardmetal part machined from a green billet is shown in Fig. 1. This part requires no less than 14 machining steps to reach the final shape, typically machining away 30-40% of the billet material.

Bose believed that PIM could be successfully used for the production of such hardmetal wear parts even in low numbers if a number of technical and economical challenges could be overcome. He stated that PIM is normally used to produce small size parts in large volumes which require an expensive injection tool. To amortise the cost of PIM tooling for larger, low volume complex shaped parts could be a major issue. WC-Co powders are much finer (0.5 to 5 μm) compared with conventional PIM grade powders, which would typically be in the 5 to 25μm range, and binder removal from such ultrafine WC-Co powders is also a problem. Generally, high pressures would be required to fill mould cavities.

The advantage of Low Pressure PIM

There is, however, an alternative to conventional PIM and that is low pressure powder injection moulding. Bose stated that years of R&D has been spent on developing an organic binder with very low viscosity at low moulding temperatures (ca 80°C). The binder is said to have the ingredients which result in good wetting of the ultrafine WC-Co powders so that a solids loading of 50 vol% or higher is possible. The WC-Co(Ni)/binder feedstock can be moulded at very low pressures so that even large moulds can be effectively filled, and allowing a range of complex shaped PIM wear parts to be produced.

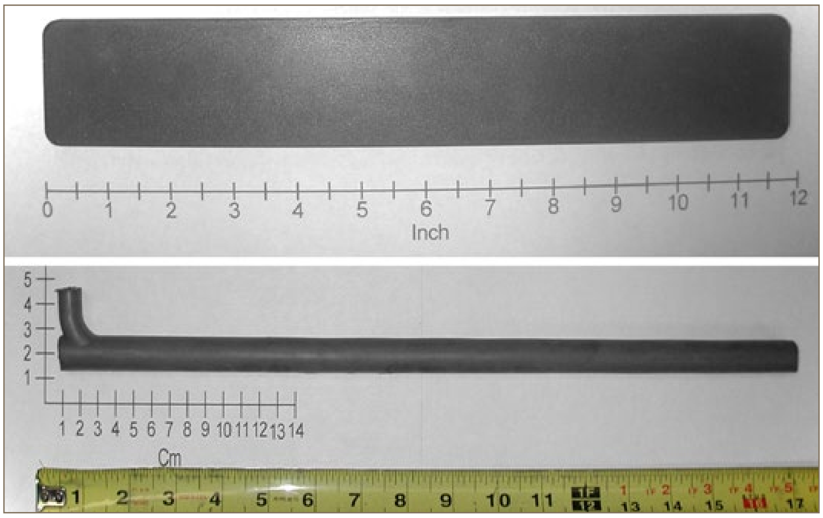

Fig. 4 As-moulded PIM tube and blade showing MPI's capability to produce long parts

The PIM parts can also be easily machined or ground if needed in the green state. The issue of injection moulding tooling for low volumes has been resolved by the use of low cost metals such as aluminium or bronze, which allows the amortisation of the tool over less number of parts, stated Bose. The low viscosity feedstock allows the fabrication of large size PIM wear parts using low pressure PIM with a relatively simple injection moulding machine which has the flexibility to produce both large and small size parts (from few grams to more than a kg), he said. Tooling costs can be 40 to 60% lower and with faster delivery (typically four to six weeks) than for conventional PIM tooling. Tolerances are normally held to ±0.005 in./in. but can be held tighter to ±0.002 in./in. if needed. As-moulded finish is generally < 30 Rma.

Bose gave some examples of WC-based wear parts produced by PIM. These included a 5 inch long twist blade having a 35° helix (Fig. 2). A number of these twist blades go into a cutter body used for cutting specialty materials. The 35° helix has to be accurate or else it will not slide in and fit the cutter. Another wear part shown had a rifling pattern in the ID (Fig. 3), and an as-moulded PIM tube and flat blade showed the capability of the process to produce fairly long parts (Fig. 4).

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MIM2013
Next year's conference is provisionally scheduled for March in Florida. Keep an eye on the MIMA website for updates. **www.mimaweb.org**

New Micro Injection Moulding module presents new opportunities for PIM producers

With its new Micro Injection Moulding module, ARBURG GmbH + Co KG, based in Lossburg, Germany, is offering PIM producers an effective route towards series production of metal and ceramic micro-components. As Marko Maetzig explains, this next-generation system can be used on the company's standard electric machine range and overcomes many of the traditional challenges associated with the production of parts with extremely small shot volumes.

Micro injection moulding is an established technology for the production of a variety of plastic components for many applications. In recent years there has been a growing interest in the production of Micro Powder Injection Moulded (µPIM) components for different industrial sectors that include micro systems technology, medical devices, biosensors and others [1].

For the injection moulding of micro components two machine technologies have primarily been used to-date. On the one hand, standard injection moulding machines with injection units utilising a reciprocating screw with screw diameters between 12 mm and 15 mm are common. On the other hand, machines with screw pre-plasticising systems and an injection plunger are used [2, 3]. Both technologies have advantages and disadvantages. Reciprocating screw machines are comparatively inexpensive and perfectly utilise the "first in - first out" principle, thanks to the directional transportation of the feedstock within the injection barrel. Nevertheless, their use for micro moulding requires comparatively large sprue and runner systems, or multi cavity moulds, in order to get into a suitable screw stroke range and thus achieve a high reproducibility. Using this method, the residence time of the material can also be reduced to an acceptable level. In some cases, moulds are even equipped with blind cavities to further reduce the residence time. The use of screws with diameters smaller than 15 mm usually requires the use of special micro pellets.

Machines with screw pre-plasticising systems and an injection plunger allow the injection of very small shot volumes, but the sealing of the injection plunger due to the injection pressure is difficult and results in leakage of the material [3]. At the same time, the "first in - first out" principle cannot be maintained by the injection piston.

Requirements of the moulding machine

Micro injection moulding places very high demands on machine technology. As the moulded components can be

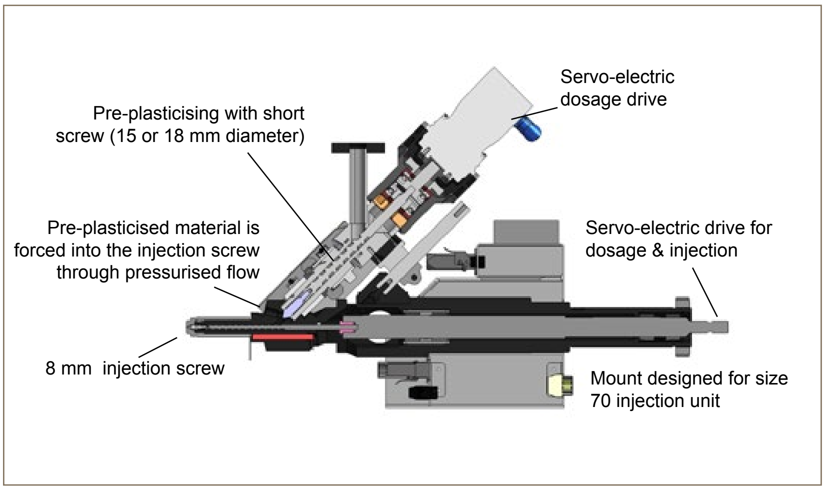

Fig. 1 Micro-injection module with pre-plasticising system and 8 mm injection screw. Image ARBURG

Fig. 2 An ALLROUNDER 370 A 600 – 70 and a micro-injection module. Image ARBURG

smaller than a single grain of granulate, high-quality production is only possible with precisely and dynamically operating machine drives. These are required in order to guarantee the highest possible process reliability and repeat accuracy. For this, precisely controlled hydraulic and electric ALLROUNDER machines are available. The precision of the injection moulding process is directly related to the dynamics and reproducibility of the injection movement.

'The precision of the injection moulding process is directly related to the dynamics and reproducibility of the injection movement.'

This can be achieved by a position regulated screw, which is optionally available for hydraulic machines or on servo electrically driven injection units. All machines feature large clamping units with three-platen technology and four tie-bar guidance for precise mould use and can be equipped with clean-room modules, ionisation or automation.

The new micro-injection module

When processing extremely small shot weights, the long residence times of the material in the barrel and extremely short displacement strokes of the screw are the main challenges.

A practically oriented solution to overcome these challenges is the newly developed micro injection module (Fig. 1). This combines an 8 mm injection screw with a second screw for melting the feedstock. This servo-electrically driven pre-plasticising screw, which is installed at 45 degrees to the horizontal injection screw, ensures homogeneous preparation of the melt. The available screw sizes of 18 mm and 15 mm allow the processing of standard sized granules. The geometry of the short plasticising screws is similar to the design of conventional three-zone screws.

During processing the molten feedstock reaches the injection screw from the pre-plasticising screw through pressurised flow. The injection screw has a diameter of only 8 mm and is used as a feeding screw only. It is fitted with a quick reacting, short stroke non-return valve and operates as a reciprocating screw according to the screw-piston principle. This

Pre-plasticising			
Screw diameter	mm	15	18
Effective screw length	L/D	11	
Material trough put	max kg/h PS	0.8	1.4
Injection screw			
Screw diameter	mm	8	
Effective screw length	L/D	12	
Calculated injection volume	cm^3	2.5	
Shot weight	max g PS	2.3	
Injection pressure	max bar	2000	
Injection Flow	max cm^3/s	15	

Table 1 Technical data of the micro injection module

Fig. 3 Test parts as sintered (top) and as moulded (bottom). Image ARBURG

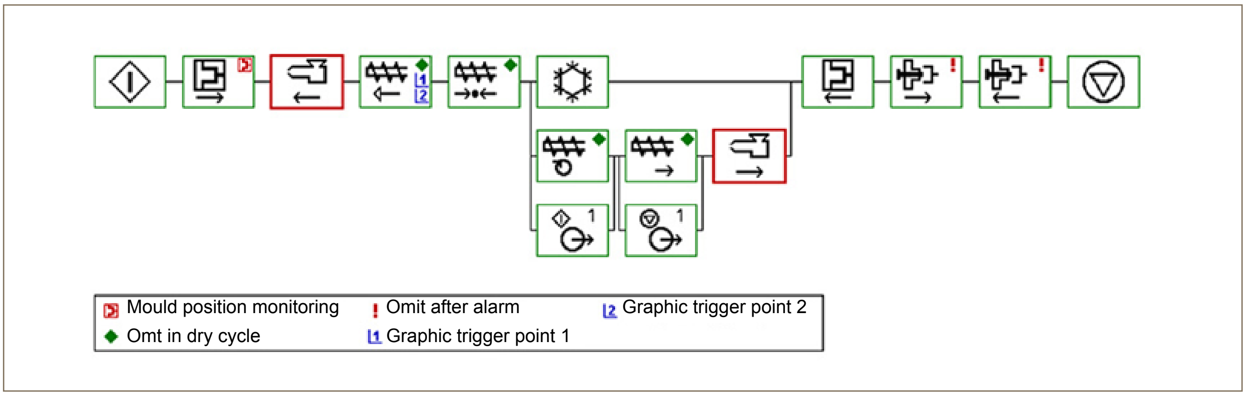

Fig. 4 The moulding process sequence. Image ARBURG

allows the smallest shot weights to be achieved at high precision thanks to longer screw strokes.

The total displacement distance of 50 mm accounts for a theoretical shot volume of 2.5 cm³. With this, the displacement distance for a shot volume of 0.5 cm³ is 10 mm for the 8 mm screw, where as it is only 2.8 mm for a 15 mm screw. Because of the perfect interaction between the two screws, the melt is continuously fed from the material inlet to the tip of the injection screw. This ensures that the "first in - first out" principle is fully observed and for every shot a homogeneous, freshly dosed melt is available.

Minimised residence times prevent the material from being thermally damaged, thus ensuring a high processing quality. There are additional advantages of the design with a pre-plasticising and an injection screw, including the leak tightness of the system. The ability to lift the nozzle from the mould, which allows for thermal separation of nozzle and mould, thus eliminating the heat transfer into the mould, is another important advantage. The micro-injection module is designed to be mounted on an injection unit 70 and can be used on standard electric machines [4]. Selected technical data on the micro-injection module are summarised in Table 1 [5].

Experimental set-up

To test the micro-injection module an all electric injection moulding machine ARBURG ALLROUNDER 370 A 600 – 70 was used (Fig. 2). The micro injection module was equipped with a 15 mm pre-plasticising PIM screw, having a lower compression and modified zone splitting compared to standard screws for thermoplastic processing and an 8 mm injection screw.

'Different metal and ceramic feedstocks including commercially available grades and custom feedstocks have been tested'

Different metal and ceramic feedstocks, including commercially available grades and custom feed-stocks, were tested. Table 2 gives an overview on the commercial grades that were used.

All tests were carried out using a two cavity mould with a shot volume of 0.6 cm³. The test part, a small insulator, is shown in Fig. 3.

The setup of the moulding process

Material	Feedstock	Supplier
316L	Catamold 316L A	BASF SE
316L	Embemould 316L S 16 D1	Embe Products und Service GmbH
17-4 PH	Catamold 17-4 PH A	BASF SE
17-4 PH	Embemould 17-4 PH S 16	Embe Products und Service GmbH
ZrO_2	Catamold TZP C	BASF SE
ZrO_2	Inmafeed K1012	Inmatec Technologies GmbH

Table 2 The materials tested

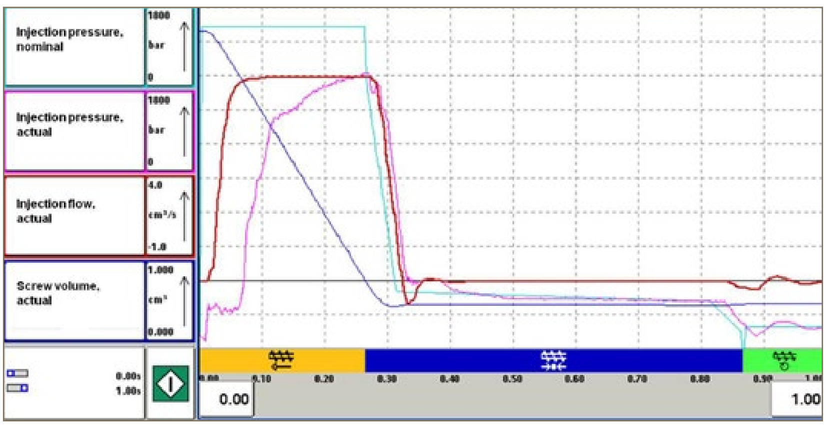

Fig. 5 Injection profile for Catamold 316L A. Image ARBURG

	Mean value	Min	Max	Spread	Standard deviation
Cycle time / s	18.489	18.460	18.490	0.030	0.00
Injection time / s	0.263	0.260	0.270	0.010	0.00
Dosage time / s	3.469	3.150	3.750	0.600	0.11
Pressure at change over / bar	970	949	1003	54	10.86
Max injection pressure / bar	984	968	1017	49	9.19
Material cushion / cm³	0.121	0.119	0.123	0.004	0.00
Change over volume / cm³	0.199	0.199	0.200	0.001	0.00

Table 3 Summarised results of Catamold TZP C

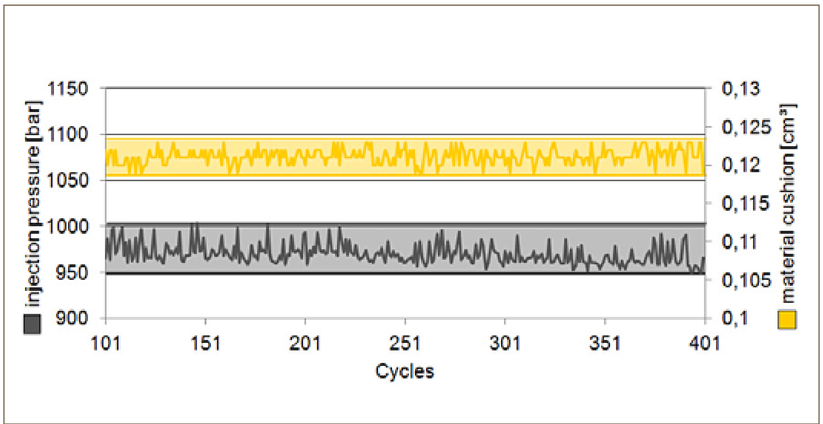

Fig. 6 Pressure at change over and material cushion for Catamold TZP C. Image ARBURG

was adapted for each of the tested feedstocks. The process sequence for the trials is shown in Fig. 4.

During the trials, the actual process data including injection pressure, material cushion, injection time etc. were recorded for each test run. Fifty consecutive shots were taken out of the process and the parts were subsequently weighed.

Results

With all of the feedstocks tested, constant productions of the insulator parts in automatic mode were possible using the micro-injection module. Fig. 5 shows an injection profile for Catamold 316L A as an example. A good shot to shot consistency could be achieved. Table 3 summarises the results for Catamold TZP C and Fig. 6 illustrates this for the same material showing the consistency of the pressure at change over and of the material cushion.

As can be seen from Table 3 the spread of the injection pressure at change over, for instance, is only 54 bar with a mean value of 970 bar. The material cushion only has a spread of 0.004 cm³.

As previously described, after each test the weight of 50 consecutive

	Catamold TZP-C	Catamold 316LA	Embemould 316 LS 16 D1	Catamold 17-4 PH A	Embemould 17-4 PH S 16
Weight / mg	67.22	106.23	96.84	95.4	94.54
Standard dev. / mg	0.0454	0.1378	0.1594	0.1164	0.1779
Min /mg	67.10	106.00	96.50	95.15	94.05
Max / mg	67.35	106.65	97.20	95.65	94.95
Spread / mg	0.25	0.65	0.70	0.50	0.90

Table 4 Statistical data for weight of parts processed

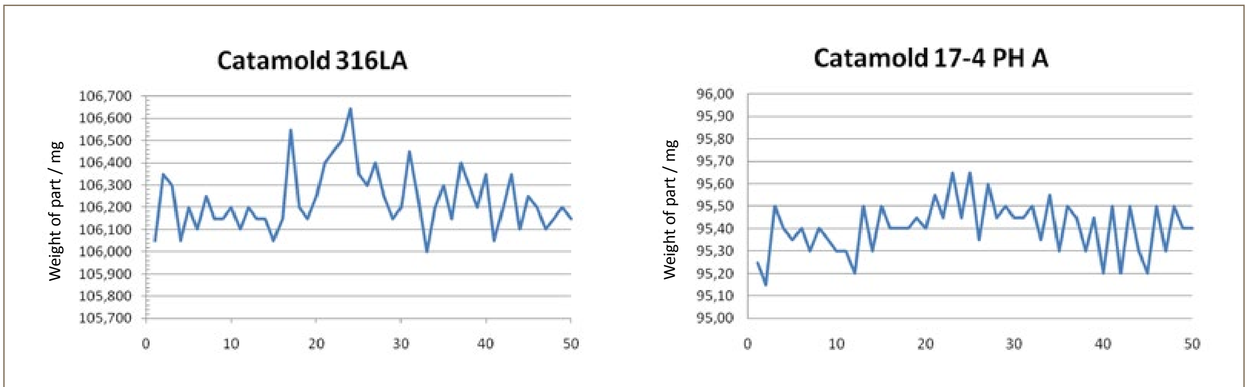

Fig. 7 Part weight for Catamold MIM feedstocks. Image ARBURG

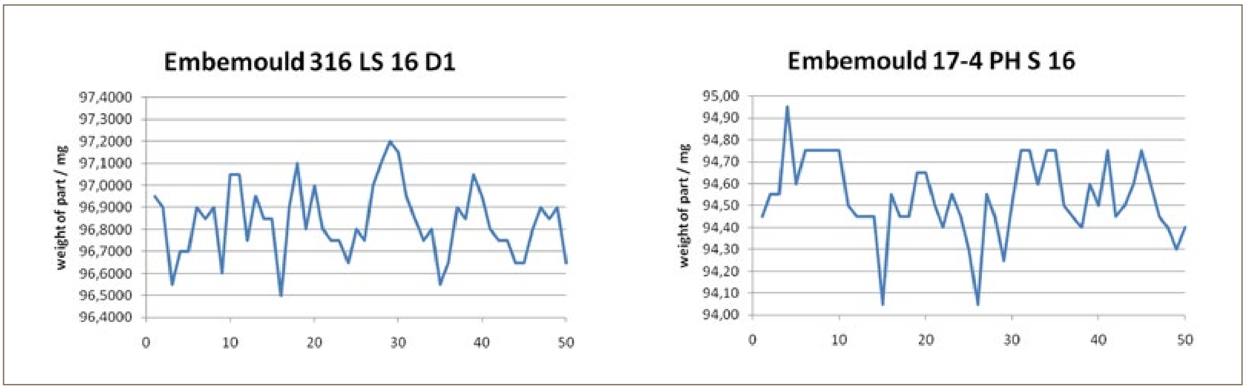

Fig. 8 Part weight for Embemould MIM feedstocks. Image ARBURG

parts was determined. The results for the tests are summarised in Table 4, showing a high consistency of the part weight for the different materials tested. Figs. 7 and 8 indicate the shot to shot consistency for Catamold and Embemould MIM feedstocks respectively.

Conclusions and outlook

As can be seen from the results, the new micro-injection module is well suited to produce PIM micro parts using a wide range of PIM feedstocks, including metals and ceramics, at a high level of consistency and reproducibility. It could be demonstrated, that the green parts produced have a very narrow weight range, which can be used as an indication that the micro-injection module allows for the high precision production of micro components.

Future tests will include further test materials and comparative studies of the dimensional tolerances that can be achieved during production of PIM micro parts.

Contact

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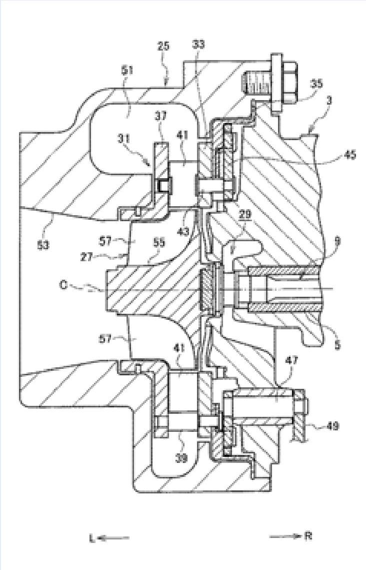
[3] M. Ganz: Kleinstteile höchst wirtschaftlich, Kunststoffe 09/2010, Seite 133-135
[4] ARBURG: Efficient solutions for complex tasks, ARBURG Application information 10/ 2010 [5] ARBURG: Micro-injection module, ARBURG Technical data 10/ 2010
[5] ARBURG: Micro-injection module, ARBURG Technical data 10/ 2010

Global PIM Patents

The following abstracts of PIM-related patents have been derived from the European Patent Organisation databases of patents from throughout the world.

JP2010275880 (A)
ROTOR ASSEMBLY, SUPERCHARGER, AND METHOD FOR MANUFACTURING THE ROTOR ASSEMBLY
Publication date: 2010-12-09
Inventor(s): Inoue Tomohiro et al, IHI Corp, Japan

This patent identifies steps to improve productivity (manufacturability) of a rotor assembly. A turbine impeller is formed by sintering a moulding produced by metal powder injection moulding. It is formed with a cylindrical fitting hole opened in the centre of the back surface of a turbine wheel and fitted around the left end of a rotor shaft. With the rotor shaft inserted into a portion corresponding to the fitting hole in the moulding, the turbine wheel and rotor shaft are bonded to each other by heat contraction occurring when the moulding is sintered.



EP 2158051 (A1)
METAL INJECTION MOLDING SYSTEM AND PROCESS FOR MAKING FOAMED ALLOY
Publication date: 2010-03-03
Inventor(s): Frank Czerwinski, Husky Injection Molding, Canada

Disclosed in this patent is: (i) a metal injection-moulding system, (ii) a metal injection-moulding system including a combining chamber, (iii) a metal injection-moulding system including a first injection mechanism and a second injection mechanism, (iv) a metal injection-moulding system including a first injection mechanism being co-operable with a second injection mechanism, (v) a mould of a metal injection-moulding system, and (vi) a method of a metal injection-moulding system.

TW201030626 (A)
RFID TAG AND ITS MANUFACTURING METHOD
Publication date: 2010-08-16
Inventor(s): Yun Man-Sun, Santoma Ltd, Taiwan

This patent identifies an invention to improve the characteristics of a tag antenna for RFID with a ceramic material exhibiting characteristics of a relaxor ferroelectric substance. More specifically, the present invention relates to an RFID tag that is formed of a relaxor ferroelectric substance having a dielectric constant of 3,000 or more and comprising a non-lead based oxide to have an expanded usage, and to exhibit improved orientation by forming the non-lead based relaxor ferroelectric substance in a planar disc or other shapes by a general dry-forming method or by forming the non-lead based relaxor ferroelectric substance in various shapes by powder injection moulding.

CN101797645 (A)
BINDER FOR MICRO-POWDER INJECTION MOULDING AND APPLICATION METHOD THEREOF
Publication date: 2010-08-11
Inventor(s): Hao He; Yu Liu et al, Changsha University, China

This invention discloses a binder for micro-powder injection moulding and an application method thereof. The binder comprises the following components by mass percentage: 15% to 25% of industrial paraffin, 20% to 30% of Brazilian wax, 15% to 32% of high-density polyethylene, 10% to 20% of low-density polyethylene, 5% to 20% of vegetable oil and 1% to 7% of stearic acid. The application method of the binder comprises the following steps: mixing the binder and metal powder by a volume ratio of (50-58):(50-42); injection moulding; de-binding and sintering to obtain a micro-metal part.

The binder of the invention has lower viscosity but enough strength, and the binder has better injection moulding capacity and green-pressing stability; the binder, due to the flowability, facilitates the micro-injection moulding process and avoids the damage caused by demoulding green bodies. The density of injection-moulded green bodies is uniform; and the de-bound micro-metal parts resistant to cracks and deformation can be produced through the thermal de-binding process at low temperature and at a low heating rate.

Influence of surface aspects and properties of MIM titanium alloys for medical applications

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The Metal Injection Moulding (MIM) process is a near net shape manufacturing method allowing the production of small to moderate sized complex shaped components and it presents significant innovation potential for the implantable devices industry. The French Regional Centre for Innovation and Technology Transfer, CRITT-MDTS, associated with the University of Compiègne, has assessed the properties of MIM-titanium alloys for medical applications. To this end, titanium alloy rods have been machined and titanium feedstocks have been injected, debound and sintered to assess the biological properties of these materials. Chemical and physical features, cytocompatibility and surface aspects have been comparatively studied on each sample. The results revealed that MIM-Titanium, compared to machined titanium, has demonstrated a specific surface roughness with an excellent biological response. Moreover the conformity of chemical and mechanical properties to international standards leads us to consider the injection moulding process as a flexible manufacturing method for future implantable devices in contact with bone.

The medical market has experienced strong growth in recent years thanks to lengthening life spans combined with a desire for a higher quality of life. For these reasons new materials and processes are being established to reduce the cost of medical devices and to allow more people to have access to "this luxury". Today, titanium and its alloys are widely used for medical applications. Indeed this material has many advantages such as biocompatibility, light weight and high corrosion resistance. The cost of these materials is, however, very high. For this reason MIM technology could be a good route to reduce the cost of parts. Indeed, unlike machining, there is no waste of material and moreover, MIM technology could be a good flexible manufacturing method for the mass production of complex parts and thus obtain lower prices per part than with conventional machining [1].

As titanium is a reactive material and the binders employed are commonly composed of organic materials, particular attention should be given to carbon and oxygen contamination that can affect the material's mechanical properties [2-4]. Moreover, commercial feedstocks revealed relatively high carbon and oxygen content as also stated by Nyberg *et al*. [4]. In recent studies alternative binders and powders have been investigated to avoid interstitial contamination. When oxygen content in the material is raised, mechanical stiffness is increased but at the expense of ductility. An oxygen rate lower than 0.25% is advised to preserve ductility [5]. Otherwise, time, temperature, vacuum level or even gas atmosphere used during sintering or removal binder steps have a great influence on the risk of contaminating the component.

For bone integration, it is important to have a specific surface topography on implants [6]. Either a porous coating is applied such as hydroxyapatite or titanium coats, or implants are blasted. Both methods provide an increase in roughness at the surface of the implants and therefore better tissue in-growth and integration, as well as better long term stability of the implants in the human body. So what about the surface aspects of MIM? Except for the Zhu *et al*. study, which has shown a good biocompatibility for 316L MIM [7], there are few works concerning the biological properties of MIM materials. This is important for MIM implants, because MIM parts are considered as a net-shape process to study the influence of cellular response on the surface aspects of the MIM implants.

The aim of present study was on the one hand to compare machined TA6V and this same material realised by the MIM process according to the published standards. On the other hand, a biocompatibility study has been assessed on machined grade 4 titanium, sintered grade 4 titanium and sintered grade 4 titanium with three different coatings used for medical implants.

Experimental Methods

TA6V sample production and characterisation methods

The feedstock used was the PolyMIM® TA6V commercially available from POLYMIM (Germany). The feedstock is a mixture of pre-alloyed TA6V spherical powder and binder as illustrated in [8]. The chemical composition of the powder used in the feedstock is described in Table 1.

Material	Ti	V	Al	Fe	C	O	N	H
TA6V powder	balance	4.10	6.20	0.10	0.02	0.10	0.001	0.005
TA6V ASTM F136	balance	3.5-4.5	5.5-6.5	≤0.25	0.08	<0.13	<0.05	0.0125
TA6V MIM	balance	3.90	5.90	0.11	/	0.36	0.05	/
TA6V machined	balance	4.20	6.10	0.11	0.01	0.08	<0.01	0.0073

Table 1 Chemical composition of feedstock by percentage weight

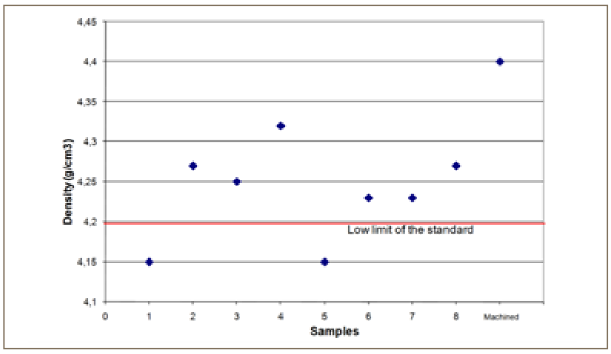


Fig. 1 Density responses according to the sintering test

Variable	Confidence %
Constant	100
AC	91.13
BC	94.35
A	96.11
B	99.32
C	99.48

Table 2 Confidence factor analysis for the density response

Injection moulding of the samples was performed on an Arburg 320C 600-100 machine. An injection pressure of 900 bar, a barrel temperature from 178 to 186°C for the nozzle and a mould temperature of 60°C turned out to be adequate parameters providing consistent properties. The material of the screw, plasticising cylinder and mould were specifically made to resist abrasion and corrosion because of using MIM feedstock. Moreover, efforts had to be made to clean the barrel, the screw, the mould and the feed hopper before the injection step.

A two-step debinding process was necessary for the binder system chosen: Water debinding at 60°C followed by thermal debinding performed with three soaks of 60 minutes at 350°C, 470°C and 600°C in the sintering furnace in order to remove the binder entirely. Sintering was carried out in an Elnik furnace with tungsten heating elements and molybdenum shield packs. Samples were set on zirconia plates in the furnace. TA6V samples produced by MIM processing are named MIM-TA6V. Taguchi experimental design (L8) was applied to optimise the sinter conditions. Three factors at two-levels were studied. For confidentiality, the factors are named A (Pressure), B (soaking time) and C (sintering temperature). The software "Lumière", using the analysis of variance, was chosen to determine the significant level and contribution of each variable to the different responses.

In parallel, commercially available TA6V titanium, namely C-TA6V, rod certified following surgical implant standards ISO 5832-3 and ASTM F 136 was machined in order to make a comparison with MIM-TA6V. Firstly, the density of sintered parts was controlled by the laboratory balance Sartorius Din 83. Secondly, a metallurgical analysis using optical microscope images of polished cross-sections was done with ETTC 1 etching. Then, the mechanical tests on tensile samples (ISO 2740) were undertaken. Chemical analyses were assessed by the LECO system for gas and ICP spectrometer Ultima by Horiba for vanadium, iron and aluminium. Lastly, surface properties were observed using an Altisurf 500 (ALTIMET).

Surface preparation and characterisation for cytocompatibility study

In this part of the study, the feedstock used was Catamold® Ti from BASF. The binder system used is essentially POM (PolyOxyMethylene). The titanium powder used is grade 4. An Arburg 320C 600-100 machine was used for the injection moulding of the feedstock with a temperature from 160 to 170°C for the barrel and a mould temperature of 130°C. The same efforts had to be made to clean the parts of the press in contact with the feedstock in order to avoid contaminating the titanium particles. After injection, the binder was removed from the specimen by catalytic and thermal debinding. The catalytic debinding was applied with pure nitric acid >98% under nitrogen atmosphere at 120°C. Treatment duration depends on sample thickness; about 1 hour per mm. Thermal debinding was then performed at 600°C for 3 hours in the sintering furnace in order to remove the remaining binder. Sintering was carried out at 1300°C under argon partial pressure (~100 mbar) for 100 minutes. Samples were set on zirconia plates into the furnace. Ti grade 4 samples produced by MIM process are named MIM-Ti.

Commercially pure titanium, namely CP-Ti, grade 4 rod certified following surgical implant standards ISO 5832-2 and ASTM F 67, was machined and used as the reference. Then the MIM-Ti as well as CP-Ti samples all underwent the same preparation steps: degreasing, blasting with zirconia, etching with a mixture of nitric and hydrofluoric acids (BIOETCH) and passivation. Three different surface treatments were applied on the sintered parts: a colour anodisation (BIOCOAT®), an alkaline anodisation (BIODIZE®) and a glow discharge anodisation (BIOCER®). These surface treatments are described in the literature [9-12] and used for medical devices. The final rinsing occurred in biologically controlled water (<1 mesophylic aerobic germ per ml). The samples were dried in hot air and packaged in a cleanroom (ISO Class 7). Sterilisation with gamma rays (35 kGray) was applied.

The features of the titanium samples relating to surface micro topography have been assessed in this study using an optical platform Altisurf 500 (ALTIMET). Material features have also been analysed using an optical microscope, gas analyser and mechanical tests in order to assure their conformity with ASTM F67 (described in Table 7). The coating features are presented in a previous study [13]. Then, Cp-Ti, MIM-Ti, Biocer®, Biodize® and Biocoat® were used to cultivate in a semi-solid medium, as described by Sigot-Luizard *et al.* [16, 17], bone tissue samples obtained from the tibias of 14 day old chick embryos. These trials have to evaluate the behaviour of bone explant cultures (standard AFNOR NFS 11-146) and the behaviour of pre-osteoblast MC 3T3 E1 cultivated in standard conditions [13].

Results and discussion

TA6V samples

According to the Taguchi experimental design L8, density, microstructure, chemical analysis and mechanical analysis were the four responses studied to optimise sintering parameters.

Density

Fig. 1 presents the density responses according to the eight trials. The density depends on the parameters B and C (Table 2).

Microscopic observation of samples

Fig. 2 represents the colonies of the fully lamellae microstructure, the MIM TA6V microstructures correspond to alpha and beta phases. Nevertheless, it is impossible to give a grain size, hence why the lamellae of the grains were measured. Fig. 3 shows that the size of lamellae depends on the density: the higher the density, the larger the size of lamellae. The size of lamellae only depend on parameter C.

Chemical analysis

This primarily depends on parameter C (Table 3). The percentage of oxygen is very high compared to the machined TA6V and the standards (Fig. 4).

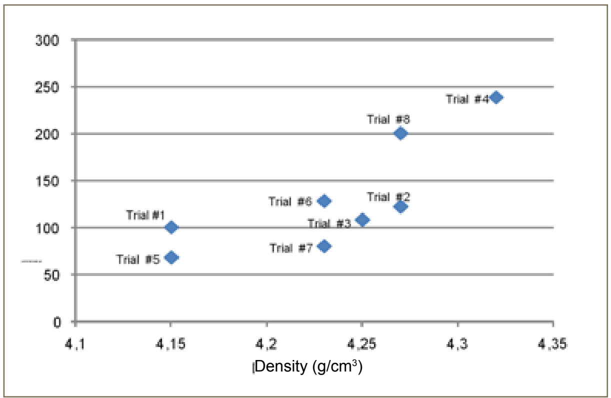


Fig. 2 Size of lamellae according to density

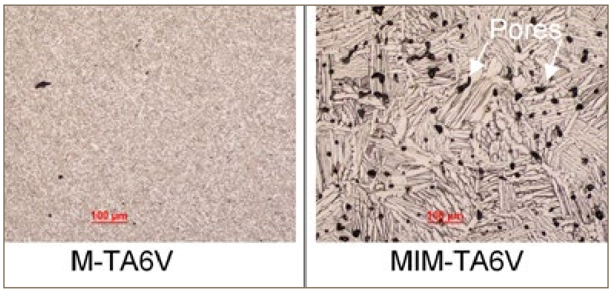
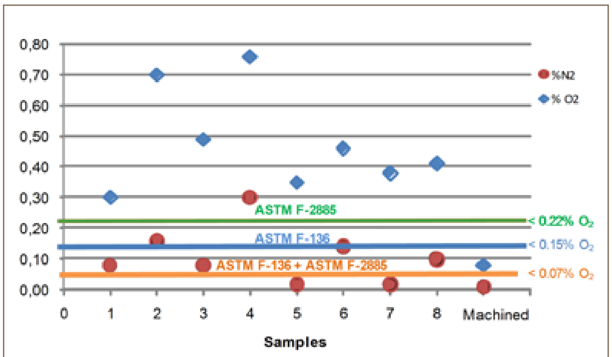


Fig. 3 Microstructures of M-TA6V and MIM-TA6V (Mx100)



ASTM F-2885: Metal Injection Moulded TA6V Components for Surgical Implant Applications

Fig. 4 Oxygen and nitrogen content according to the sintering test

Variable	Confidence %
Constant	100
AC	93.69
A	96.48
C	98.25

Table 3 Confidence factor analysis for the oxygen and nitrogen content

Mechanical results

Parts #5 and #7 manufactured by the MIM process were assessed in accordance to the standard ASTM F 136 and ASTM F 2885 and closer to M-TA6V. Nevertheless the ductility with A% is very low (~2%) compared to 10% given by the ASTM F 136 (Table 4). Samples carried out with the parameter A (low level) have poor mechanical properties, the samples are brittle with a zero yield strength. The mechanical properties depend on the parameters A, C and the interaction AC (Table 5).

To conclude this first part, to reach convenient properties of MIM-TA6V materials some compromise should be made in the choice of parameters (Table 6). Parameters A and B had the most significant effect on the studied responses. The optimum parameters are A1 B1 C-1 or A1 B-1 C-1.

Samples	R_p 0.2 (Mpa)	R_m (Mpa)	A (%)	E (Gpa)
Machined	891	939	18.32	104.8
1	0	693	0.75	99.1
2	0	315	1.04	114.7
3	0	729	0.22	104.6
4	0	292	0.97	85.15
5	808	896	2.87	101
6	0	729	2.20	106.1
7	864	944	2.16	98.4
8	0	776	1.41	100.9
ASTM F136	795	860	10	/
ASTM F2885	680	780	10	/

Table 4 Mechanical properties according to the sintering tests

	R_p0.2	Rm
Variable	Confidence %	Confidence%
Constant	100	100
AC	100	99.62
A	100	99.99
C	100	99.99

Table 5 Confidence factor analysis for the R_m and R_p0.2

Responses	A	B	C
Low oxygen content	1	-1	-1
High density	-1	1	1
Fine lamellae size	1	-1	-1
High R_p 0.2	1	No effect	-1
Synthesis	**Level 1**	**Level 1 or -1**	**Low level -1**

Table 6 Analysis of important parameters according to the chosen effects

The features of the MIM parts obtained in this study correlate with the literature. It has been reported that the typical fully lamellae microstructure with the additional presence of pores (Fig. 3) is similar to titanium manufactured by casting. Compared with the literature, the R_p 0.2 and the R_m (samples #5 and #7) are as good as the standard specifications, especially the MIM TA6V for medical applications, however because of the high oxygen concentration inside the matrix, our samples have a very low ductility [2-5]. The MIM process, in particular the sintering step, could be optimised in order to decrease the gas contamination and increase tensile properties.

At the PM2011 Congress in Barcelona, October 10-12 2011, further results of oxygen and nitrogen contents in the TA6V matrix were presented. Indeed, since then new trials, according to the mass of titanium parts per batch and purity of the sintering atmosphere, were run to reach the standard values. In this way, the oxygen and nitrogen content have been assessed according to the standard ASTM F 2885:

- $[O_2] < 0.20^{+0.02}\%$
- $[N_2] < 0.05^{+0.02}\%$

	Cp-Ti	MIM-Ti	ASTM F 67
Density [g/cm³]	4.50	4.32	4.50
Microstructure	Alpha phase	Alpha phase	Alpha phase
Grain size	9	5	>5
Carbon [w%]	/	0.09-0.11	0.08-0.010
Oxygen [w%]	/	0.23%	<0.25%
R_m [MPa]	639±1.4	603±12.7	>550
A%	23.5 ±0	20.5 ±0.7	>15%

Table 7 Structural, mechanical and chemical data of grade 4 titanium

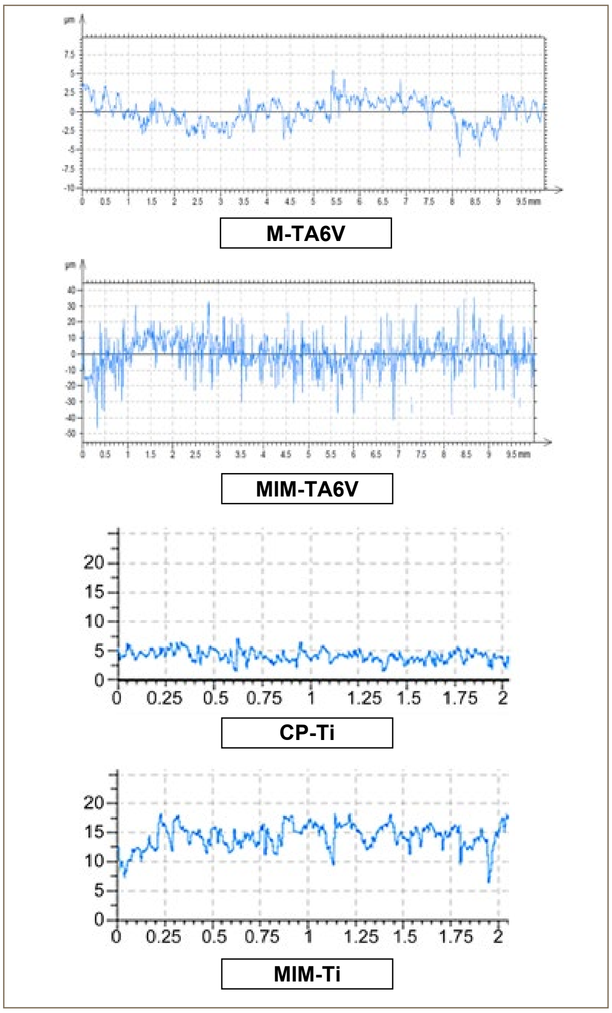


Fig. 5 Surface profiles coming from machined samples and sintered samples

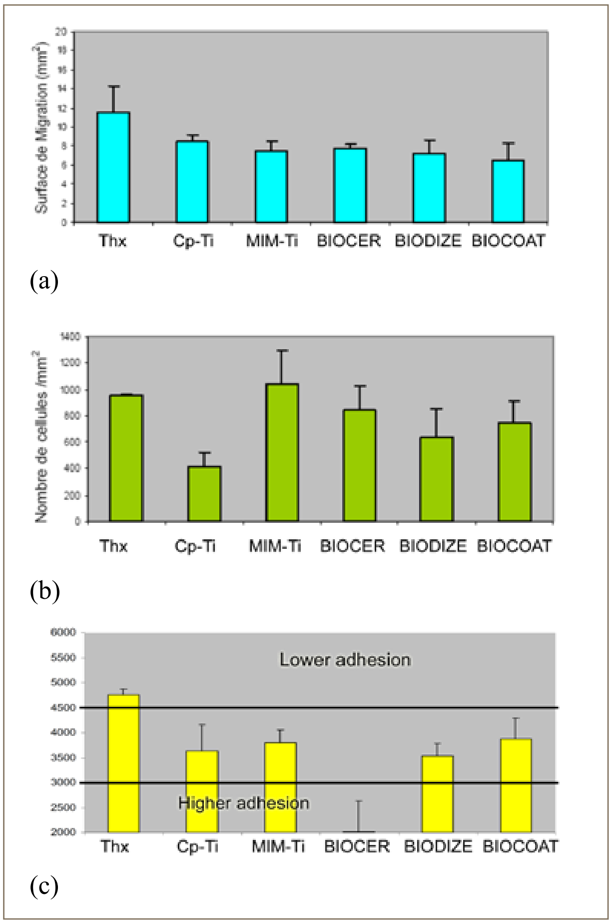


Fig. 6 Migration surface (a), cell density (b) and cell adhesion (c)

Surface aspects of MIM titanium

On the whole, the MIM titanium grade 4 properties have been assessed according to standard ASTM F 67 for medical devices (Table 7); compared to the study [14] where the oxygen content is 0.3%, the mechanical strength is 525 MPa with a plastic elongation of 17% to 25% if the oxygen content decreases.

Topographic examinations of the surfaces have revealed significant differences between the machined and sintered samples. At a micrometer level, the MIM-Ti and MIM-TA6V surface present a higher roughness than CP-Ti (Table 8). In Fig. 5, it appeared that the peak high is about 5 µm for CP-Ti and M-TA6V, whereas the surface profile has nearly 15 µm of amplitude on the MIM-Ti and 35-40 µm of amplitude on the MIM-TA6V.

In the MIM process, specific roughness is influenced by the particle size scattering. The larger the diameter of initial powder particles, the higher the surface roughness after sintering that could be reached. Nevertheless, it has been reported that a larger particle size could decrease carbon contamination [15] but at the expense of final grain size. Surface roughness enhances good osseointegration, but grain size has a direct impact on mechanical properties. The post-treatments have also impacted the surface morphology as we can see in Table 8.

Cytocompatibility study

When considering biological response, two complementary approaches were used to assess the cytocompatibility of Ti material samples. Bone explants were cultured to compare the capability of bone cells to migrate, to colonise the surfaces and to adhere,

	M-TA6V	MIM-TA6V	CP-Ti	MIM-Ti	BIOCOAT®	BIODIZE®	BIOCER®
R_a (µm)	0.8	4.01	0.69	1.74	1.79	2.06	1.82
R_z (µm)	4.77	34.65	5.02	11.55	12.23	15.54	11.29

Table 8 Roughness parameters (length of measure: 4.8 mm – cut-off:0.8mm)

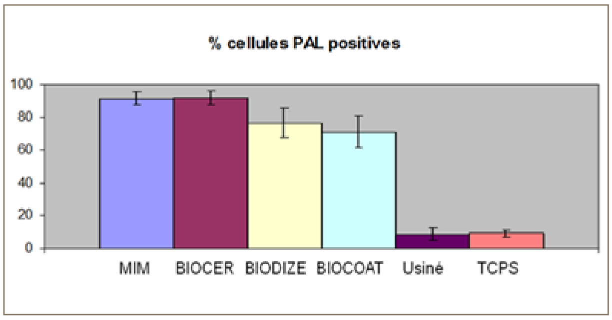


Fig. 7 Differentiation of osteoblasts

depending on the treatment applied to the Ti.

Results in Fig. 6 indicate that bone cell migration and surface colonisation were promoted on Thermanox® used as a control. If cell migration was roughly the same on the different Ti material samples regardless of the treatment applied, cell colonisation was obviously improved by the MIM process (MIM-Ti, BIOCER®, BIODIZE®, BIOCOAT®). Cell adhesion was poor on the Thermanox® control, much better on the MIM-Ti, BIODIZE® and BIOCOAT®, and dramatically increased on BIOCER®.

The second approach consisted of verifying the capability of pre-osteoblasts to support formation, secretion and mineralisation of extracellular bone matrix when seeded on the different Ti surfaces and TCPS used as a control. For that purpose, we first checked ALP positivity as a precocious marker of the differentiation of osteoblasts. A significant increase of ALP + cells was observed from MIM-Ti and BIOCER® (Fig. 7).

Conclusion

The cytocompatibility study on the MIM processing of pure titanium has demonstrated that this manufacturing process is suitable for the implantable device industry as it, firstly, notably enhances biological properties in terms of adhesion, migration and proliferation, and secondly, because it fulfils the standard requirements of mechanical strength, chemical composition and microstructure.

Some processing parameters could be adapted in the future to find the best balance and optimisation between all these requirements, especially MIM-TA6V, for which, the surface aspects include higher roughness than that of MIM-Ti and consequently should offer biological properties as good as those for pure titanium. Indeed, surface parameters have probably played a major role in favour of cytocompatibility. Moreover, functionalisation treatments on titanium by anodic oxidation processes have demonstrated nearly similar achievement compared to sintered material; especially for the BIOCER® treatment. Generally this study highlights how surface aspects such as roughness and chemical issues could affect cellular activity.

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Manufacturing of a 316L stamper for imprinting by Micro Sacrificial Plastic Mould insert MIM (µ-SPiMIM)

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This study aims to develop a manufacturing method for a metallic stamper via the Metal Injection Moulding (MIM) process for the imprinting of micro structures on a plastic sheet. In the Micro-Sacrificial Plastic Mould Insert MIM process, or µ-SPiMIM process, the feedstock composed of stainless steel 316L (D_{50}=2 µm) or Ni (D_{50}=0.74 µm) powder and a polyacetal-based binder was filled into a polymethylmethacrylate mould with line and space patterns from 47 µm wide and 150 µm high, to 6 µm wide and 19 µm high. It was debound and sintered in a H_2 and Ar gas atmosphere. The filling state of the feedstock into the micro-channels and the transcriptional property of the sintered parts was evaluated by cross-sectional SEM observation. The experimental results revealed reasonable evidence that submicron Ni powder could be sintered at low temperatures and accomplished high transcription in a narrow cavity mould. It can be concluded that the µ-SPiMIM process offers the potential to mass-produce the stamper for imprinting made of versatile highly-durable metals.

Metallic micro parts and micro structured surfaces can be manufactured by micro metal injection moulding (µ-MIM). As further micro-miniaturisation of µ-MIM parts develops, the application areas are expected to expand from simply the manufacturing of mechanical components to micro integrated devices such as micro reactors, micro mixers, micro actuators and micro sensors, which have being manufactured by micro system technology or micro-electro-mechanical systems (MEMS) technology. These fabrication methods are based on the semi-conductor process, thus the applicable material is mainly silicon, gallium arsenide or also limited to metals which can be deposited by electroplating, evaporation and sputtering. In addition, for a polymer, a film formed by etching on silicon wafer, or plastic patterns replicated by using a stamper via nano-imprint lithography (NIL) are available. However semiconductor wafers and metallic imprint stampers are very high in production cost, because they are fabricated by photolithography, focused ion beam (FIB) etching, or ultra precision milling and so on.

In this study, the production of the imprint stamper was attempted by the Micro Sacrificial Plastic Mould insert MIM (µ-SPiMIM) method, in which the authors have developed the µ-MIM process using a sacrificial plastic mould (SP-mould) to solve the problems of filling, demoulding and handling against fine microstructure. The SP-moulds, produced by a variety of plastic fabrication techniques such as injection moulding, rapid-prototyping, LIGA and NIL, were used to manufacture metallic sintered parts with fine microstructures [1-2]. The effects of the particle size of the metal powder, the sintering temperature and the size of pattern on the shape accuracy of the imprint stamper and its replicated plastic sheet were investigated. The usefulness of the MIM-stamper for imprinting was also evaluated.

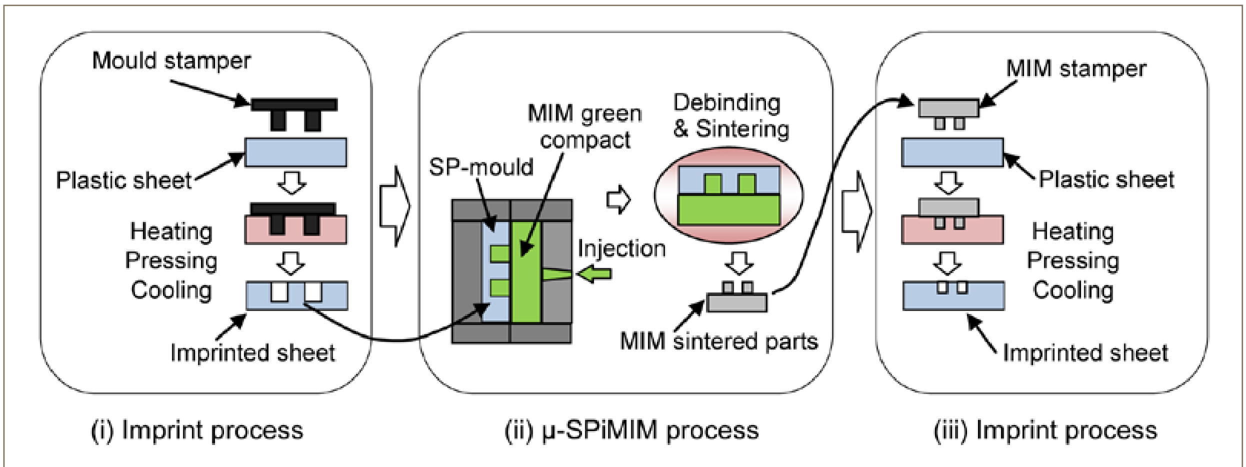

Fig. 1 Flow diagram of the µ-SPiMIM and imprint processes

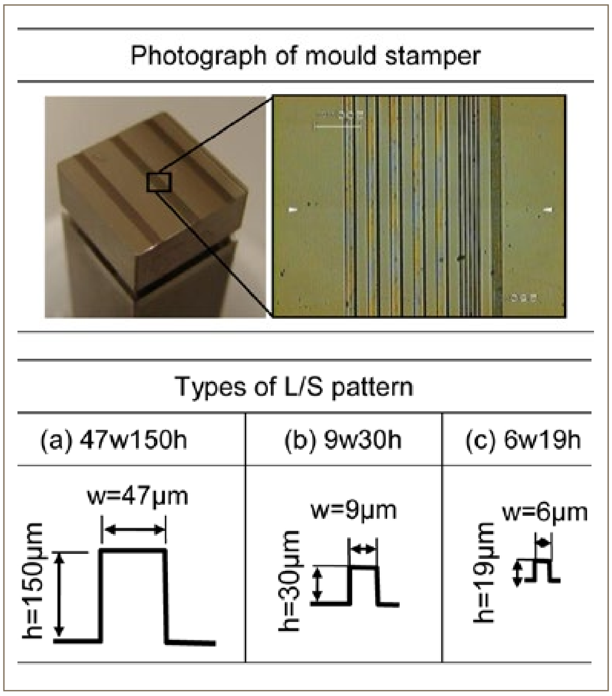

Fig. 2 Overview and geometry of mould stamper with various sized L/S patterns

Micro Sacrificial Plastic Mould inserted MIM (μ-SPiMIM) and the imprint process

Fig. 1 shows the flow of the μ-SPiMIM and imprint process which is basically divided into three steps; i) the imprint process for manufacturing of the SP-mould, ii) injection moulding of MIM feedstock into SP-mould insert, de-moulding the green compact and SP-mould insert as one component and debinding for lost of SP-mould and polymeric binder followed by sintering process for manufacturing MIM-stamper. And finally iii) the imprint process for manufacturing of plastic devices.

Experimental details

Mould stamper: A mould stamper with various sized line and space (L/S) patterns was produced by ultra high precise cutting using a diamond bit, as shown in Fig. 2. The dimensions of the L/S pattern are 6, 9 and 47 μm in width and 19, 30 and 150 μm in height with an aspect ratio of approximately 3.

Materials: The material used for the sacrificial plastic mould (SP-mould) was polymethylmethacrylate (Mitsubishi Rayon Co., Ltd.,VH001). The metal powders used were austenitic stainless steel 316L (D50=2 μm, Epson Atmix Co. Ltd., PF-2F) and Ni powder (D50=0.74 μm, Mitsui Mining & Smelting Co., Ltd., 2060ss). The binder used was polyacetyl and paraffin wax, mixed with 40 vol% and 50 vol% of stainless steel 316L and Ni powder, respectively.

Fabrication conditions: The SP-mould was manufactured by imprint using a hot press machine (Izumi Tec Co., Ltd.), and the MIM feedstock was moulded into them using an injection moulding machine (Nissei Plastic Industry Co., Ltd.). The green compacts with the SP-mould were debound at 773 K for 2 hours in H2 gas, followed by sintering at Ts=1323~1523 K or Ts=873~1173 K, for stainless steel 316L or Ni powder respectively, for 2 hours in an Ar gas atmosphere using a vacuum debinding and sintering furnace (Shimadzu Mectem Inc., VHSgr, 40/40/100-M). The material used for the imprint process to MIM-stamper is polycarbonate seat (Mitsubishi Engineering-Plastic Co., Ltd., lupilon H3000) with 0.4 mm in thickness. The imprinting was carried out under 1 MPa for 90 s at 463 K.

Results and discussions

The sacrificial plastic mould and MIM stamper: Fig. 3 shows SEM images of line and space patterns of the SP-moulds. Very high replication behaviour is seen for any sizes of pattern. Schematic drawings of the green compact with the SP-mould, as well as photographs of the sintered parts used as the MIM-stamper, are shown in Fig. 4.

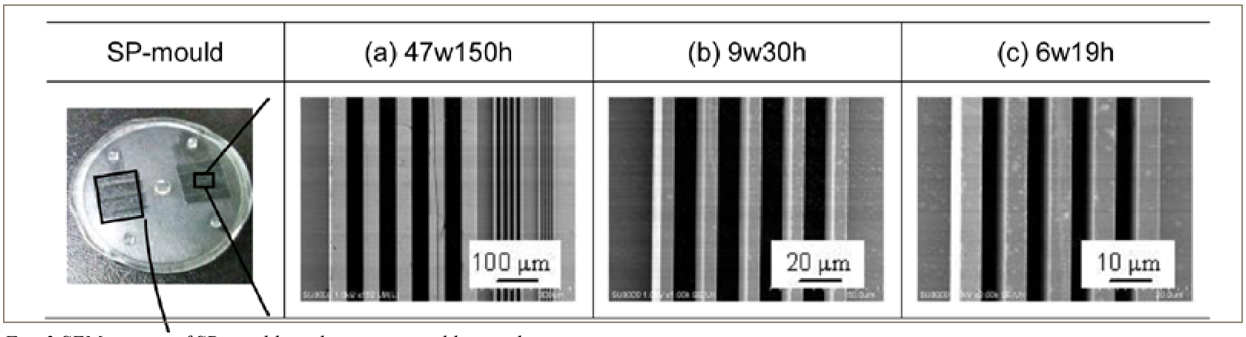

Fig. 3 SEM images of SP-moulds with various sized line and space structures

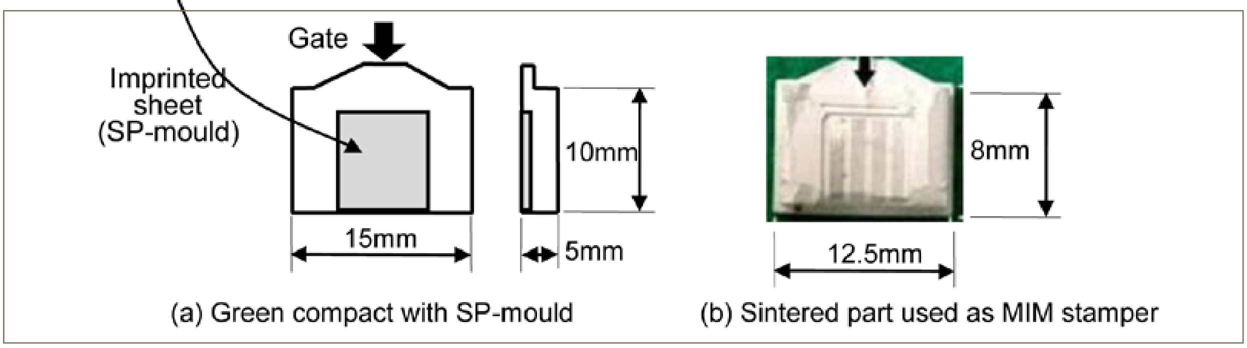

Fig. 4 MIM-stamper manufacturing by μ-SPiMIM process

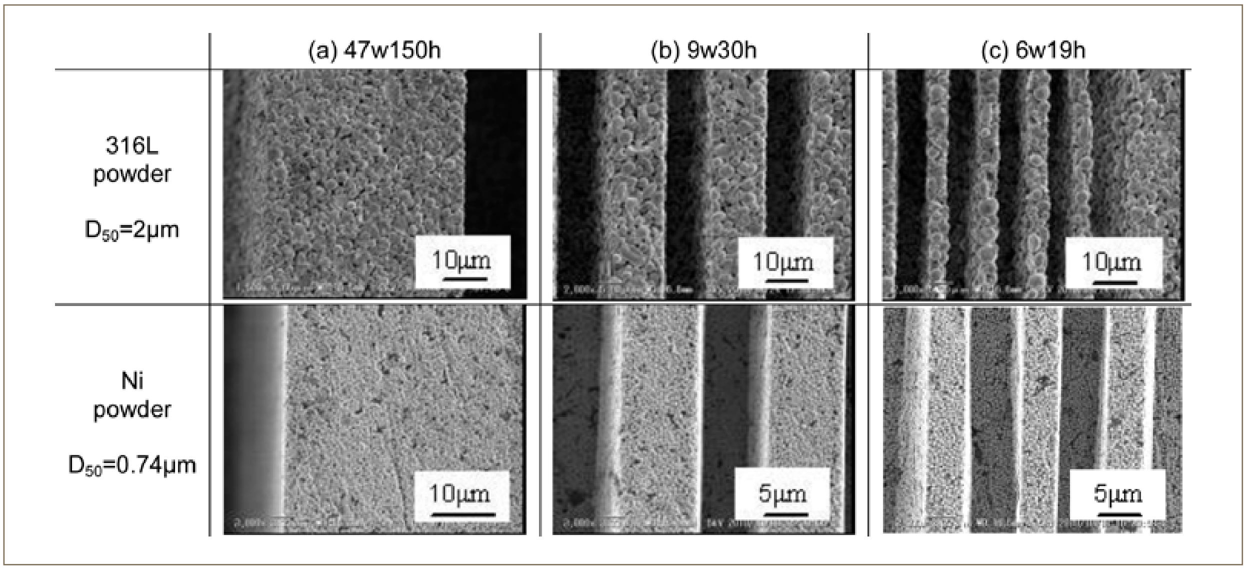

Fig. 5 SEM images of debound parts with various sized line and space patterns

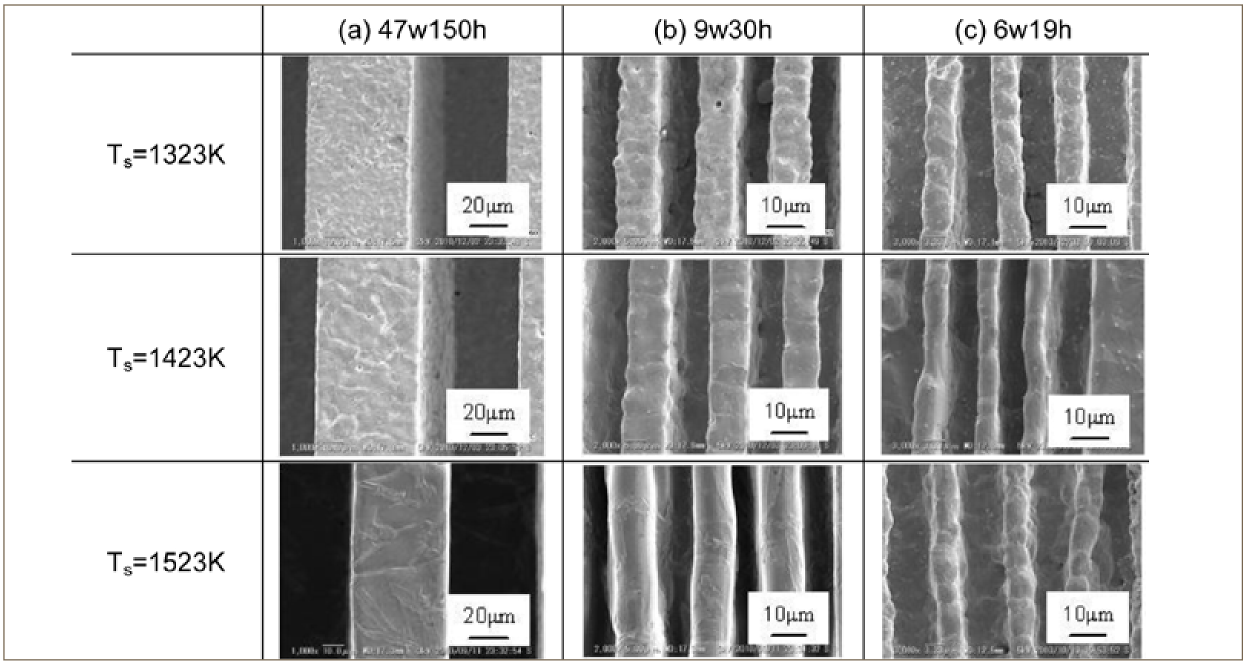

Fig. 6 SEM images of 316L-stampers sintered at various temperatures

Filling of the metal powder in the green compact: Fig. 5 shows SEM images of the surfaces of the debound parts with various sized patterns. The metal powders were filled densely into the lined patterns. Thus moulding pressure was applied sufficiently in the injection step. In (a) 47w150h specimens, the granular shape is not seen so significantly. However, in (c) 6w19h specimen, moulded using 316L powder, only a few particles were filled into a line pattern, with the edge line roughly marked. On the other hand, in case of the sample using Ni powder, a number of particles were filled into a line pattern.

Sintered parts (MIM-stamper): Fig. 6 shows SEM images of the surface of the sintered parts manufactured by the µ-SPiMIM process using 316L powder. As the sintering temperature increases, the surface becomes smooth and the grain size grows remarkably in (a) 47w150h specimen. However, in (b) 9w30h and (c) 6w19h specimens, the edge lines are rounded and undulate significantly. Likewise, Fig. 7 shows SEM images of the surface of sintered parts produced using Ni powder. In (a) 47w150h specimen, the surface is smooth even when processed at lower sintering temperature.

In comparison to sintered parts produced using 316L powder, the line pattern holds straight even though it is slightly tilted. Therefore, it is clearly found that the shape accuracy of MIM-stamper can be improved by using finer powder at lower sintering temperature.

Imprinted plastic sheets: Fig. 8 shows the SEM images of plastic sheets replicated using the 316L-stamper which was manufactured at various sintering temperatures by the µ-SPiMIM process. The plastic sheets were replicated closely into the shapes of 316L-stampers shown in Fig. 6. As they are observed by higher magnification in finer patterns, line edges become very granular when the sintering temperature is low as Ts=1323 K and 1423 K. When the sintering temperature is high up to Ts=1523 K, on the other hand, the boundaries of crystal grains grown coarsely are visible on the surface of (a) 47w150h specimen and also the top edges are rounded in (b) 9w30h specimen.

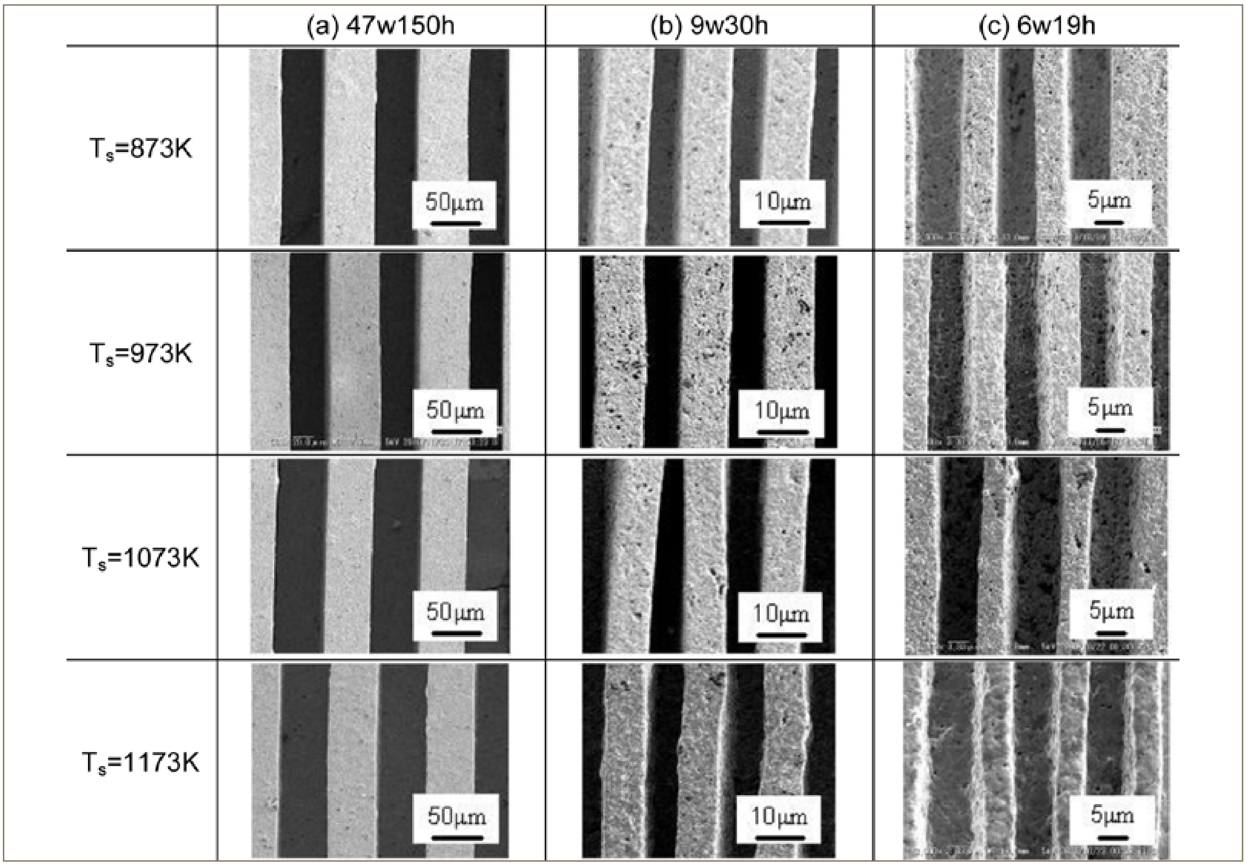

Fig. 7 SEM images of Ni-stamper sintered at various temperatures

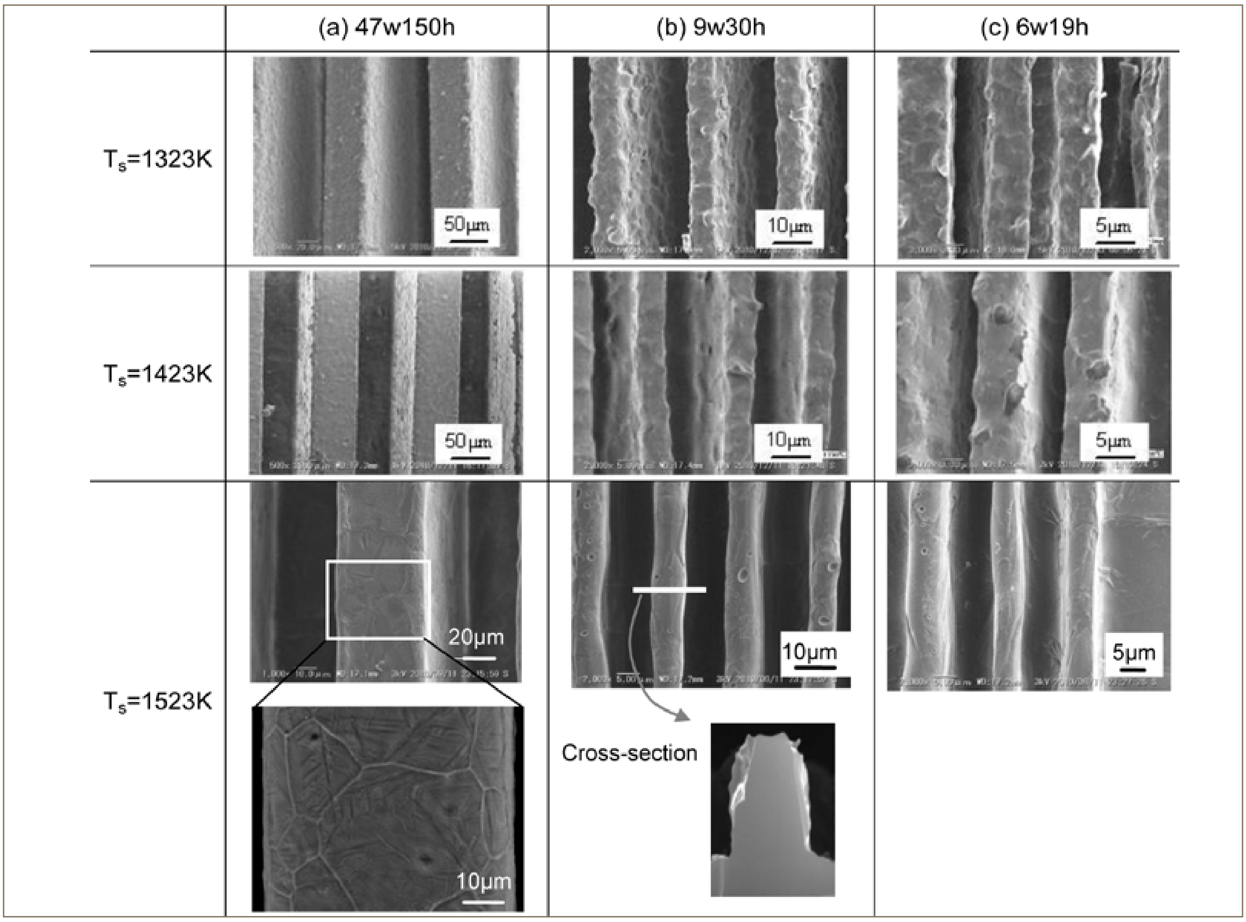

Fig. 8 SEM images of plastic sheets replicated using the 316L-stamper

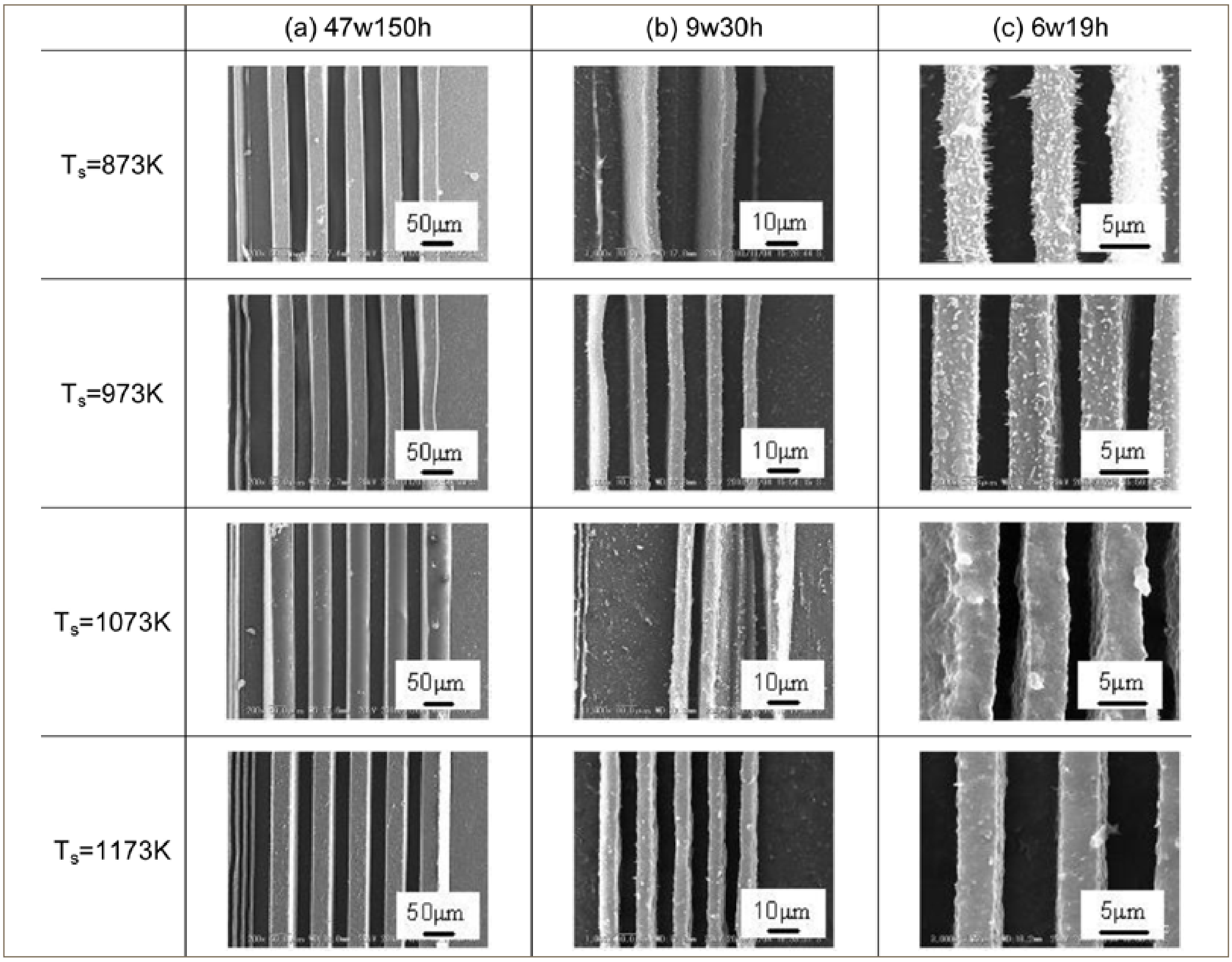

Fig. 9 SEM images of plastic sheets replicated using the Ni-stamper

Likewise, Fig. 9 shows the SEM images of plastic sheets replicated using the Ni-stamper. In (a) 47w150h specimens at any sintering temperature, the plastic sheets were replicated closely into the shapes of Ni-stamper shown in Fig. 7. The defective parts are seen in (b) 9w30h specimens at Ts=873 K and 1073 K. It is believed that this is a result of the high frictional forces that occurred between the side faces of the Ni-stamper and the plastic sheet during demoulding. However, the Ni stamper can fabricate plastic sheets with a high shape accuracy and smooth surface in line and space patterns when compared to 316L stamper. Therefore it is expected that the shape accuracy of MIM-stamper as shown in Fig. 6 and Fig. 7 is very important for manufacturing the plastic sheets with finer micro-structures. Thus the sintered density of the MIM-stamper seems to be not so significant for the replicating process of plastic sheets.

Conclusions

In this study, a manufacturing method for the MIM-stamper for imprinting with micro-structure was developed by the μ-SPiMIM process. The sacrificial plastic mould (SP-mould) used was manufactured by an imprinting process. The MIM-stamper with a line and space pattern of 6 μm wide and 19 μm high in minimum size was obtained by injection moulding the feedstock composed of stainless steel 316L or submicron Ni powder and polyacetyl binder into an SP-mould, followed by debinding and sintering at various temperatures. Plastic sheets were then fabricated using these MIM-stampers by an imprinting process. It was proven by the experimental results that using finer metal powder can fabricate a MIM-stamper and the plastic sheet with high shape accuracy, and that the shape deforms as the sintering temperature increases. It was also concluded that the combination of μ-SPiMIM and the imprint process was one option for mass producing the plastic parts with fine micro-structures like MEMS devices, and thus a further shape and dimensional accuracy of μ-MIM parts was required.

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A comparative study of Micro Powder Injection Moulding (MicroPIM) and simultaneous Micro Powder Injection Compression Moulding (MicroPICM)

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Less material shear, the minimisation of sink marks and warpages, as well as a reduction of injection pressure, clamping force and cycle time are just a few advantages of the Injection Compression Moulding Process. The aim of this work is to investigate powder injection compression moulding (MicroPICM) by use of full factorials Design of Experiments (DoE) and to compare the accurate replication of micro structures with the micro powder injection moulding (MicroPIM) process. The investigation was focused on simultaneous MicroPICM processing. The influence of compression force, compression speed, compression starting time, and holding time of compression force was investigated using zirconia feedstock on a commercial injection moulding machine using a micro structured mould insert. The results show that, in comparison to MicroPIM, an improved replication was achieved with the simultaneous MicroPICM process. Compression force and compression speed are shown to have a significant influence on replication. Furthermore, the position of the structure to the gate is relevant. The comparative study of MicroPIM and MicroPICM was carried out on both green bodies and sintered parts.

The injection moulding and the Injection Compression Moulding (ICM) processes are well known for the manufacture of polymer micro parts or micro structured parts, for example in the production of optical lenses, light-guided plates and DVD's. Some studies in this field have already been undertaken and discussed. The ICM process often achieves better replication and/or better optical performance [1-6]. Furthermore, investigations of micro part fabrication by combined micro powder injection and compression moulding have also been performed successfully [7].

The injection moulding process includes, in general, three phases: filling of the cavity, packing and cooling. After freezing of the moulded part, ejection can start. In spite of many advantages, some problems are also known regarding the injection moulding process. The main difficulty is the freezing of the melt in a micro cavity upon touching the relatively cold cavity wall. The prior freezing of the melt can be reduced by an increasing of melt and /or temperature. An alternative could be to start with the compression step before the mould is completely filled i.e. as long as the feedstock is still flowing. This procedure can be simultaneous injection compression moulding.

The ICM process is similar to the injection moulding process and just includes an additional stroke. In detail, after closing the mould to compression gap the melt can be injected and fills the cavity to 80-95% of the cavity volume. Sequential or simultaneous compression can be achieved by clamping of the mould. After hold pressure, cooling and opening of the mould, the resulting part can be ejected [8]. The basic peripheral conditions for ICM are determined by mould design (vertical flash face, stamping frame and plug) and machine technology. The process variants are generally characterised by three variables: coining axis type (main, secondary), direction of the coining (clamping, opening) and temporal sequence (sequential or simultaneous) [9].

ICM permits the reduction of injection pressure, clamping force and cycle time. Less material shear, uniformly acting holding pressure and the compensation of shrinkage by compression are just

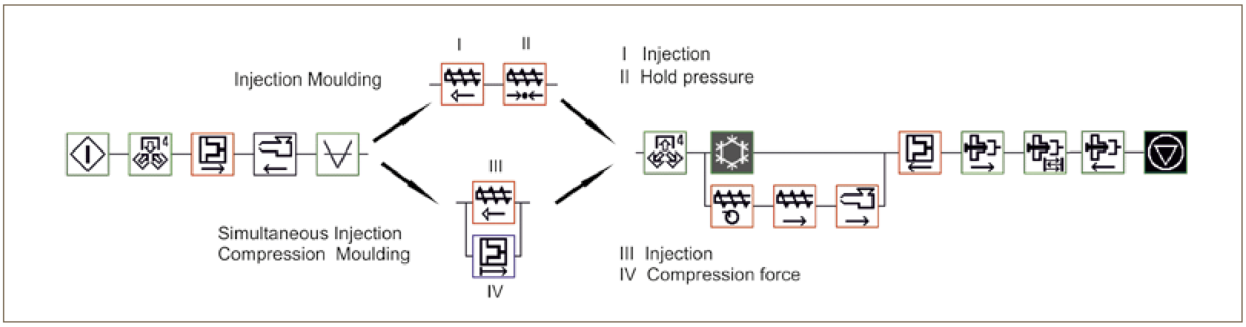

Fig. 1 Process sequences of MicroPIM and simultaneous MicroPICM

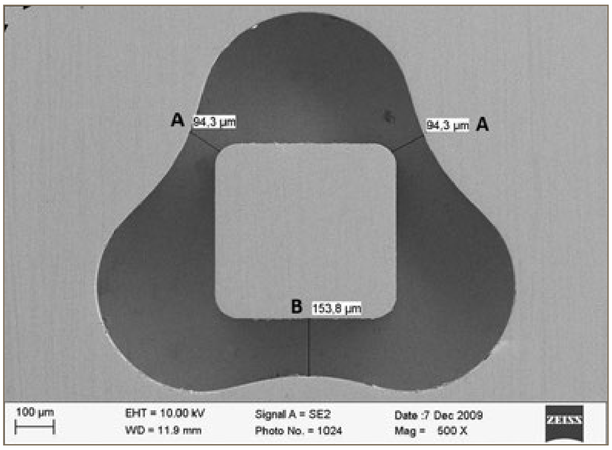

Fig. 2 Investigated micro cavity mould of tool test insert produced by the LIGA-process. The relevant dimension are A (94.3 µm) and B (153.8 µm)

Process parameter	Low level	High level
Compression force [kN]	200	400 / 600
Compression speed [mm/s]	1	3 / 6
Compression starting time [s] after injection of feedstock	0.5	0.7
Holding time [s]	1	2
Other process parameters		
Tool temperature [°C]	75	
Injection speed [mm/s]	95	
Hold pressure [bar] for MicroPIM	750	
Hold time [s] for MicroPIM	2.2	
Cooling time [s]	30	

Table 1 Process parameters used in full two-level four-factorial (2^4) injection compression experiments

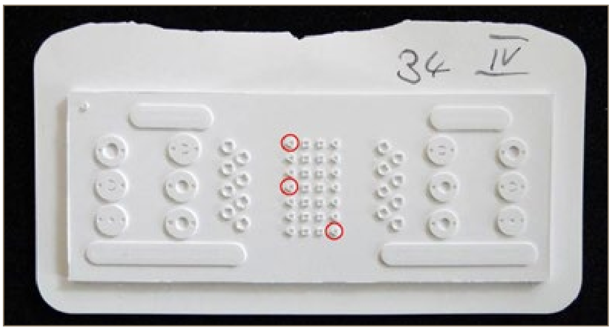

Fig. 3 Appropriate micro structure areas for comparative study

a few advantages of the process. Because of this, the ICM process has an influence on the final moulded parts. The minimisation or elimination of sink marks and warpage is just one aspect [8].

The objective of this paper is to study the effects of process parameters on the quality of the micro part geometry by using the micro ICM process for powder materials. Full factorials Design of Experiments (DoE) allows the complete analysis of the chosen process parameters: compression force, compression speed, compression starting time and holding time of compression force. For the comparative study of MicroPIM and MicroPICM the best parameters of the MicroPICM process were determined and compared with the best process parameter of MicroPIM. The results of the replication by MicroPIM and MicroPICM are discussed.

Experimental

Performing of the micro powder injection moulding (MicroPIM) and micro powder injection compression moulding (MicroPICM)

For the production of MicroPIM and MicroPICM parts the tool and the injection moulding machine have to be suited for both processes. Therefore a commercial injection moulding machine (ARBURG Allrounder 420C) and a tool with shearing edges was used. The machine control of the ARBURG Allrounder 420C allows for free and individual programming of both processes. Process sequences with all process steps for MicroPIM and simultaneous MicroPICM are illustrated in Fig. 1.

The tool used includes a micro-structured insert manufactured by the LIGA-method (German acronym for Lithographie, Galvanoformung, Abformung (lithography, electroplating and moulding)), which ensures that the micro structures have parallel and smooth side walls. The selected and measured structure of the test insert, with relevant dimensions, is illustrated in Fig. 2. The aspect ratios (flow length to wall thickness) are 4.1 and 2.5.

The material used in this investigation is a ceramic feedstock. For the feedstock, an yttrium-stabilised zirconia powder ZrO_2 TZ-3YS-E manufactured by Tosoh Cooperation (Japan) was used. According to the manufacturer, the powder has a specific surface of 6.6 m^2/g and a medium particle size of 0.44 µm. The binder system used consists of polyethylene, paraffin wax and stearic acid as an additive. The solid loading of the powder in the feedstock was 50 vol.% and the feedstock was mixed in a twin-screw extruder. After homogenisation the material was granulated for further processing.

Design of Experiments (DoE) and the investigated process parameters

The best process parameters for the MicroPIM trials were determined from previously undertaken research work and are not part of this paper. To investigate a large variation range of process parameters, and to determine the effect of various process parameters on the replication quality, a full two-level four-factorial (2^4) Design of Experiments (DoE) was designed. The process parameters under consideration were compression force, compression speed, compression starting time and holding time of compression force. The high and low levels of these process parameters are shown in Table 1. Other process parameter settings were held constant throughout the DoE. The compression gap was fixed to 1.1 mm based on the empirical value for the ICM of polymers.

After the 2^4 DoE and characterisation of quality a further investigation with an increased compression force of 600 kN (the maximum compression force of the ARBURG Allrounder 420C at chosen injection speed) and an increased compression speed of 6 mm/s (maximum compression speed of ARBURG Allrounder 420C) were performed and the resulted micro structures were analysed. The new setup was chosen to bring the parameters of the MicroPICM process closer to the MicroPIM process.

Product characterisation: analysis of micro structure

In this study, it has been observed that there are differences in the quality of micro structures, especially in high aspect ratio areas. Focused on this, the first step includes the qualitative analysis of the micro structure at high aspect ratios. Furthermore, the influence of the position of micro structure (near to and far from the gate) is discussed. Previous microscopic analysis and SEM of appropriate micro structures clarified the influence of the process on accurate replication.

For the comparison of the DoE three micro structures, as illustrated in Fig. 3, different positions relative to the gate were qualitatively analysed and compared with each of the 2^4 trials. The resulting qualitative rating by the use of binary evaluation and arithmetic average of each structure in each of the 2^4 trials are summed up and discussed. The micro structures produced by MicroPICM, with optimum process parameters, were compared with MicroPIM micro structures, also processed with optimum parameters.

The influence of the two processing methods was investigated in the green body and also in the sintered state. To reach the sintered state the binder system has to be removed and the micro structured parts have to be sintered to a compact and homogeneous part. The debinding was carried out in two steps: 1) solvent (Hexane) and 2) thermal debinding. The debound ceramic micro-structured parts were sintered with variations of heating rate up to a maximum temperature of 1450°C.

Results and Discussion

The statistical evaluation shows the effects of process parameters for MicroPICM of all DoE experiments which are illustrated in Fig. 4.

It can be seen that the quality of the micro structures advanced significantly with increasing compression force and compression speed. The holding time of the compression force shows just a small influence on the quality. Increasing the starting time of the compression has an undesirable impact on structure quality. The compression force cannot push the feedstock into the micro structured features at later starting of the compression step, because of the freezing of the feedstock, especially near to the gate.

The comparative analysis between MicroPIM and MicroPICM (best parameters) showed just a marginal improvement of replication. A possible explanation could be the large difference between the hold pressure of 750 bar for MicroPIM and 400 bar for MicroPICM. Therefore the significant parameters for MicroPICM were increased: compression force (600 kN) and compression speed (6 mm/s). The resulting parts were analysed and compared with micro structures for MicroPIM, as illustrated in Fig. 5.

The effect of the compression force and compression speed can be mainly recognised on the micro structure near to the gate. The filling of the structure in selected areas is considerably superior with MicroPICM. Observing the micro structure, subject to position to the gate, it could be determined that the replication accuracy of one selected area using MicroPICM showed minor declines with increasing distance from the gate, as illustrated in Fig. 5.

Fig. 6 and Fig. 7 show SEM images of the micro structure close to and far from the gate for the investigated processes. As already commented, a clear improvement in the replication by MicroPICM could be detected near to the gate. The poorer replication of micro structures near to the gate in the MicroPIM process results, on the one hand, from the shadow position to flow direction of feedstock, and on the other hand, because the feedstock cooled down before the hold pressure for the MicroPIM process starts. Furthermore, in the MicroPICM process a wrinkle in the bottom of the structure can be seen near to the gate (Fig. 6 right), also as a result of compression of already cooling feedstock. The SEM images of the micro structure far from the gate (Fig. 7) show no major differences between the investigated processes. However, when considering the total replication quality, the MicroPICM process achieves better accuracy of micro structures, especially at areas with high aspect ratio.

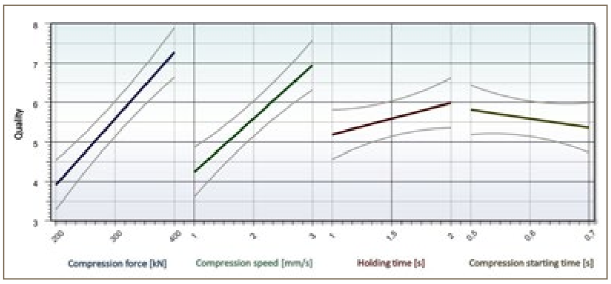

Fig. 4 Effect of different process parameters at MicroPICM on the quality of the micro structure

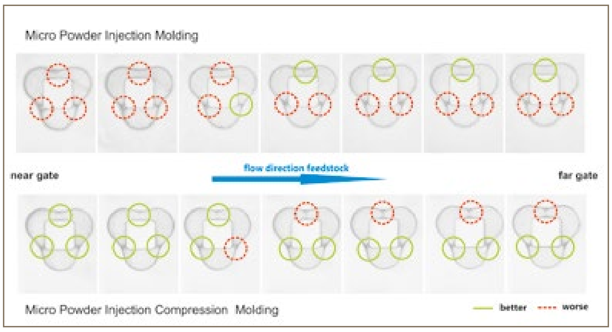

Fig. 5 Microscopic comparison of MicroPIM and MicroPICM structures as a function of position to the gate

To better understand the replication differences between MicroPIM and MicroPICM near to the gate, further investigations after debinding and sintering were performed on these micro structures, and these are compared in Fig. 8.

It was found that the crack in the unfilled area of the injection moulded micro structure (Fig. 6 left) grew during heat treatment (Fig. 8 left). The failure can possibly be explained by the volume contraction of the bulk sections during sintering. As a consequence,

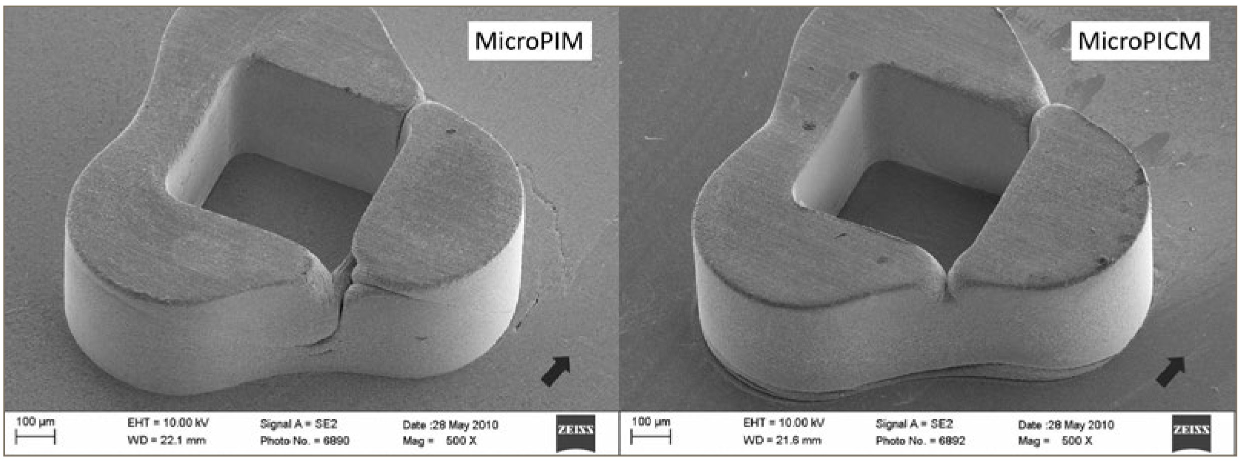

Fig. 6 SEM images of the micro structure of green body near to the gate: MicroPIM process (left) and MicroPICM process (right). The arrow indicates the flow direction of the feedstock

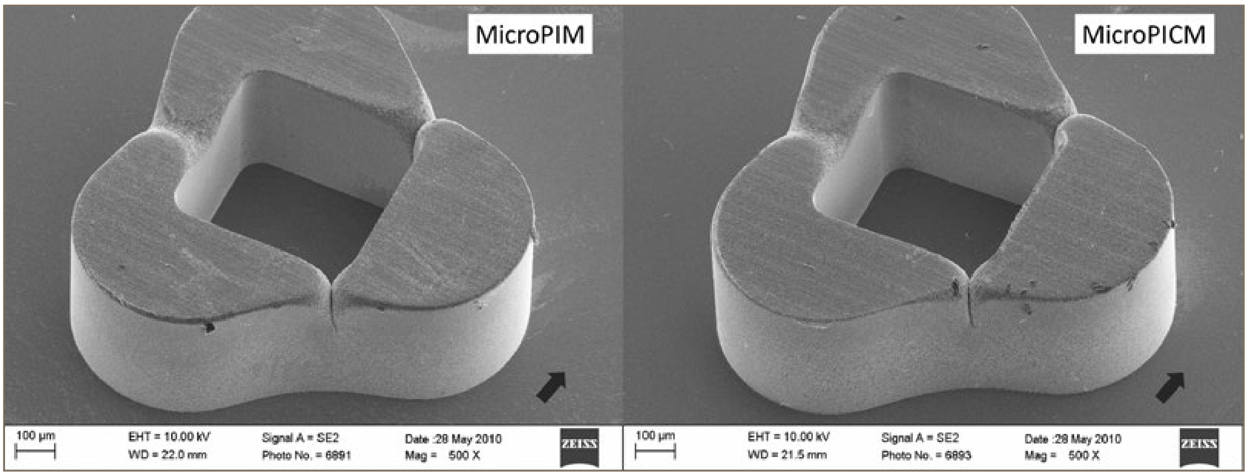

Fig. 7 SEM images of micro structure of green body far from the gate: MicroPIM process (left) and MicroPICM process (right). The arrow indicates the flow direction of the feedstock

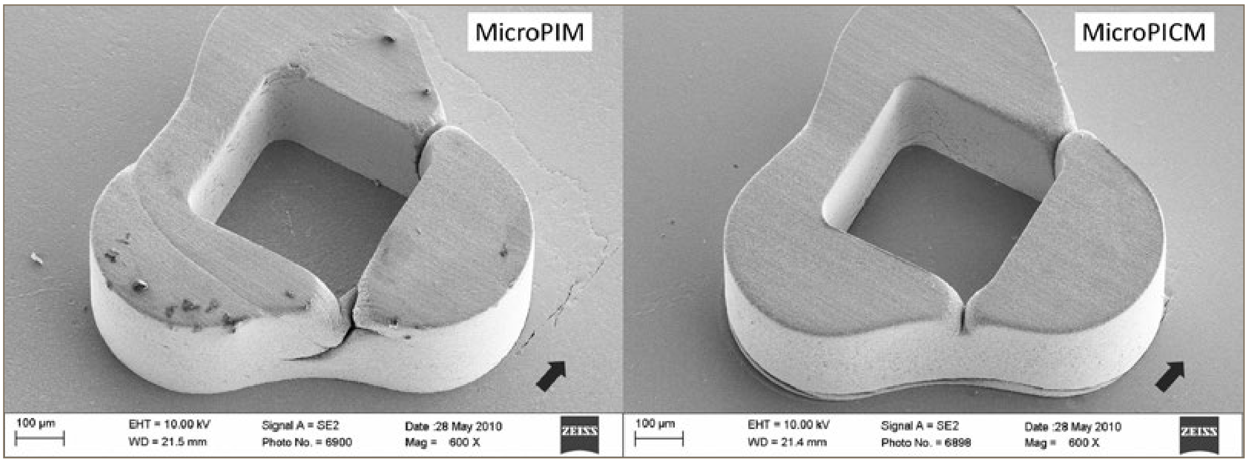

Fig. 8 SEM images of micro structure of sintered part near to the gate: MicroPIM process (left) and MicroPICM process (right). The arrow indicates the flow direction of the former feedstock

the existing crack between these bulk sections will grow during heat treatment. This effect is illustrated in Fig. 8 (left), when compared with Fig. 6 (left). In contrast, in the micro structures without defects produced by MicroPICM no difference between the green body (Fig. 6 right) and the sintered part could be determined (Fig. 8 right).

Summary

The current work shows that compression force and compression speed are the most significant process parameters for the manufacture of micro structures using the simultaneous MicroPICM process. Furthermore, the comparison of replication accuracy between powder injection moulding and simultaneous powder injection compression moulding shows a clear improvement of the micro structure near to the gate. Far from the gate no major differences between the investigated processes could be determined.

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