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FOR THE METAL, CERAMIC AND CARBIDE INJECTION MOULDING INDUSTRIES

POWDER INJECTION MOULDING INTERNATIONAL

in this issue

MIM developments in Asia

AP&C: Titanium powder production

3DEO: Prototyping for MIM

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POWDER INJECTION MOULDING INTERNATIONAL

For the metal, ceramic and carbide injection moulding industries

New applications drive capacity expansion

Within the pages of this issue of *PIM International*, readers will find much to be optimistic about. Investments in production capacity for MIM components are being made worldwide, whilst powder producers expand their operations to keep up with demand from both the MIM and metal Additive Manufacturing industries

Asia is the world's largest region for MIM component production and whilst the industry there has experienced dramatic growth on the back of applications for consumer electronics, many producers are exposed to the fluctuations in demand that are an inherent risk when operating in this sector. As Sandvik Osprey's Paul Davies reveals in his review of MIM in Asia (page 45), there is optimism that MIM smartphone frames will usher in the next growth phase for the technology.

Since the establishment of the Asian Powder Metallurgy Association (APMA) in 2008, the organisation's biennial conference series has steadily grown in importance to become a must-attend event for anyone involved in the Asian PM and PIM sectors. This year we present our first technical review from the series, with Prof Jai-Sung Lee reporting on developments which will strengthen the competitiveness and applications of MIM technology (page 75).

Looking ahead to 2018, the PM World Congress will return to Asia, where the flagship industry event series will be held in China for the first time. Given the size and importance of China's MIM industry and the prestigious event venue located in the Olympic Park complex, World PM2018 will present a unique opportunity to both do business and discover contemporary Beijing.

Nick Williams,
Managing Director & Editor

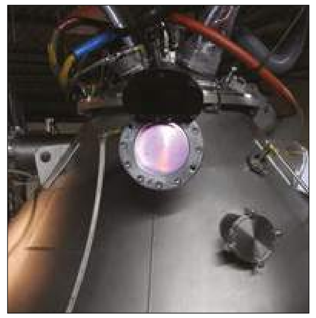
Cover image
Plasma torches during a titanium powder atomisation run at AP&C (Courtesy AP&C)

Powder Injection Moulding International


47


52


60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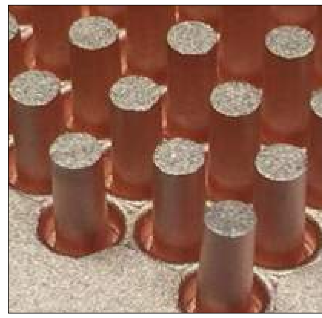

73

In this issue

45 Metal Injection Moulding in Asia: A story of continuing success for the world's largest MIM region

The MIM industry in Asia is the world's largest, whether considered in terms of number of parts produced, sales turnover or production volume. China alone claims to have half of the world's available MIM capacity, with production predominantly focused on 3C applications. In this report, Dr Paul A Davies, Sandvik Osprey Ltd, provides an overview of the evolution of the region's MIM industry from a powder producer's perspective.

57 Ceramic Injection Moulding: Baselworld 2017 sees luxury watch brands launch new offerings

Baselword 2017 was the 100th anniversary of this, the most important marketplace for the global watch and jewellery industries. Over 106,000 visitors came to see the latest collections, including the most recent offerings in watches using CIM cases, bezels and bracelet parts. Bernard Williams reports on some of the launches from leading players.

65 Titanium MIM moves into the mainstream with plasma atomised powders from AP&C

When it was announced earlier this year that Canada's AP&C had received an order for 30 tons of plasma atomised titanium powder for a Metal Injection Moulding application, it became clear that titanium MIM had reached the mainstream. AP&C explains the attraction of MIM for titanium components, outlines the company's plasma atomisation process and presents its growing range of products specifically suited to the MIM process.

73 APMA 2017: MIM strengthens its competitiveness with novel technologies and new applications

Advances in MIM applications, materials and processing featured prominently at APMA 2017, the 4th International Conference on PM in Asia, held in Taiwan, April 9-11 2017. In this report Prof Jai-Sung Lee, Hanyang University ERICA, focuses on developments which will strengthen the competitiveness of MIM and broaden its applications.

83 Prototyping for Metal Injection Moulding: 3DEO's AM solution matches the density and chemistry of MIM parts

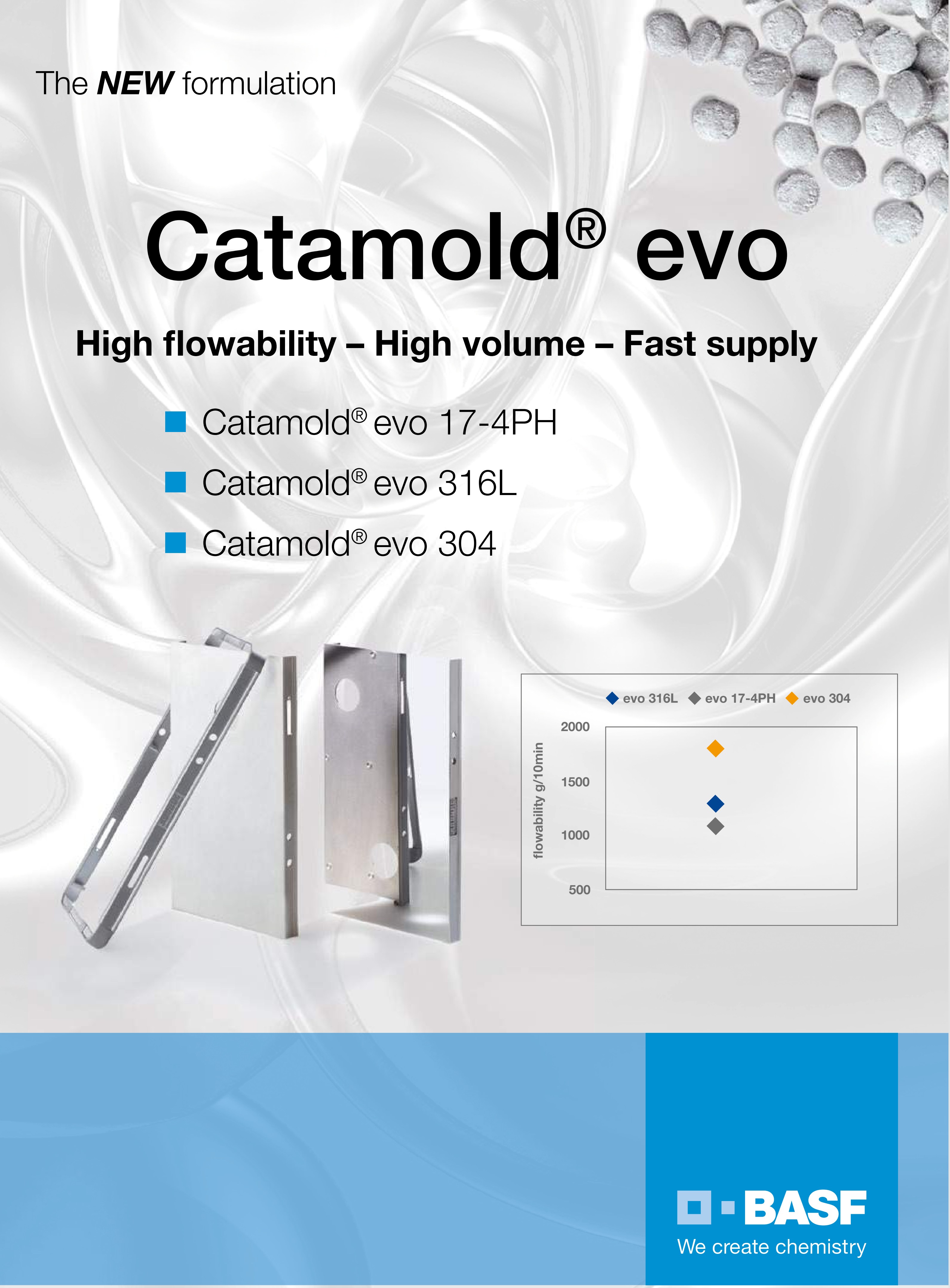
The nature of MIM technology means that creating functional prototypes that match the density and chemistry of the final parts can be both expensive and time consuming. 3DEO's Matt Sand presents a new service that promises to deliver prototype and low to medium volume runs of components that match the performance of MIM parts.

Regular features

5 Industry news

91 Event guide

92 Advertisers' index



Industry News

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

Ford uses MIM valve rockers in its new EcoBoost engine

Ford has announced that its multi-award-winning 1.0 litre EcoBoost petrol engine will feature valve rockers produced by Metal Injection Moulding. MIM valve train components have become an important application area for the technology in the automotive industry, with early manufacturers of MIM rocker arm components including Japan's Nippon Piston Ring Co Ltd and Germany's Schunk Sintermetalltechnik GmbH.

In early 2018, Ford's 1.0 l EcoBoost engine will become the first three-cylinder engine in the world to feature cylinder deactivation. The company stated that the achievements in developing this engine were delivered through innovative engineering by Ford engineers across Europe and defies industry opinion that a three-cylinder, variable capacity engine cannot deliver the refinement needed for passenger car applications.

"Ford has pushed back the boundaries of powertrain engineering once again to further improve the acclaimed 1.0-litre EcoBoost engine and prove that there is still untapped potential for even the best internal combustion engines to deliver better fuel efficiency for customers," said Bob Fascetti, Vice President, Global Powertrain Engineering, Ford Motor Company.

Cylinder deactivation will deliver reduced running costs for 1.0-litre EcoBoost customers by automatically stopping fuel delivery and valve operation for one of the engine's cylinders in conditions where full capacity is not needed, such as when coasting or cruising with light demand on the engine. The cylinder deactivation system developed by Ford engineers in Aachen and Cologne in Germany, Dagenham and Dunton in the UK and Dearborn in the US, in collaboration with Ford's engineering partners at the Schaeffler Group, improves fuel efficiency and CO_2 emissions by reducing friction and pumping demand inside the engine.

Ford's single-cylinder deactivation design reduces complexity to make volume production achievable, but also presented significant challenges in maintaining the 1.0-litre EcoBoost engine's refinement, something achieved through innovations including an offset crankshaft configuration and deliberately 'unbalanced' flywheel and pulley that counteract vibration. A new dual-mass flywheel and a vibration-damping clutch disc help neutralise engine oscillations when running on two cylinders, especially at lower rpm, and enable a wider operating range. Intake and exhaust valves are closed when the system is active, trapping gases to provide a spring effect that helps balance forces across the three cylinders for refinement and also retain temperatures inside the cylinder that maintain fuel efficiency when reactivated.

New engine mounts, drive shafts and suspension bushes have also been specially tuned for refinement. The 1.0-litre EcoBoost features enhanced durability to cope with the different loading forces resulting from cylinder deactivation, including a new camshaft chain and the MIM valve rockers.

www.ford.com

Liquidmetal adds MIM production line to its amorphous metal expertise

The location of Liquidmetal's new MIM facility in Lake Forest, California, USA

Liquidmetal® Technologies, Inc. has added Metal Injection Moulding capability as part of its expansion into a new 3,800 m^2 (41,000 ft^2) manufacturing centre in Lake Forest, California, USA. As well as being equipped with a state-of-the-art MIM line, the new facility offers globally unmatched amorphous metal forming capabilities and equipment.

Paul Hauck, one of Liquidmetal's manufacturing experts and Executive Vice President of Sales and Marketing, told *PIM International*, "We are excited to be able to offer customers both MIM and amorphous metal technologies, ensuring the right process is applied to the right application. Liquidmetal is also working with EONTEC to establish China sourced tooling through EONTEC's in-house mould making operation for both metal moulding technologies. The outcome is intended to provide customers with globally competitive mould costs." Hauck added that, "the decision to go into MIM was an easy one for the company. EONTEC is an established MIM supplier in China and our US engineering and sales staff includes MIM industry veterans."

With the addition of MIM, Liquidmetal will now be able offer two metal forming technologies from two continents. Working from a clean slate also allowed the company to match its MIM process technology to the needs of the marketplace. Arburg injection moulding machines and automation matched with large scale Elnik debinding and sintering furnaces are used in the company's first MIM manufacturing line. Liquidmetal plans to use BASF feedstock, but its technology partner EONTEC also has in-house custom compounding capabilities.

The company will offer customers both US and China sourced amorphous metal and MIM production. To simplify the offshoring interests of US customers, Liquidmetal will manage all purchase order transactions and scheduling, including inventory management services with warehousing capacity, through its Lake Forest location.

The new facility is a short drive from the current Liquidmetal manufacturing centre. The company stated that ample floor space is now available for expansion in all primary manufacturing operations; MIM, ENGEL cold-crucible amorphous metal production and EONTEC hot-crucible amorphous metal production. Secondary operations will also grow, providing customers with a greater range of finished-part options; these operations include CNC machining, waterjet cutting, bead blasting, vibratory deburring, heat oxidising, passivation and PVD.

Currently, Liquidmetal has two operational ENGEL amorphous alloy moulding machines. Two EONTEC amorphous alloy moulding machines have just recently been delivered to the new Lake Forest facility. Along with the introduction of complementary EONTEC machine technology, the company has successfully completed several biocompatibility tests including an implant study of LM105 alloy and is introducing new low-cost amorphous alloys developed in cooperation with EONTEC.

"Our engineering and operations teams are working aggressively to qualify lower-cost amorphous alloys, implement new production processes and prepare our new building for move-in this summer. This investment provides us the increased capacity we need to serve customer opportunities and space to grow our business substantially over the next three to five years," stated Bruce Bromage, Executive Vice President of Engineering & Operations.

In 2016, Liquidmetal signed a cross-licence agreement with EONTEC, a publicly-traded global manufacturer located in China. The agreement has made the two businesses the recognised global leaders in amorphous metals with over 160 combined patents and patents pending. In addition, a stock purchase by the now CEO and Chairman of The Board, Professor Lugee Li, generated $63.4 million for the company. The investment has put the business in a position to grow with customer demand and make other important investments into its future.

The company recently released an updated design guide, version 4.2, covering cold and hot-crucible amorphous metal processing, an expanded alloy offering and new design characteristics. Liquidmetal is also in the process of finalising a new website that will help communicate useful information to engineering and procurement professionals on amorphous metals and Metal Injection Moulding. Liquidmetal plans to host an open house following its move into the new facility.

www.liquidmetal.com

Japan's Iwaki Diecast expands MIM capacity with new factory

Iwaki Diecast's new MIM facility in Miyagi prefecture, northern Japan

A continuous MIM sintering furnace at Iwaki Diecast

Atsushi Kamata, President of Iwaki Diecast Co., Ltd. (right) and Junichi Takahashi, Plant Manager (left)

Japan's Iwaki Diecast Co., Ltd. has officially opened a new state of the art Metal Injection Moulding facility in Miyagi prefecture, part of the Tohoku district of Northern Japan. The new 5,700 m^2 factory is located on a 520,000 m^2 site and employs 80 people. It is expected that around two million MIM parts will be shipped every month.

Iwaki Diecast was founded in 1968 by Yoshio Saito, now its Chairman, as an aluminium, zinc and magnesium die-casting manufacturer and in 2018 will celebrate its 50th anniversary. It is today a major supplier of investment castings to Japan's automotive industry. The company launched its MIM business in 1986 and as early as 1990 it began producing MIM parts in continuous sintering furnaces, an innovative development at a time when batch furnaces dominated the industry.

Iwaki Diecast's plant currently operates three continuous MIM sintering furnaces, however this number is planned to increase as demand for components rises. In addition to serving well-established markets such as automotive, orthodontic and industrial equipment/robotics, the company plans to use its expertise in MIM technology to expand into the medical device market.

The company's Metal Injection Moulding business was badly affected by the earthquake and tsunami of March 11, 2011, which caused devastation to the region. Fortunately, no employees were injured and the MIM operation had partly reopened by May 2011. The rapid reopening of the facility was regarded as critical given the importance of its products to major national industries and the revival of the company was seen as a symbol of the revival of the Tohoku area, receiving nationwide media coverage. The MIM division's new factory is built on land that wasn't affected by the 2011 tsunami.

One of the reported characteristics of the Iwaki Diecast's MIM operation is that it can debind and sinter MIM parts of different steel types and shapes at the same time in its continuous sintering furnace. This technological development has improved operational efficiency and allows the factory to overcome some of the inherent disadvantages of continuous sintering furnaces with regards to multiple materials and component types.

www.iwakidc.co.jp

Precious metal powder producers at Baselworld 2017

Two of Europe's leading producers of precious metal and alloy powders exhibited their range of products at Baselworld 2017, the leading global market place for the watch and jewellery industries held in Basel, Switzerland, March 23-30.

Hilderbrand & Cie, based in Thonex (Geneva), Switzerland, uses state of the art atomisation technology and classification and analytical equipment to produce pure and alloy forms of precious metal powders based on gold, platinum, palladium and silver for use in the jewellery and watchmaking industries. The company states that its powders are tailored to today's market demands for innovative manufacturing processes such as Metal Injection Moulding, metal Additive Manufacturing and powder spraying. The company has also been producing precious and non-precious metal brazing pastes for the jewellery and watch sectors since 1972 and offers a complete range of pastes which, it states, not only offers users substantial economies of materials, time and inventories, but also a significant improvement in the quality and appearance of their finished products. The company has been part of C.Hafner of Winsheim, Germany, since 2013, a family owned company focusing on high-tech products and solutions in the precious metals industry.

Cooksongold, based in Birmingham, United Kingdom, is part of the Heimerle + Meule Group, one of Europe's largest refiners and processors of precious metals. The company exhibited its range of Advanced Metal Powders produced by gas atomisation, which included 18 k 3N yellow gold, 18 k white gold, 18 k 5N red gold, Brilliante 925 silver, and an addition to its existing portfolio of a new platinum alloy powder designated 950 Pt/Ru, first launched in collaboration with the Platinum Guild International (PGI) in 2016.

The Advanced Metal Powder range from Cooksongold is said to be ideal for a number of processes, including Metal Injection Moulding. Whilst there appears to be growing interest in MIM for the production of jewellery, the company stated that its new 950 Pt/Ru alloy powder has been specifically developed for Additive Manufacturing. This ensures that, once the designs have been built in the Precious M 080 AM machine developed for this application by EOS, Germany, they can be post-processed, milled and polished to the high standards required without any of the common problems associated with other Pt alloys.

www.hilderbrand.ch

www.cooksongold-emanufacturing.com

Major expansion in gas atomised powder production at Sandvik Osprey

Sandvik Osprey has signaled a major expansion of gas atomised powder production capacity with the commissioning of a new atomising facility in Neath, UK. According to the company, the expansion is prompted by strong demand for its premium metal powders from the well-established Metal Injection Moulding and rapidly growing metal Additive Manufacturing industries. News of this latest expansion follows a considerable capacity expansion in late 2012.

Sandvik Osprey has been atomising metals for more than forty years and has twenty-five years' experience producing fine gas atomised powders, typically of less than 30 microns, for the global MIM industry. Over that time, it has invested continually in new capacity and has extended its range of powders to cover many thousands of alloys, including a comprehensive selection of pre-alloyed stainless steels, master alloys, low-alloy steels, tool steels, nickel-based super alloys, cobalt alloys, copper alloys and specialist alloys, including soft magnetic alloys and controlled expansion alloys.

The company states that its extensive powder offering serves diverse market sectors including consumer, hand tools and medical devices, aerospace components and automotive turbochargers; fast growing sectors whose demand for high quantities of metal powder necessitate Sandvik's continued growth. Expansion at the company's Red Jacket Works, Neath, will include a new fine powder atomiser - providing a substantial increase in production capacity and a commensurate increase in powder processing capability - with additional sieving and air classification equipment, as well as new blending facilities offering homogeneous batch sizes of up to 6000 kg.

Sandvik Osprey's powder production equipment has been designed using the latest atomisation modelling and simulation techniques to produce powders which are also optimised for metal Additive Manufacturing. Here the company is focused on key markets including maraging tool steel for conformal mould cooling, stainless and low-alloy steels for structural parts and nickel-based alloys for high temperature applications. Aluminium alloys are a new addition to Sandvik's portfolio, aimed at satisfying the specific demands of the Additive Manufacturing market.

Recent growth in dental market applications, including custom-fit crowns and bridges, has also prompted investment in a purpose-built facility for cobalt powder processing equipped with sieving, air classification blending and automated packing facilities. New rounds of expansion are planned over the coming years to further increase capacity and capability.

www.smt.sandvik.com/metal-powder

PM database updated to include microstructures

The Global PM Database (GPMD) has been enhanced to include examples of PM microstructures to assist PM parts manufacturers and end-users during the interpretation of PM microstructures. The new inclusion aims to help to build an appreciation of metallography as a powerful engineering tool for component design and quality control solutions.

The updated database will now allow the user to reference the microstructural phases in materials processed by conventional sintering, elevated temperature sintering, accelerated post-sintering cooling and more. The update also offers users guidance on specimen preparation and proper etchant selection.

www.pmdatabase.com

Moldex3D R15: Groundbreaking moulding simulation presented at Stuttgart's Moulding Expo

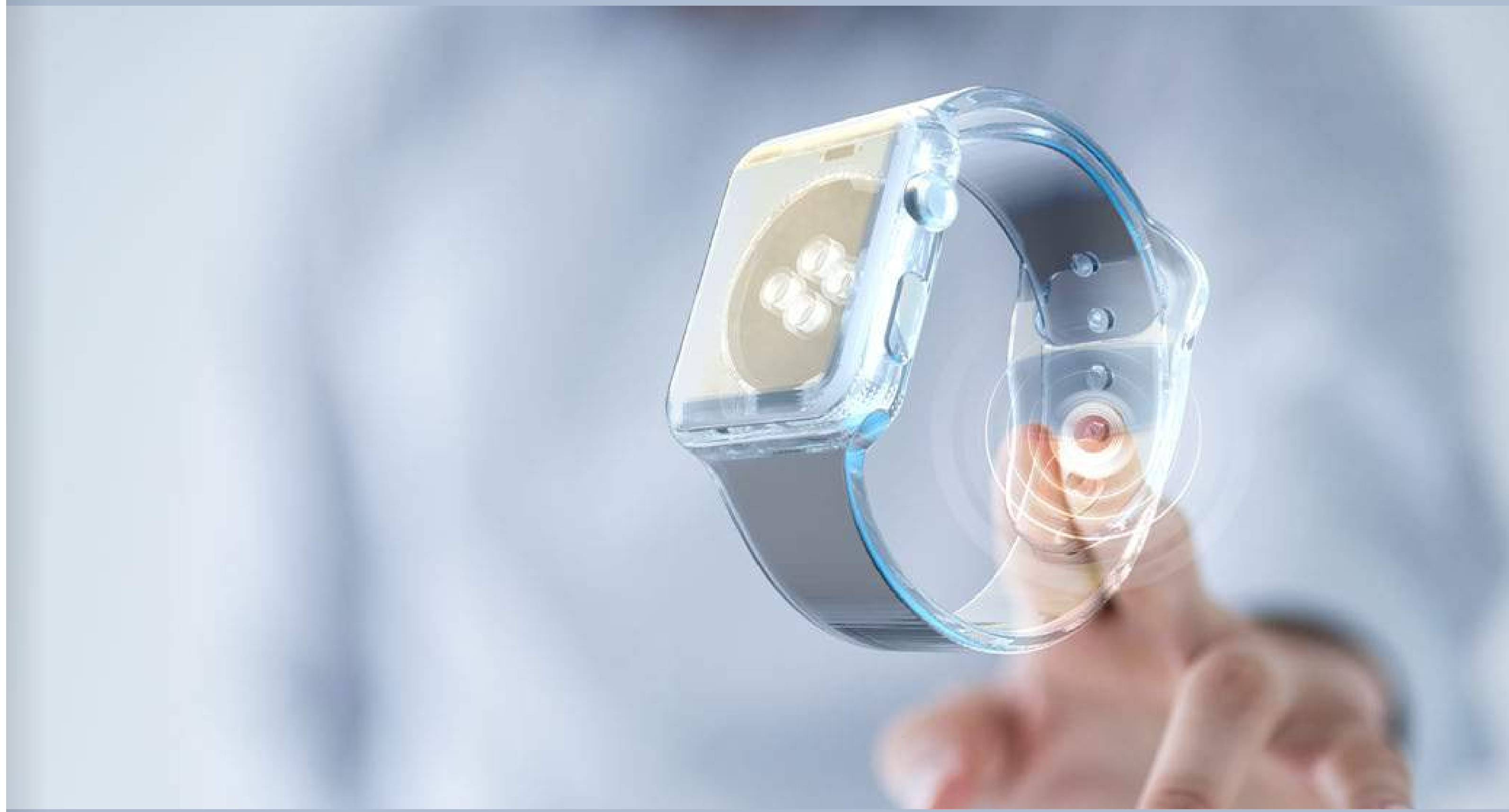
SimpaTec GmbH, based in Aachen, Germany, presented the latest innovations featured in Moldex3D R15 at the Moulding Expo in Stuttgart, Germany, May 30 to June 2. The focus of the company's participation was SimpaTec's comprehensive range of services for product and process optimisation for injection moulded components through advanced software technologies. Moldex3D, developed by Taiwan's CoreTech Systems, is a dedicated software package designed to assist part designers and mould makers in developing and producing higher quality products in form, fit and function at lower costs and reduced times-to-market.

The company stated that updates in a recent release of Moldex3D were welcomed by users thanks to its numerous developments, but added that far more ground-breaking enhancements had now been incorporated in Moldex3D R15 to dramatically improve the speed, robustness and reliability of simulation and thus allow enterprises to get the most out of virtual simulation for injection moulding, creating core competiveness and adding a substantial amount of value to their products.

One ground-breaking development is a new Moldex3D platform called Studio, with the company stating that the necessity of using two applications to perform a simulation is now a feature of the past. Simulations and pre-post operations can now be completed in one application and a ribbon-style user interface, combined with high-performance rendering, promises smooth and fast operations. File sizes have all been reduced and multi-run comparisons are now supported, as well as hot-key operations.

SimpaTec added that the new version of Moldex3D R15 takes the Boundary Layer Mesh (BLM) generator to a completely new level. BLM 3.0 not only allows the use of fewer meshing elements, which dramatically reduces the meshing time whilst maintaining the maximum wall thickness resolution, but also enables new possibilities in terms of advanced meshing and flexibility. Furthermore, the company explained that the capabilities and options of non-meshing technology have been extended, optimised and intensively modified. More components such as cooling channels, heating rods, mould inserts and mould base are supported. This makes the solid mould base mesh preparation job easier and cuts down meshing hours significantly and temperature results show a smooth outcome.

www.simpatec.com



XJet presents ceramic Additive Manufacturing capabilities at Ceramics Expo 2017

XJet Ltd., Rehovot, Israel, presented its new ceramic inkjet Additive Manufacturing capabilities at Ceramics Expo 2017 in Cleveland, Ohio, USA, April 25-27, 2017. During the three-day event, the company shared details about its ceramic AM printing capabilities and displayed a number of sample ceramic AM parts. Dror Danai, XJet CBO, also took part in a special panel on the challenges of ceramic Additive Manufacturing.

"After many years of research and development, we are excited to have reached this important milestone of producing ceramic parts using our NanoParticle JettingTM technology," stated Hanan Gothait, CEO and Founder of XJet. "NPJ is a truly disruptive technology as it offers a totally new level of ceramic and metal 3D printing."

According to XJet, NanoParticle Jetting™ works by producing an ultra-thin layer of droplets containing ceramic nanoparticles which are deposited onto the system build tray, enabling the production of ceramic parts using a method similar to inkjet printing. The liquid dispersions are delivered as sealed cartridges and can be loaded easily into the XJet system, where high temperatures cause the liquid 'jacket' around the ceramic nano-particles to evaporate, allowing them to be deposited on the build plate.

XJet reports that parts produced using the system exhibit the same mechanical properties as parts made in more traditional ways, with size and shape of particles randomly distributed to allow "natural" packing. In addition, XJet's system prints soluble support material, which is expected to facilitate simple and clean support removal.

XJet Ltd. was founded in 2005 and employs 60 multidisciplinary R&D specialists. To date, the company has filed over 60 registered and pending patents.

www.xjet3d.com

The XJet Additive Manufacturing system (Courtesy XJet)

Straumann and Maxon Motor to produce CIM dental implant components

Swiss dental implant specialist Straumann has entered a partnership with Germany's Maxon Motor to develop components for dental implant systems produced by Ceramic Injection Moulding (CIM) instead of conventional manufacturing techniques.

The partnership includes a joint venture company, Maxon Dental GmbH, based near Freiburg, Germany, which will develop and produce CIM components for Straumann. Under the terms of the agreement, Straumann will obtain a 49% stake in Maxon Dental GmbH, subject to approval by the German Federal Cartel Office, and has the option to increase its equity stake to full ownership in 2026. Financial terms were not disclosed.

Maxon Motor has twenty years' experience in CIM for mechanical precision parts. During the past ten years, the company has broadened the application of its CIM technology to include dental implants and owns various patent applications and patents. The partnership provides Straumann with access to this technology and Maxon's corresponding expertise.

Marco Gadola, CEO of Straumann, commented, "There are few – if any – technology providers in the world that can equal Maxon Motor with regard to innovation, expertise and reliability in CIM. Combining our strengths in dentistry with their technology leadership, the initial goal of our joint venture is to make ceramic implant treatments easier for dentists and more affordable for patients who want highly aesthetic, metal-free solutions. We expect to launch our first CIM components in the near term – providing that the outcome of laboratory and clinical programs and regulatory applications is favourable".

www.maxonmotor.com
www.straumann.com

Maxon Motor has twenty years' experience in CIM for mechanical precision parts (Courtesy Maxon Motor)

CeramTec announces acquisition of UK Electro-Ceramics

CeramTec is headquartered in Plochingen, Germany

German-based manufacturer CeramTec has announced its acquisition of specialist electro-ceramics manufacturer UK Electro-Ceramics. The £47 million cash deal was expected to complete in April 2017 and sees UK Electro-Ceramics change hands from Morgan Advanced Materials PLC, a global materials technology company, to CeramTec, which specialises in advanced ceramic products.

In the year ended December 31 2016, UK Electro-Ceramics reported revenues of £22.7 million and employed 251 at its Ruabon and Southampton sites. The business produces a range of piezo and dielectric ceramic products, used in a wide range of industrial, electronic, medical and defence applications. Components produced by UK Electro-Ceramics are designed for the most technically challenging applications and include the widest range of products available for polycrystalline piezo and dielectric applications across core target markets.

Headquartered in Plochingen, Germany, CeramTec is a large international manufacturer which aims to supply its customers with premium ceramic products from sites across the globe. With a customer base in medical engineering, automotive manufacturing, electronics, equipment and mechanical engineering, as well as defence systems, energy and environmental technologies, the ceramics manufacturing company employs around 3,200 employees worldwide and reported revenues of approximately £435 million in 2015.

"This transaction opens the door to many new opportunities and possibilities for CeramTec: new markets, new application areas and new developments," stated Henri Steinmetz, Chief Executive Officer of CeramTec. "We are excited by the prospect of bringing together our significant expertise and knowledge in piezo and dielectric ceramics, which complement each other perfectly."

Pete Raby, Chief Executive Officer of Morgan, commented, "UK Electro-Ceramics is a specialist business with excellent customer relationships. This transaction will build its scale and combine its expertise with that of CeramTec, creating a stronger and more resilient platform for the future."

www.ceramtec.com

GKN anticipates continued growth for 2017

GKN plc has reported that the global engineering group achieved good overall organic sales growth in the first quarter 2017 (January – April), with the automotive market performing better than expected, as well as continuing to benefit from currency translation. Growth in aerospace has, however, been slightly slower than planned, the company stated. "GKN delivered a good performance in the first quarter. The encouraging growth rate achieved to date may not be sustained as the year progresses and comparators get tougher, nevertheless, we expect 2017 to be another year of growth," stated Nigel Stein, GKN's Chief Executive.

The company stated that its trading margin has moved ahead of the previous year's, although GKN Driveline and GKN Aerospace have seen some impact from the increased cost of raw materials. GKN Aerospace is tracking in-line with the company's plans, with an operating cash-flow similar to the equivalent period in 2016.

GKN Powder Metallurgy has seen organic sales growth in line with global auto production rates and has also benefited from currency translation. Its growth includes the direct pass through of higher raw material prices, which have also reduced margins slightly.

www.gkn.com

MPIF launches new Powder Metallurgy video series

The Metal Powder Industries Federation (MPIF) has announced the launch of a new series of educational videos focused on Powder Metallurgy. The four-part series, based on the popular PickPM Day Seminars will be presented and distributed during POWDERMET2017, Las Vegas, Nevada, USA.

The first video in the series, "Introducing Powder Metallurgy and the PM Industry", is available to watch now. Hosted by John Engquist, FAPMI, former President of the Centre for Powder Metallurgy Technology (CPMT), this introductory video covers a brief history of PM, followed by a discussion on market segments, common PM applications, the technical advantages of using PM and a brief overview of PM processes.

Future videos in the series will cover conventional press-and-sinter PM, Metal Injection Moulding, and metal Additive Manufacturing, with an isostatic pressing video also in early development, stated the MPIF.

www.MPIF.org
www.youtube.com/watch?v=iVe1fa5z45o

Over 6,700 guests attend Arburg's Technology Days 2017

Over 6,700 guests from more than fifty different countries attended Arburg GmbH & Co. KG's Technology Days 2017, the company reports. The event was held from March 15-18, 2017 at Arburg's Headquarters in Lossburg, Germany, and included over fifty technology exhibits as well as specialist presentations and factory tours. Arburg is the market leading supplier of injection moulding equipment to the Powder Injection Moulding industry.

A highlight in the Powder Injection Moulding area was the world's first frame for smartphones produced by Metal Injection Moulding. A hydraulic Allrounder 470 C Golden Edition processed feedstock from BASF to produce a green compact to an Arburg design, with a thickness of only 1 mm and a length of 136 mm.

Michael Hehl, Managing Partner and Spokesperson for the Arburg Management Team, stated, "For our annual Technology Days, we do everything we can to ensure that our invited guests get a comprehensive insight into the Arburg product range. Our customers really appreciated the unique atmosphere, made great use of the opportunity to talk with our experts and, at the end of the day, took away some key ideas for their own production".

Over 2,000 participants attended specialist presentations in German and English. Here, some of Arburg's experts spoke about lightweight construction, Arburg Plastic Freeforming and turnkey solutions. External specialist presentations covered topics such as Industry 4.0 and the partnership offered by Arburg from the customer's perspective. Almost 1,500 visitors from Germany attended factory tours.

Arburg reported that 43% of visitors travelled to the event from abroad, with 170 attendees travelling from North America and 125 from China. From within Europe, 210 attendees travelled from Switzerland, 180 from the Czech Republic and 160 from France.

www.arburg.com

Arburg's Technical Days included more than 50 technology exhibits (Courtesy Arburg GmbH & Co. KG)

CMG reports success in reshoring MIM production from Asia

UK MIM specialist CMG Technologies is celebrating re-establishing a successful partnership with a major industrial product manufacturer. CMG stated that through the reshoring of the production of a series of complex MIM components, its customer has achieved significant cost savings whilst boosting the UK economy.

CMG's customer first moved its manufacturing plant to China four years ago but reportedly it found that, after taking into account the costs of shipping, duties and quality issues, little money was being saved in the long-term.

CMG's Managing Director, Rachel Garrett, stated, "Most UK-based manufacturers are familiar with outsourcing the production of some of their more complex components to MIM companies based overseas, thanks to the cost efficiencies that can be achieved. However, many remain unaware that this service can in fact be accessed in the UK for around the same, if not lower, costs - with the added bonus of a much higher production standard and finished result."

Garrett added, "Working with UK suppliers also means communication can be far easier, lead times can be shortened and the reduction in shipping, as well as the MIM process itself which is a recognised green technology, means the carbon footprint from the production process can be substantially reduced. Add all of this to the fact that manufacturing is one of the main contributors to the UK's economy by creating and safeguarding jobs and it's easy to see why reshoring offers such huge potential and why we continue to grow."

CMG Technologies is the UK's largest MIM specialist, with more than twenty-five years of experience in MIM manufacturing. The company believes that its strategy of keeping the whole of the process in-house means it can tightly control all aspects of production, consistently ensuring that the highest levels of quality are maintained. CMG strongly promotes the environmental and economic benefits of MIM, stating that the process offers significantly lower scrappage volumes than traditional machining methods.

www.cmgtechnologies.co.uk

CMG manufactures MIM components for a range of industries including the medical sector

eMBe introduces new binder for catalytic debinding feedstocks

Powder Injection Moulding binder and feedstock specialist eMBe Products & Service GmbH, Thierhaupten, Germany, has introduced a new binder for the production of catalytically debindable feedstocks. The new binder, set to be released under the brand name Embemould CAT, will initially be made available in limited test quantities from July 2017.

Embemould CAT will allow companies to produce custom feedstocks in-house. The binder is suitable for both ceramic and metal powders and the company stated that it has already begun using Embemould CAT for the production of its own feedstocks.

Michael Bayer, Managing Director of eMBe Products & Service GmbH, told *PIM International*, "Embemould CAT completes our Powder Injection Moulding range. The series of products includes Embemould K 83 and Embemould C for thermal debinding and water debinding processes."

www.embe-products.com ■

Cortec releases new EcoAir® mould release

Cortec, St Paul, Minnesota, USA, has released its new EcoAir® Mould Release, a dual-function mould lubricant which includes a bio-based corrosion inhibitor. When sprayed onto a mould, the company reports, the new lubricant will form a thin silicone coating, making it easier to release the finished product after moulding.

The new lubricant aims to prevent some of the defects and delays which can be caused by forced demoulding and to prevent corrosion to moulds by forming a bio-based molecular passivating layer to protect the mould surface.

www.cortecvci.com ■

Innovnano's 2YSZ ceramic powder offers alternative to 3YSZ for structural ceramic applications

Innovnano, Coimbra, Portugal, has developed a ready-to-press 2mol% yttria-stabilised zirconia (2YSZ) with an outstanding fracture toughness. According to the company, Innovnano's 2YSZ offers all the desired mechanical performance of 3YSZ, the current industry-standard powder of choice, combined with the highly desirable added benefit of high fracture toughness. Despite having a lower percentage of the stabilising yttria, Innovnano's 2YSZ has the added benefit of ageing and stability comparable to that of 3YSZ. Innovnano's 2YSZ, therefore, provides an excellent alternative to 3YSZ for physically demanding structural ceramic applications.

Recent testing by Innovnano and an independent laboratory has shown that the mechanical strength of 2YSZ remains above 1,000 MPa, while fracture toughness is significantly increased up to 14 MPa. $m^{0.5}$. 2YSZ bars that had undergone Cold Isostatic Pressing (CIP) and conventional sintering were subjected to cyclic stress-strain ageing tests in saline solution, with all test pieces passing the ISO 13356 standard methodology of 1 million cycles at 320 MPa (maximum) and 20 Hz frequency without failure. The four-point bending strength was also determined for 2YSZ bars before and after the cyclic stress-strain experiment. After 10^6 cycles, the test showed only a 13% loss in flexural strength. Further cyclic stress-strain ageing experiments were also successfully performed (10^6 cycles at 20 Hz) using 1100 MPa as maximum pressure, highlighting the outstanding resistance of these 2YSZ powders to mechanical ageing.

The unique properties of Innovnano's 2YSZ, combining enhanced fracture toughness with high levels of stability and ageing resistance, are attributed to the powder's nanostructure, formed during Innovnano's unique industrial synthesis process. All of the zirconia ceramics in the company's range are manufactured using Innovnano's proprietary Emulsion Detonation Synthesis (EDS) method. EDS involves a unique cycle of high temperatures, pressures and rapid quenching in a fully automated system, based on the detonation of two water-in-oil emulsions in a single step reaction. This produces nanostructured powders with guaranteed small grain sizes and high chemical homogeneity. In the case of 2YSZ, its nanostructure, as well as the EDS process itself, contributes to the increased powder stability.

2YSZ is the latest product to be added to Innovnano's growing product portfolio. The desirable properties of 2YSZ mean that it is appropriate for hard-wearing applications, especially those that require a material with high fracture toughness. It is available from Innovnano as a ready-to-press powder for CIP and uniaxial pressing. It can also be incorporated as the zirconia phase of zirconia-toughened alumina/alumina-toughened zirconia (ZTA/ATZ), as well as other cermets.

Paul Newbatt, Sales & Marketing Director at Innovnano, commented, "Taking advantage of the energetic nature of our unique manufacturing process, we have developed a nanostructured 2YSZ powder that offers a high fracture toughness alternative to conventional micron-sized 3YSZ engineered ceramics. It provides the fracture toughness of a low-yttria containing YSZ with the stability of a higher yttria-containing YSZ, striking the balance between two key structural ceramics needs. We believe a powder with this unique combination of properties to be an exciting new development for the ceramics market."

Innovnano told *PIM International* that further development of the new powder is underway to ensure its suitability for Ceramic Injection Moulding, with a CIM powder planned for later in the year (Q2 2017).

www.innovnano-materials.com ■

MPIF announces 2017 Distinguished Service to PM Award recipients

The Metal Powder Industries Federation's (MPIF) Awards Committee has announced the recipients of the 2017 MPIF Distinguished Service to Powder Metallurgy (PM) Award. The award recognises individuals who have actively served the North American PM industry for at least 25 years and is judged by a panel of industry peers.

The 2017 award recipients are as follows:

- Iver Anderson, FAPMI, Ames Laboratory
- Diran Apelian, FAPMI, Worcester Polytechnic Institute
- Sherri R. Bingert, Los Alamos National Laboratory (retired)
- Matthew Bulger, NetShape Technologies, Inc.
- Dean Howard, PMT, North American Höganäs, Inc.
- Mark D. Kesterholt, Rio Tinto Metal Powders (retired)
- Sydney H. Luk, Royal Metal Powders Inc.
- Glen Moore, Burgess-Norton Mfg. Co. (retired)
- Thomas J. Pontzer, Gasbarre Products, Inc. (retired)
- JoAnne Ryan, Alpha Sintered Metals, Inc.
- Rohith Shivanath, Stackpole International Canada
- John Sweet, FMS Corporation

All awards will be presented at a special awards ceremony to take place at the PM Industry Luncheon, June 14, 2017, at the POWDERMET2017 conference, Las Vegas, Nevada, USA. Those wishing to attend the awards ceremony can find further information via the POWDERMET2017 website.

www.powdermet2017.org
www.mpif.org

MIM2018 returns to California, issues Call for Papers

The Metal Powder Industries Federation's (MPIF) Metal Injection Molding Association (MIMA) has issued a Call for Papers for the MIM2018 International Conference on the Injection Molding of Metals, Ceramics and Carbides. The event once again returns to Irvine, California, USA, and takes place from March 5–7, 2018. The deadline for the submission of abstracts is September 29, 2017.

The conference is targeted at product designers, engineers, consumers, manufacturers, researchers, educators and students. All individuals with an interest in this fascinating technology and application of its parts are encouraged to attend. Nearly 160 participants attended the MIM2017 conference, held in Orlando, Florida, from February 27 to March 1.

www.mim2018.org

Profits up at Japanese MIM producer Nippon Piston Ring Co Ltd

Nippon Piston Ring Co Ltd. (NPR), based in Saitama, Japan, manufactures a wide range of Powder Metallurgy products that include piston rings and valve seats used in internal combustion engines, metal injection moulded parts and dental implants. The latter are now produced in a new facility in Tochigi Prefecture, established in 2015.

The company reported sales of Yen 52.121 billion ($469 million) for the fiscal year to March 31, 2017 – a drop of just 0.2% on the previous year. Net profit was up 18.7% to Yen 2.899 billion ($26 million). NPR has manufacturing facilities in Japan, China, Indonesia, India and the USA.

www.npr.co.jp

Kobe Steel acquires HIP equipment specialist Quintus Technologies

Kobe Steel, Ltd., Tokyo, Japan, has announced its acquisition of Swedish-based Quintus Technologies AB from private shareholders led by US private equity firm Milestone Partners on April 5, 2017. The total purchase price was reported at $115 million. Quintus is now a wholly owned subsidiary of Kobe Steel.

Quintus manufactures a range of hot and cold isostatic presses (HIP/CIP) and has achieved a strong presence in Europe, the USA and China. Its isostatic presses are used in the manufacture of high-performance products, particularly in the aerospace sector where they are used for aircraft parts, power generation turbine blades and semiconductor materials.

Under its medium-term management plan, Kobe Steel's Machinery Business aims to increase the profitability of its Industrial Machinery Division, including the IP business. According to the company, Kobe Steel's IP sector is a relatively high-profit business within the Industrial Machinery Division, but IP sales in Japan and the wider Asian market have remained at about Yen 3 billion a year, and market expansion has been an issue.

The acquisition of Quintus is expected to enable Kobe to expand its line-up of IP products and enter new growth markets. Kobe has also expressed that it hopes to benefit from the interchange of product menus and from the synergy of manufacturing efficiency and cost reductions through the joint procurement of parts.

www.kobelco.co.jp/english/
quintustechnologies.com/hot-isostatic-pressing/

Maxon Motor invests in new Innovation Centre

Maxon Motor has announced that it will expand its Swiss headquarters with the construction of a CHF 30 million Innovation Centre. The new facility will provide space for the research, development and production of medical drives, the company reports.

The expanded medical department will utilise double its current floor space, over a floor area of more than 2,000 m^2 (nearly 25,000 ft^2). Here, the smallest Maxon motors will be manufactured, some with a thickness of only 4 mm (0.16 in). These motors are used in applications such as insulin pumps, medication delivery systems and surgical robots.

In order to meet the stringent quality demands of the medical field, the production area will be equipped with clean rooms, including a biocompatible room. With these measures, Maxon Motor hopes to form the basis for further growth in this important field.

Maxon Motor has more than thirty sales companies and six production sites worldwide, including its own facility for Metal Injection Moulding and Ceramic Injection Moulding in Sexau, Germany. The company employs more than 1,200 staff at its Obwalden headquarters, Switzerland, where the expansion will take place.

Following the expansion, the company reports that it expects to place a stronger focus on research & development, medical technology, complete drive systems (mechatronics) and Industry 4.0. Eugen Elmiger, Maxon CEO, stated, "The new Innovation Centre is a move to strengthen our Swiss headquarters in order to become stronger internationally."

www.maxonmotor.com

Maxon Motor's new facility will provide space for the research, development and production of medical drives (Courtesy Maxon)

World PM2018: Powder Metallurgy world congress series heads to China

The 2018 World Conference on Powder Metallurgy, World PM2018, organised by China Powder Metallurgy Alliance (CPMA), will take place September 16 - 20, 2018, in Beijing, China. The event marks the first time that the World PM series has been held in China and will give those from outside the country an insight into PM, MIM and AM developments in one of the fastest growing economies in the world.

The conference will cover the full range of Powder Metallurgy topics, ranging from metal powder production and technology, powder compaction, sintering and post-processing to Metal Injection Moulding, cemented carbides, porous materials, Additive Manufacturing and the design and simulation of Powder Metallurgy parts. The conference is expected to include over 500 presentations, giving a detailed overview of the latest developments in Powder Metallurgy.

In addition to the conference there will be an exhibition held over four days. In excess of 200 international exhibitors are expected to participate, providing the ideal opportunity to network with material and equipment suppliers, part producers and end-users.

The World PM2018 exhibition is being managed on behalf of the PM2018 organising committee by IRIS Exhibitions Service Co.,Ltd, organiser of the annual PM China exhibition series held in Shanghai each Spring. Exhibition sales enquiries should be addressed to Maggie Song, exhibition@worldpm2018.com. Those wishing to submit abstracts should note the submission deadline of October 15, 2017.

www.worldpm2018.com

The China National Convention Center in Beijing will host the PM2018 World Congress. The venue is close to the city's Olympic Park

17-4 PH stainless steel MIM parts successfully sintered by microwave assisted sintering

Research undertaken at Southwest University of Science and Technology, Mianyang and Southwest Jiaotong University, Chengdu, China, in collaboration with FEMTO-ST Institute, Besancon, France, has been evaluating the application of microwave (MW)-assisted sintering for MIM 17-4 PH stainless steel powders with the most recent results published in the *International Journal of Advanced Manufacturing Technology*.

17-4 PH stainless steel is a martensitic precipitation hardened material having high performance mechanical properties and excellent corrosion resistance. 17-4 PH stainless steel components produced by Metal Injection Moulding are normally sintered using conventional resistive heating (CRH) to reach near full density for high strength applications, or controlled porosity for parts requiring functional properties.

J Shi and colleagues stated that the dominant factors affecting the sinterability of a material using MW-assisted sintering include sintering temperature, holding time, heating rate and the pre-sintering stage. The primary role of pre-sintering is the removal of any remaining binder in the MIM parts and to provide sufficient part stiffness to prevent distortion or damage during the initial stages of sintering. Sintering atmospheres and the particle size of the starting powder also impact final properties and corrosion resistance. The authors had previously reported on their work to develop a complete framework for the simulation of microwave assisted sintering using COMSOL software. This included heat generation in the powder due to the microwaves and the densification process during MW-assisted sintering of the MIM components. This latest report further focuses on the examination of densification and also on the microstructural evolution of the 17-4 PH stainless steel during MW-assisted sintering.

The authors reported that, in the present work, MIM 17-4 PH stainless steel specimens were produced using water atomised powders, having irregular particle shape and particle size averaging 11 µm. Powders were mixed with a wax based thermoplastic binder, using a previously optimised formulation, and injection moulded to produce specimens having a green density of 5.05 g/cm^3, or 64% of theoretical density of pure 17-4PH stainless steel. The green specimens were debound first by heating in argon to 130°C to prevent oxidation, followed by increasing the temperature to 220°C to remove the paraffin wax portion of the binder.

Before the formal sintering stage the green specimens were heated to various pre-sintering temperatures to provide sufficient strength to prevent distortion or damage at the onset of MW-assisted sintering. However, optimal results were also obtained by heating directly from ambient temperature to 1150°C (see Table 1). This yielded MW-assisted sintered 17-4PH specimens having the highest density (96.6%) and best mechanical properties (Vickers hardness = 316 HV; ultimate tensile stress = 940 MPa). For all process variants, specimens were heated at the same optimal rate of 30°C/min up to the peak sintering temperature of 1150 °C, which was held for 10 min.

A high-temperature microwave laboratory furnace (HAMilab-V1500, 2.45 GHz) was used for the final MW-assisted sintering stage. The furnace is based on a multi-mode microwave cavity with continuously adjustable microwave power from 0.2 to 1.35 kW and maximum working temperature of 1600°C. During microwave sintering heat is generated inside the bulk material and sent out via radiation and convection from the outer surfaces of the specimen, thereby creating a thermal gradient where the temperature at the core of the part is generally greater than the temperature at the surface. The authors used argon as the protective atmosphere during MW-assisted sintering. None of the MW-assisted specimens showed any visually observable distortion despite the high heating rates, which demonstrates the important advantages of volumetric heating using microwaves.

The authors also pointed out that, in addition to using lower peak sintering temperatures – 150°C to 200°C below the optimal temperature used in conventional sintering, the high heating rates in MW-assisted sintering reduced the required processing time by 90%. This is due to the different sintering mechanisms in MW-assisted sintering, such as the enhancement of the diffusion coefficient and the eddy current of metals. In addition to the improved mechanical properties of MIM 17-4PH specimens produced using MW-assisted sintering, compared with conventional sintering, the MW-assisted sintered parts showed a more homogeneous microstructure and better surface qualities.

www.english.swust.edu.cn
www.femto-st.fr/en
english.swjtu.edu.cn
https://link.springer.com/journal/170

Pre-sintering temperature (°C)	Size shrinkage (%)	Relative density (%)	Vickers hardness (HV)
900	9.33 ± 0.45	83.7 ± 0.04	182 ± 2
600	10.12 ± 0.55	87.8 ± 0.13	190 ± 2
400	12.15 ± 0.35	89.9 ± 0.08	207 ± 3
270	13.94 ± 0.08	93.4 ± 0.10	274 ± 1
No pre-sintering stage	16.11 ± 0.10	96.6 ± 0.05	316 ± 2

Table 1 Relative density and Vickers hardness values obtained from MW-assisted sintering with and without pre-sintering stages at different temperatures. (From the paper 'Sintering of 17-4PH stainless steel powder assisted by microwave and the gradient of mechanical properties in the sintered body', by J Shi, et al., International Journal of Advanced Manufacturing Technology)

Innovative press concept for low pressure Metal Injection Moulding

Researchers at the Ecole de Technologie Superieure in Montreal, Canada, have developed an innovative concept for Low Pressure Powder Injection Moulding (LPIM) which, they state, eliminates the problem of segregation in low viscosity moulding feedstock within the LPIM machine during process dead time. S G Lamarre, V Demers and J-F Chatelain recently published the results of their research into developing the new LPIM process in the *International Journal of Advanced Manufacturing Technology*, available online.

It was stated that, over the past twenty years, the conventional high-pressure Powder Injection Moulding (HPIM) process (injection pressure of up to 200 MPa) has transitioned to LPIM by taking advantage of low-viscosity feedstocks (e.g. <10 Pa·s) to achieve good mouldability during injection at a pressure lower than 0.7 MPa. This has also made LPIM technology attractive for the production of both complex shape Metal Injection Moulded parts as well as Ceramic Injection Moulded parts, which are more commonly produced by LPIM. However, current commercial LPIM machines are all equipped with an interconnecting pipe for the transportation of the feedstock between the feedstock container and the mould. This necessitates the use of more viscous feedstocks in order to prevent segregation in this interconnecting pipe when the machine is idle between injections or during other process dead times. Since it is not possible to mix the feedstock in the interconnecting pipe, any segregation in the low-viscosity powder-binder mixtures within the injection pipe could make the feedstock inappropriate for further injections.

The researchers therefore developed a new injection moulding concept, which eliminates the interconnecting pipe and injection valve normally found in LPIM machines, and used instead a sliding platform, which was adapted for the transportation of the feedstock from the container to the mould cavity. Fig. 1a shows a schematic of the new injection feed system, which is described in detail in the paper, and Fig 1b to Fig. 1g show partial sections with the sequence of how the feedstock is injected. Three different feedstocks were used to produce MIM test parts based on 316L gas atomised stainless steel having average particle size of 6.7 µm mixed with (1) paraffin wax (PW) at 40 vol.%, (2) 30 vol.% paraffin wax - 10 vol.% stearic acid, and (3) paraffin wax 30 vol.% - 5 vol.% stearic acid (SA) - 5 vol.% ethylene vinyl acetate (EVA) - see Table 1. The minimum viscosities

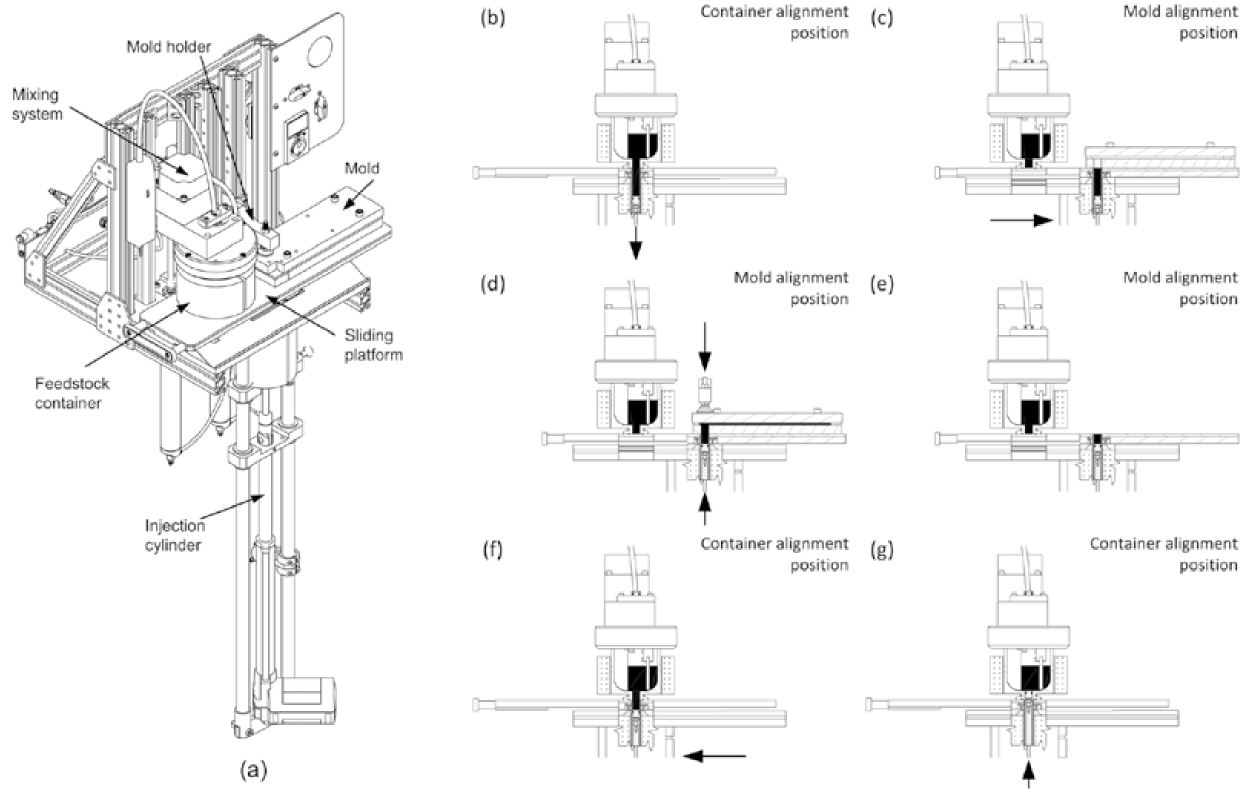


Fig. 1(a) General view of the low pressure injection system in a mould alignment position, and (b–g) showing partial section views for injecting feedstock (From the paper 'Low Pressure powder injection moulding using innovative injection press concept' by S G Lamarre et al, International Journal of Advanced Manufacturing Technology) were achieved at high shear rates for the three feedstocks and a viscosity value as low as 0.1 Pa·s was obtained for the feedstock 30PW-10SA. The authors stated that this new concept, combined with the low-viscosity feedstock and the elimination of segregation in MIM feedstock, should help promote the full realisation of the new LPIM process also for complex shaped MIM components.

Each feedstock was injected into two different mould cavities at a constant temperature of 90°C to obtain a rectangular dog bone shape (according to ASTM E8) and spiral-shaped specimens (Fig. 2). The temperature of the moulds was maintained at 35°C. Between the two injections, the feedstock remaining in the injection cylinder was returned into the container to be re-blended. Because any remaining feedstock is returned to the container after injection moulding, no feedstock remains trapped during process dead time. Injection moulding was performed using a controlled constant stroke (5.8 mm/s), while the value of the pressure was recorded according to the piston position. The mouldability of the feedstock was correlated with the injected length and the pressure profiles.

Constituent	Melting point (°C)	Density (g/cm³)	Source
Metallic powder (MP)	>1370	8.00	Epson Atmix
Paraffin wax (PW)	56.2	0.90	Sigma-Aldrich
Stearic acid (SA)	73.8	1.00	Sigma-Aldrich
Ethylene vinyl acetate (EVA)	54.6	0.94	Sigma-Aldrich

Table 1 Formulation of the 316L stainless steel feedstock used to evaluate the new concept of LPIM. (From the paper 'Low Pressure powder injection moulding using innovative injection press concept' by S G Lamarre et al, International Journal of Advanced Manufacturing Technology)

The authors stated that examination of the injected rectangular test bar specimens (Fig. 2) shows incomplete mould filling for feedstock 40PW and complete mould filling for the two other feedstocks. They believe that this mould geometry is therefore not well adapted to quantify the relative moulding potential of feedstocks. The feedstocks were also injected into a spiral mould to measure the injected length. Examination of the injected spiral specimens (also shown in Fig. 2) clearly shows that the injected length is smaller for the feedstock containing only paraffin wax (85 mm for feedstock 40 PW), compared to those containing paraffin wax, stearic acid, and EVA (295 mm for feedstock 30PW-5SA-5EVA) or paraffin wax and stearic acid (625 mm for feedstock 30PW-10SA). They therefore concluded that the injection length in a spiral mould is influenced by the formulation of the feedstock.

www.etsmtl.ca | https://link.springer.com/journal/170

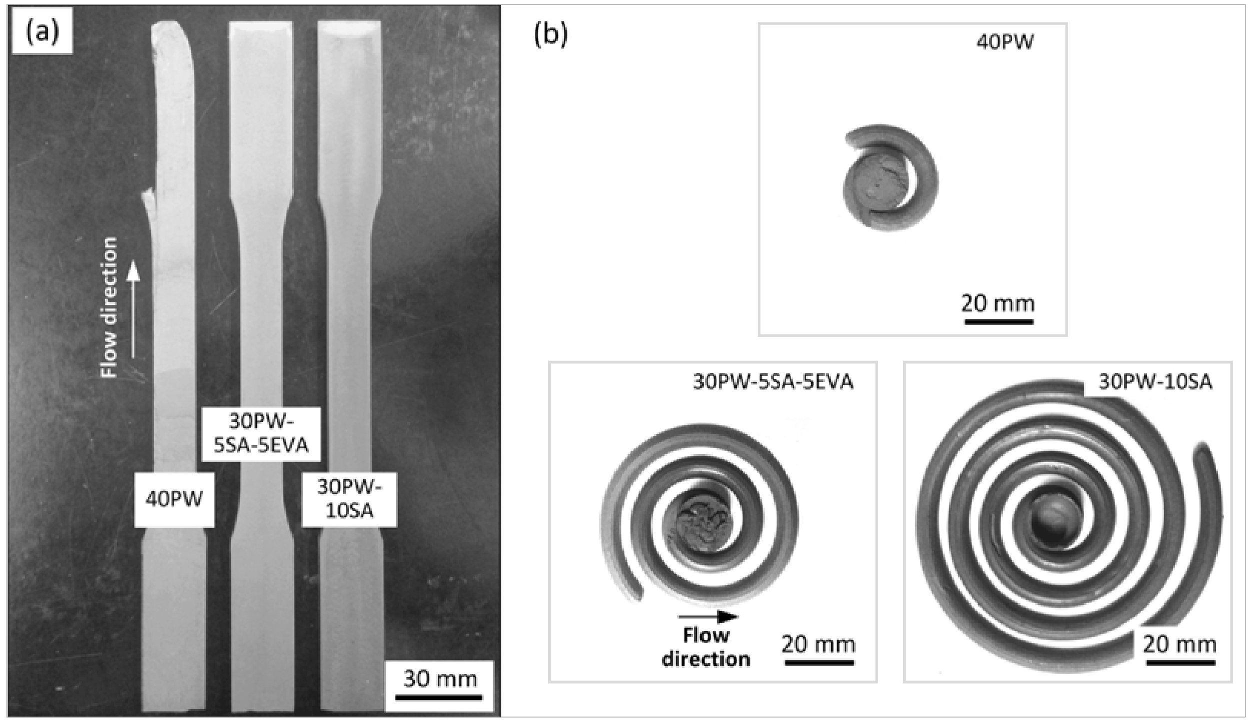


Fig. 2 Injected length of rectangular specimens (left) and spiral specimens (right). (From the paper 'Low Pressure powder injection moulding using innovative injection press concept' by S G Lamarre et al, International Journal of Advanced Manufacturing Technology)

MIM offers viable route to producing titanium aluminide alloys

The fabrication of lightweight titanium aluminide (TiAl) alloys by conventional routes is challenging because of the brittleness and sensitivity to chemical composition of the TiAl alloys. This makes the Powder Metallurgy process an attractive alternative because of the near-net shaping capabilities of the process and the good control of chemical composition and phase formation, which can be achieved particularly with gas atomised prealloyed TiAl powders. However, because prealloyed TiAl powders are harder, they are more difficult to compact in uniaxial pressing requiring >1.2 GPa to achieve an acceptable green strength. Metal Injection Moulding therefore offers a good compromise of processability, sintered density and microstructural homogeneity.

Researchers at the Institute of Materials Research, Helmholtz-Zentrum Geesthacht, Germany, working in cooperation with Universidade Federal de São Carlos, Brazil, have been studying the MIM process for the effect of sintering, microstructure formation and mechanical properties of three TiAl alloys. The results of the research, undertaken by J Soyama and colleagues, were published in *Journal of Metals*, Vol. 69, No. 4, 2017, pp 676-682.

The authors selected Ti-45Al-5Nb-0.2B-0.2C at.% (TNB-V5) as the reference alloy and two other TiAl variations containing Mo and Mo+Si: Ti-45Al-3Nb-1Mo-0.2B-0.2C at.% and Ti-45Al-3Nb-1Mo-1Si-0.2B-0.2C at.% were also included in their investigation. TNB-V5 (Ti-45Al-5Nb-0.2B-0.2C at.%) was selected as the reference material due to its balanced mechanical properties and excellent creep resistance. The objective of varying the composition was twofold: firstly, to study the sintering behaviour of these compositions, that up to now have not been reported, and, secondly, to improve the mechanical properties. The elements selected for these purposes were Si and Mo. Si leads to the formation of hard particles (silicides), while Mo affects solid solution hardening, but, depending on the heat treatment, also affects precipitation hardening with B2 particles. The authors stated that another target was to lower the high sintering temperature of around 1500°C normally required for TiAl alloys in order to reduce the cost of both sintering equipment and processing.

Sintering temperature (°C)	Porosity (%)	Sintered density (g/cm³)
1460	8.9 ± 0.6	3.81
1470	3.3 ± 0.3	3.93
1480	1.1 ± 0.1	4.06
1490	0.24 ± 0.04	4.12
1500	0.13 ± 0.1	4.13
1510	0.15 ± 0.04	4.12

Table 1 Sintering behaviour of TNB-V5 TiAl alloy at different temperatures. (From the paper 'Sintering Behavior and Microstructure Formation of Titanium Aluminide Alloys Processed by Metal Injection Molding' by J. Soyama, et al., Journal of the Minerals, Metals and Materials Society, Vol. 69, No. 4, 2017, pp 676-682)

Composition	α → a + b (°C)	Onset of melting peak (°C)	Sintering temperature (°C)	Porosity (%)	Colony size (μm)
TNB-V5	1438	1497	1500	0.13 ± 0.1	82 ± 3
3Nb-1Mo	1393	1502	1510	0.08 ± 0.05	62 ± 6
3Nb-1Mo-1Si	1392	1462	1470	0.13 ± 0.09	42 ± 4

Table 2 ß-transus temperatures, the onset of melting peaks, actual sintering temperature applied, residual porosity and colony size of the alloys investigated. (From the paper 'Sintering Behavior and Microstructure Formation of Titanium Aluminide Alloys Processed by Metal Injection Molding' by J. Soyama, et al., Journal of the Minerals, Metals and Materials Society, Vol. 69, No. 4, 2017, pp 676-682)

Tensile specimens were produced using feedstock prepared under argon atmosphere using argon gas atomised alloy powders of <45 μm particle size mixed with 10 wt.% (about 32 vol.%) binder comprising paraffin waxes, polyethylene-vinyl-acetate and stearic acid. Si powder, also of <45 μm particle size, was added during feedstock preparation. Following the removal of paraffin wax from the moulded specimens in a hexane bath at 45°C, thermal debinding and sintering were done in a single cold wall furnace from Xerion Advanced Heating Ofentechnik. The furnace was run at different temperatures, depending on the composition, for 2 h. For the reference material (TNB-V5), temperatures ranged from the ß-transus temperature up to above the solidus line.

The results are shown in Table 1. Clearly, sintering conducted completely in the solid state led to low porosity (in the order of 1% at 1480°C/2 h). However, it was found that extremely low porosities (<0.3%) were possible only with sintering temperatures slightly above the onset of the melting peak in a near-solidus sintering condition. Higher sintering temperatures (>1510°C) led to the formation of pronounced liquid phase fractions that caused dimensional distortion. It was established that the mechanical properties of TNB-V5 sintered at 1490°C would probably suffice for many load-bearing applications. Nonetheless, for applications in which the shape of the pores is important, e.g. fatigue or thermal fatigue, higher sintering temperatures are necessary for this alloy in order to achieve rounder pores and higher strength values.

Alloy	UTS (MPa)	Plastic strain (%)	Strain at fracture (%)
TNB-V5	570 ± 1	0.12 ± 0.01	0.5 ± 0.01
3Nb-1Mo	571 ± 17	0.10 ± 0.03	0.5 ± 0.01
3Nb-1Mo-1Si	607 ± 10	0.08 ± 0.02	0.5 ± 0.0

Table 3 Mechanical properties of the MIM TiAl alloys at room temperature. (From the paper 'Sintering Behavior and Microstructure Formation of Titanium Aluminide Alloys Processed by Metal Injection Molding' by J. Soyama, et al., Journal of the Minerals, Metals and Materials Society, Vol. 69, No. 4, 2017, pp 676-682)

The sintering temperatures for the two TiAl alloy variations were selected by determining their melting peaks through DSC analysis, as shown in Table 2. The addition of Mo decreased the *ß*-transus temperature by about 45°C in comparison to TNB-V5. Moreover, Mo induced an increase in the onset of the melting peak, which, in turn, is reflected in increasing the optimum sintering temperature. On the other hand, additions of Si led to a significant decrease (35°C) in the onset of the melting peak, independent of the alloy variation. With proper selection of the near-solidus sintering temperature, very low porosities (<0.2%) could be achieved in the modified TiAl alloys. With additions of Mo and Mo + Si, a pronounced decrease in the colony size also took place. In the case of the Mo + Si addition, the colonies were half the size of the reference material.

Comparing the microstructural formation of the reference TNB-V5 alloy with the two TiAl alloy variations, it was found that all the microstructures were fully lamellar and shared some common features such as pores and boride particles. The changes in chemical composition led to the formation of a stabilised ß phase and the precipitation of fine particles (titanium silicides, Ti_5Si_3) which contributed to a refinement of colony size and improved the tensile strength at room temperature, as can be seen in Table 3. The authors stated that, considering MIM is a near-net shape process, the as-sintered tensile properties are quite acceptable.

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Inserted metal injection moulded parts produced by diffusion bonding

Inserted Metal Injection Moulding, or overmoulding as it sometimes called in the injection moulding sector, can be a novel way of producing large sectioned or thick MIM components having the desired shape and mechanical properties. By using a solid wrought metal as the insert, benefits include the elimination of internal porosity by only needing to debind the outer MIM layer. Debinding times can also be dramatically reduced. Bonding between the solid metal insert and the MIM outer layer can be achieved by diffusion bonding during sintering.

Results of a research project, sponsored by the Scientific and Technological Research Council of Turkey (TÜBITAK) and involving researchers at the Gazi University, Ankara, Turkey and the Islamic Azad University in Maragheh, Iran, on the inserted Metal Injection Moulding of 316L stainless steel components were recently published in the *International Journal of Advanced Manufacturing Technology* (2017), Vol. 89, 2165-2173. The researchers, A Safarian, M Subasi and C Karatas, stated that 316L stainless steel was used for both the solid insert and for MIM overmoulding. Particle size of the water atomised 316L stainless steel powder used for the MIM layer was D_{50} 7 µm and powder loading in the feedstock was 92.5 - 93 wt.%. An injection mould with a cylindrical cavity having a diameter of 20 mm was made, into which were inserted machined wrought cylindrical 316L stainless steel inserts having three different diameters – 12, 14 and 16 mm. This procedure resulted in insert/MIM section diameter ratios of 60, 70 and 80% respectively. The 316L feedstock was injected into the mould cavity containing the inserts using an Arburg 220S moulding machine to produce the inserted MIM parts shown in the top part of Fig. 1.

The injection moulding process was followed firstly by solvent debinding in pure ethanol at 60°C for different times depending on the insert/MIM part diameter ratios. Debound inserted MIM parts were then pre-sintered and sintered in a tube furnace in $N_2 + H_2$ (95% + 5%) atmosphere. Examples of sintered 316L inserted MIM parts are shown in the bottom part of Fig. 1.

An important aim of this research work was to study the effect of sintering conditions such as temperature, dwell time and heating rate on the sinter bonding of the MIM material to the wrought metal insert and, also, on the properties of the MIM 316L stainless steel outer material. The authors stated that sintering temperature is the dominant and most effective parameter affecting the shear strength of the bonding area created by diffusion bonding during sintering of the two 316L stainless steel materials. Increasing the sintering temperature increased bonding strength significantly, whereas increasing the dwell time and heating rate did not result in any significant changes. The factors involved in sintering are shown in Table 1.

Following sintering, the inserted MIM parts were cut into disc shaped specimens having a thickness of 1.5 mm, in order to evaluate the sintering and diffusion bonding of the MIM layer to the solid insert. The disc specimens were placed inside a shear-punch die and a compressive load was applied to separate the insert from the MIM section. This yielded the ultimate shear strength data for the diffusion bonded interfaces of the different specimens.

The authors pointed out that the insert/MIM part diameter ratio is an important parameter affecting the shear strength. It was found that the shear strength values noticeably increased by using larger diameter inserts, which were found to result in mechanical pressure at the interface area of the insert and MIM outer layer leading to compressive stresses. These stresses occurred by the mismatch strain between insert expansion, based on its thermal coefficient of expansion and initial dimension, as well as the shrinkage of the injected area when starting the sintering process. Larger inserts were found to exhibit more expansion and stress, which contributes to the necessary applied pressure for good bonding. Another factor could be the use of water atomised powders in the 316L stainless steel feedstock, where the irregular shape of the powder particles is believed to result in higher inter-particle friction and higher green strength of the injected area before sintering and diffusion bonding.

Fig. 2 shows three SEM specimens with varying insert/MIM part diameter ratios sintered at 1300°C. The specimen with 60% ratio shows lower strain mismatch, with weak bonding and high porosity at the interface. Specimens with higher insert/MIM part diameter ratios of 70 and 80% have larger strain mismatch and exhibited strong bonding with lower porosity. This point is confirmed by the shear strength values of 98, 110 and 164 MPa obtained from shear-punch tests of the sliced specimens with insert/MIM part diameter ratios of 60, 70, and 80%, respectively. Shear strength values could reach as high as 342 MPa for inserted MIM parts sintered under optimum conditions.

The authors also tested the microhardness levels of the inserted MIM parts. Average hardness of parts sinter bonded at 1300°C is around 250 HV. This is said to drop to around 220 HV in the sintered injected area due to inherent porosity of the outer layer.

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Fig. 1 Injected (above) and sintered (below) inserted specimens with a diameter of 20 mm and the insert/part diameter ratios of 60, 70 and 80%. (From the paper 'The effect of sintering parameters on diffusion bonding of 316L stainless steel in inserted Metal Injection Molding', by A. Safarian, et al., International Journal of Advanced Manufacturing Technology (2017), 89:2165-2173)

Factors		Level		
		1	2	3
A	Heating rate (°K min^{-1})	1.5	3	4.5
B	Sintering temperature (°C)	1260	1300	1340
C	Dwell time (min)	30	60	90

Table 1 Factors and levels, based on a Taguchi L9 orthogonal array, for sintering the MIM 316L layers on inserted MIM parts. (From the paper 'The effect of sintering parameters on diffusion bonding of 316L stainless steel in inserted metal injection molding', by A. Safarian, et al., International Journal of Advanced Manufacturing Technology (2017), 89:2165-2173)

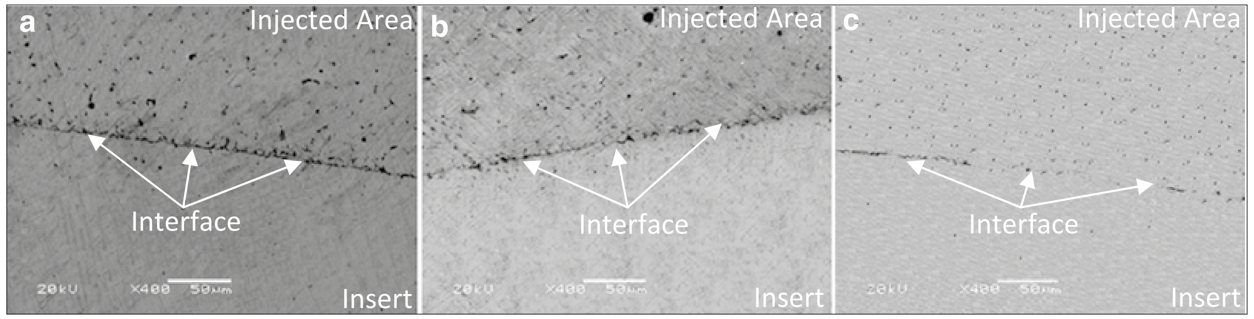
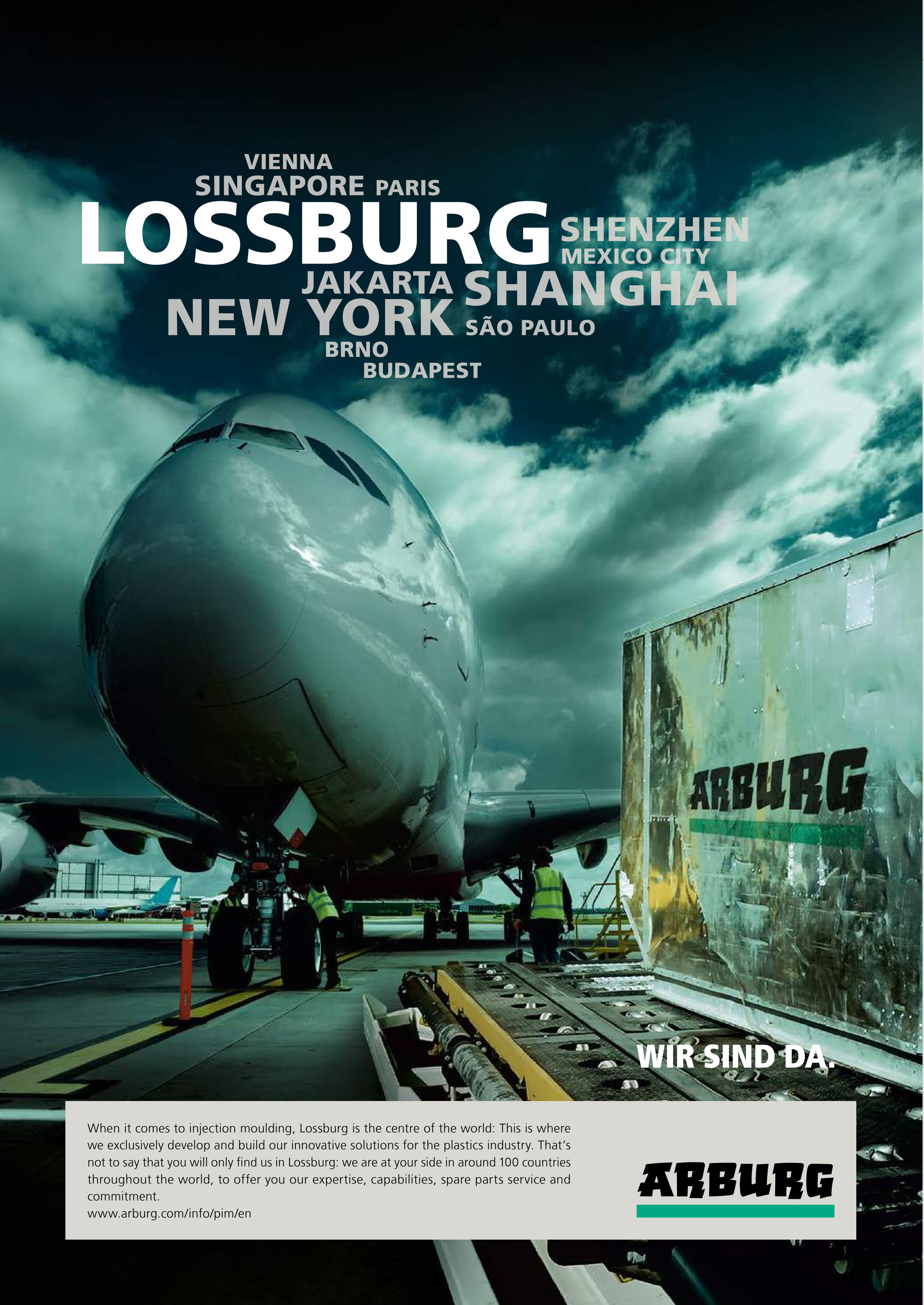


Fig. 2 SEMs of inserted MIM 316L specimens sintered at 1300°C, with insert/part diameter ratios of (a) 60, (b) 70 and (c) 80%. (From the paper 'The effect of sintering parameters on diffusion bonding of 316L stainless steel in inserted metal injection molding', by A. Safarian, et al., International Journal of Advanced Manufacturing Technology (2017), 89:2165-2173)



Metal Injection Moulding in Asia: A story of continuing success for the world's largest MIM region

The MIM industry in Asia is the world's largest, whether considered in terms of number of parts produced, sales turnover or production volume. China alone is reported to offer half of the world's installed MIM capacity, with production predominantly focused on 3C applications. In this report, Dr Paul A Davies, Sandvik Osprey Ltd, provides an overview of the evolution of the region's MIM industry from a powder producer's perspective. With selected application examples and data from the recent APMA 2017 conference, the report offers insights into the drivers for growth and how these have stimulated continued investment in capacity.

The Asian MIM market has grown significantly over the last few years based on increasing demand for high volume consumer products and the proven capability of MIM houses to deliver to the exacting standards set by OEMs. It is evident when visiting MIM houses how rapidly things are changing with expansions in the scale of MIM manufacturing operations and investments in new equipment. This is especially true when it comes to moulding machines and sintering furnaces, both batch and continuous, as well as increased adoption of robotic pick and place machines to reduce operating costs.

3C components are manufactured in extremely large quantities for a number of different OEMs including Samsung, Huawei, OPPO, VIVIO, MI and, most significantly, Apple. These companies account for approximately 50% of MIM 3C component production in Greater China. The majority of the top ten MIM factories in Asia (Table 1) are all listed on Apple's latest Supplier List [1].

A prime example of a successful 3C MIM component is the Apple Lightning/Type C connector used for power, data communication and, in more recent designs, doubling as the ear phone jack (Fig. 1). This is one of the most important applications in terms of production volumes, running at five million parts per month. Production is largely being met by Tier 1 Apple suppliers in Taiwan, some of whom also have large MIM operations in mainland China. Supplementary capacity is provided by manufacturers in China, often engaged as subcontractors. Management of the supply chain is rigorously controlled by Apple, who

Company	Location
Amphenol	Hangzhou and Yunnan, China
CN Innovations / Zoltrix	Guangzhou, China
Dou Yee Technology	Singapore and Anhui, China
Foxconn	Guangzhou, China
Gian	Changzhou and Dungguan, China
Indo-MIM Private Limited	Bangalore, India (& Texas, USA)
Shanghai Future Technology	Shanghai and Shenzhen, China
Shin Zu Shing Co., Ltd	New Taipei City, Taiwan
Taiwan Powder Technology	Taoyuan Taiwan and Wujiang, China
UNEEC	Dungguan, China

Table 1 The top ten MIM producers in Asia

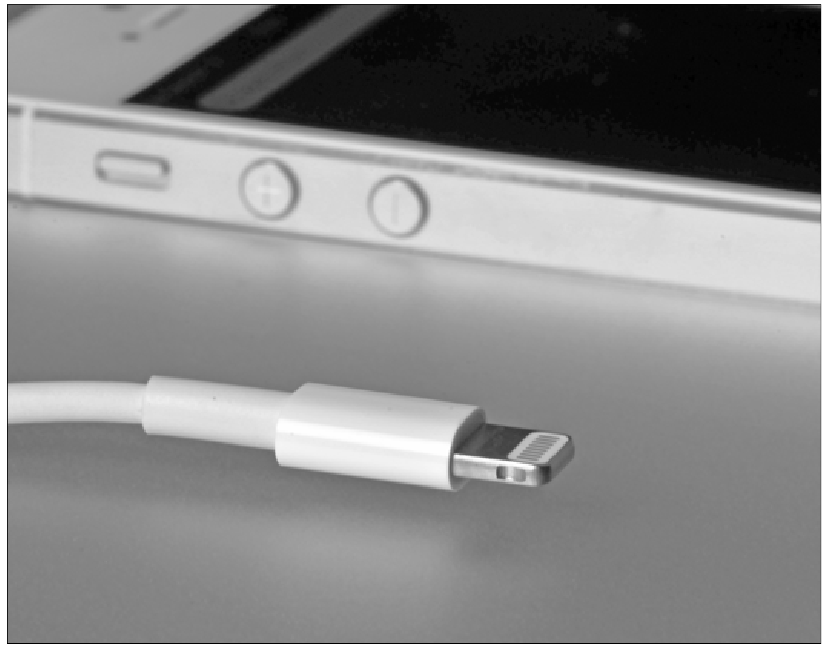


Fig. 1 The use of MIM for Apple's Lightning connector had a major impact on the Chinese MIM industry

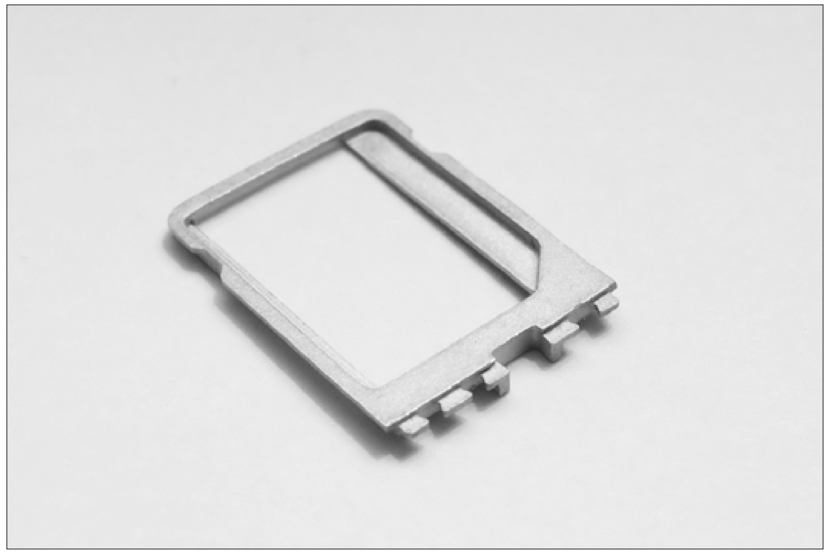


Fig. 2 MIM SIM trays have become big business, with more than half of China's MIM factories producing these parts

often prescribe single-source supply in MIM powder and feedstock for the production of MIM components. This approach ensures consistent quality standards when using a number of different component manufacturers. A preference for specific production process equipment is also evident with preferred brands specified for the furnaces used to debind and sinter parts. Other MIM components for the iPhone series amount to more than ten million parts per month, with thousands of workers required to achieve the required level of surface finish and tight dimensional tolerances.

China

The MIM market in Greater China, as reviewed by Dr Yao-Hung Qiu on behalf of the China Powder Metallurgy Association (CPMA) and presented at the APMA 2017 conference in Taiwan, April 9-11, 2017 [2], has an estimated value of CNY ¥5,920 million ($910 million), increasing from $725 million in 2015. Sales of the five top MIM companies generate more than half of the total sales ($485 million). A further fifteen companies each have sales of more than $6 million, with the remaining MIM producers, described as small scale, typically having fewer than ten moulding machines.

In total there are at least 200 MIM parts-producing companies in China. Of these, the Pearl River Delta (Guangdong) is home to up to 65 producers with a second major growth centre in the Yangtze River Delta around Shanghai having 35 producers. Both regions concentrate on 3C business. Northern China, around Beijing and Shandong, has twenty companies that tend to make specialist parts including some very large MIM components weighing up to 2500 g.

The developing area of Western China, including Hunan Province, has more than fifteen companies, typically with lower costs than established manufacturing areas near the coast. It is anticipated that as the size of the MIM industry in China continues to increase to more than $1 billion by 2020, competition will drive consolidation and specialisation in end-user markets. In terms of production technology, there will continue to be a steady improvement in the quality of domestic MIM production equipment and powder producers.

MIM materials usage in China

Total shipments of MIM materials, including both powders and feedstock, in China in 2015 was estimated by the Powder Metallurgy Branch Association of the China Steel Construction Society at between 6,000 and 7,000 Metric Tonne (MT), with market share being divided equally between domestic and foreign brands [3]. It was estimated that between 3,000 and 3,500 MT of foreign feedstock was imported in 2015. In terms of domestic MIM feedstock production, there are nine manufacturers producing a total of between 800-1,000 MT per annum. There are also eight domestic producers of MIM powder, each claiming production capacity in excess of 100 MT per annum.

The most widely processed MIM materials in China are stainless steels, including 316L and 17-4PH, and low alloy steel based on carbonyl Fe and Ni, these steel alloys collectively accounting for 85% of production. Tungsten-based materials, which also include munitions, account for 10% of production with cemented carbides, copper-based alloys and titanium alloys accounting for the remaining 5%. Imported feedstock produced by BASF SE in Germany and Taiwan remains the biggest supplier in China at 2,500 to 3,000 MT per annum [4]. Domestic MIM feedstock producers are growing with companies, including Winners, Zongtai Technology & Kadam, producing a combined 2550 MT per annum. In addition to the high proportion of prealloy stainless steels consumed in China, a high proportion of Master Alloys of 316L and 17-4PH, purchased in Europe, are converted to MIM feedstock, which is in turn destined for Asia.

Markets for China's MIM industry

The largest market for the Chinese MIM industry is the consumer electronics sector, which provides an attractive short term proposition for MIM companies, with the unit price ($/ kg) of small 3C parts equal to two to three times that of non-3C parts, but with a short life cycle of as little as a year. 3C components are dominated by structural parts and functional parts in smartphones, such as buttons, vibrator alarms (tungsten alloy) and, significantly, the SIM card tray (Fig. 2), which is being manufactured by more than half of the MIM factories in China. Other consumer components include wearable devices, watch parts and laptop hinges and, all combined, 3C MIM components account for the majority of the revenue generated by MIM houses in China (Fig. 3).

Fibre optic cable end-connectors are also a major MIM success, meeting the global challenge to expand fibre networks to satisfy ever-increasing data bandwidth demands of modern life: video-streaming, e-commerce and social media etc. The connector is a small, complex component based largely on a single design, in 304L or 316L austenitic stainless steel, and has been produced in numbers estimated at up to 50 million pieces per year.

The second largest MIM market in China features weapons and defence components (12%), produced in low alloy steel. Power tools, the lock industry and kitchenware (11%) and zippers and bag wear (3%), as styled by world famous brands, such as Gucci and Prada, are manufactured in stainless steel, often with high performance aesthetic coatings and mirror polished finishes (Fig. 4). Given these rankings, it is clear that market sectors such as automotive and medical instruments are under-represented compared with other parts of the world, but it is expected that these sectors will grow significantly in the future.

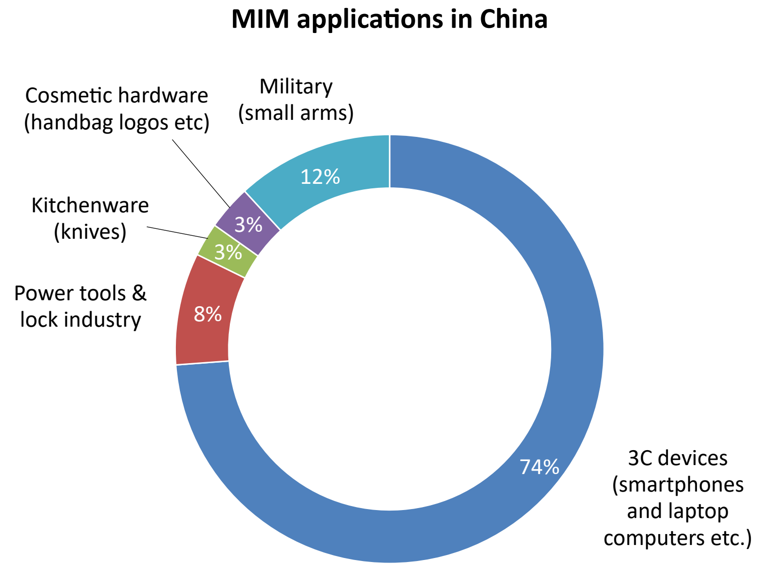


Fig. 3 The major MIM application areas in China

Fig. 4 Decorative MIM parts produced by Zoltrix Material International Limited. As published in [5]

Fig. 5 MIM is increasingly being used in the smartphone sector as a production-efficient and cost-effective alternative to conventional machining processes (Photo: Arburg)

Fig. 6 A prototype of a MIM smartphone middle frame for Gigaset, produced by Element Tech., Shenzhen, China

Unique aspects of the smartphone sector

Frequent mobile handset model updates and the emergence of new devices ensure that the 3C market continues to change in a dynamic fashion, as evidenced by the number of old phones and chargers we accumulate over time. Each new model represents a new opportunity for the MIM industry to meet the designer's aspirations while meeting cost down targets. The skills required to meet these demands should not be underestimated and the capacity reserved to simply meet the product launch is remarkable.

As well as fashion drivers, there are examples of regulatory pressures influencing the MIM industry in China. After a vote in the European Parliament in 2014, a radio equipment directive dictates that mobile device chargers must be compatible with all mobile devices effective by the end of 2017. Inevitably, enforcement will take time, but when one considers there are at least half a billion mobile phones in the EU, most using different chargers (it is estimated there are some thirty different types on the market), the impact will be far-reaching. Smartphone OEMs such as Apple, Nokia, Motorola, Samsung, Sony Ericsson and ALCATEL have now all signed an agreement to make their phones compatible with a single, USB-style charger. Therefore, the MIM industry may well benefit from the change in legislation, should the end connectors be designed with MIM in mind rather than folded strip systems.

There is also speculation that SIM cards for mobile devices will become obsolete in the near future, as programmable chips integrate the SIM card function and allow programming via data port or Wi-Fi connection. Such a change would obviously have a significant impact on demand for card holders, which have already been reduced in size from Mini to Micro and more recently to Nano SIM. For domestic mobile handset brands at least, the number

of cards per handset has increased. Therefore, while modest in weight, the sheer volume of components (>500 million produced annually) demands a lot of MIM capacity and it would be a challenge to reassign this to other components if SIM card trays do become obsolete.

Smartphone frames present opportunities for MIM

While there are some threats to the current 3C MIM industry, there are also opportunities. Recent demonstrations by Arburg, at international trade shows including the World PM2016 Congress and Exhibition in Hamburg, Germany, have highlighted the potential for production of smartphone middle frame housings by MIM [6].

The main objective is to reduce the CNC machining requirement by two thirds and the cost by one third. Demonstrator parts have been produced using an injection system with a hot-runner mould with a thickness of 1-2 mm and length of 136 mm. The 17-4PH stainless steel alloy powder was incorporated in a flow-optimised POM based feed-stock formulated by BASF. Components were sintered in a continuous furnace with an optimised heating sequence to limit part distortion and minimise finishing operations, before machining and PVD coating to create a high-quality surface suitable for polishing to a high lustre (Fig. 5). An example of another demonstration MIM smartphone frame, produced by Element Tech, is shown in Fig. 6. The structural integrity of smartphones would be enhanced by a metal middle frame, avoiding rear pocket deflection and the potential for internal damage.

Gas atomised powders are favoured for enhanced mould flow performance and superior aesthetic surface polish requirements. The materials selection for a smartphone middle frame presents an interesting challenge, requiring a non-magnetic stainless steel with tensile strength >700 MPa. Two options discussed at the

Fig. 7 The Pebble Steel smartwatch is just one example of the new wave of wearable technology that promises to keep MIM plants in China busy. As published in [7]

Fig. 8 MIM hinge cams are one of most successful MIM products to be used in the 3C industry, with production historically reaching one million pieces per day. As published in [7]

APMA conference in Taiwan were PANACEA®, which is a nickel-free (manganese-stabilised and nitrogen sintered) austenitic steel and a part-austenitised 17-4PH sintered in a nitrogen atmosphere. There are limiting factors for deployment of PANACEA®, which requires specialist heat treatment: specifically rapid quenching to attain a fully austenitic structure and post surface treatment to remove oxide scale. Similarly, for 17-4PH, compositional modification and sintering in nitrogen, in order to stabilise an austenitic microstructure, may not be enough to produce a completely non-magnetic structure and this remains a challenge. However, there is no doubt that a hand set middle frame would set an exciting precedent and could be a boon for the MIM industry for many years to come.

Further technology drivers in mobile communications, especially 5G, wireless charging, extended battery life, heat dissipation and structural integrity, will all influence the metal content of mobile handsets. The recent catastrophic battery fires, which led to the recall and cancellation of Samsung's Galaxy Note 7, are a testament to how the frontiers of functionality are being tested in mobile handsets. Competing materials include ceramic, which would aid wireless charging, and even amorphous alloys.

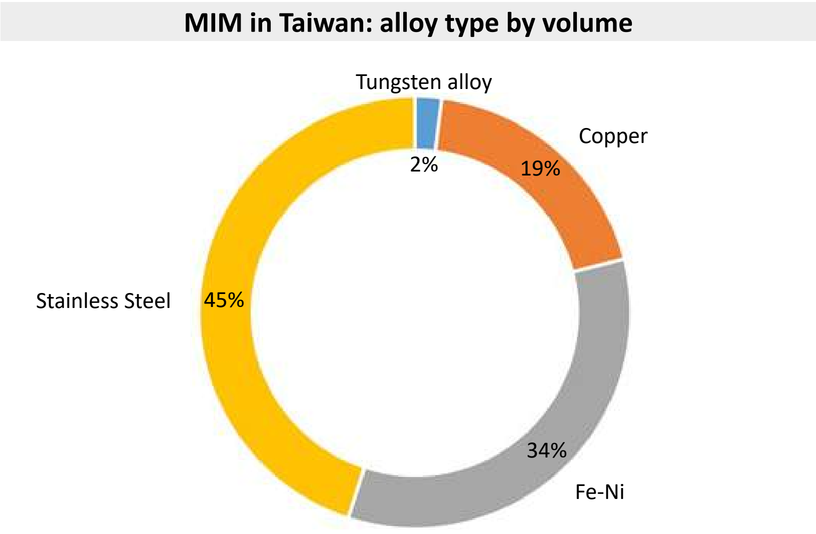


Fig. 9 MIM in Taiwan: alloy type by volume [8]

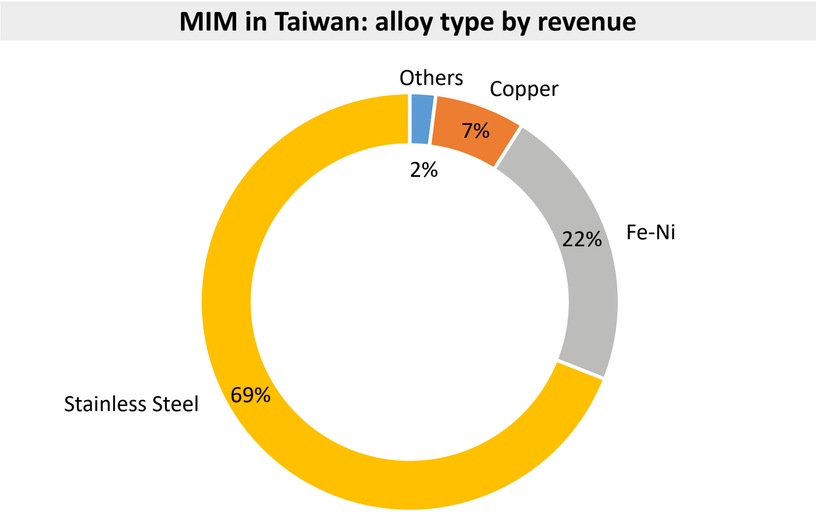


Fig. 10 MIM in Taiwan: alloy type by revenue [8]

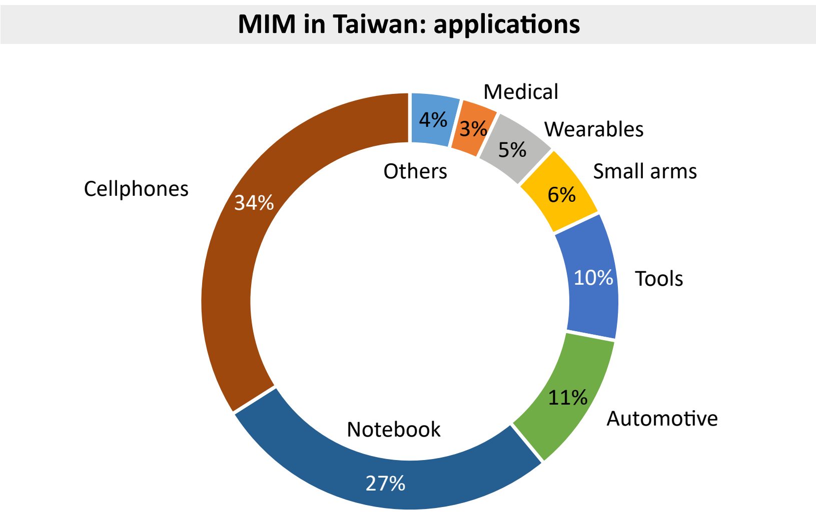


Fig. 11 MIM In Taiwan: applications [8]

Taiwan

The MIM industry in Taiwan has a long history with more than thirty years of experience and a significant value estimated at NT $7 billion ($230 million). This compares with $100 million in 2012 and $48 million in 2007, a compound growth rate of 15% per annum. There is a diverse range of companies in Taiwan and there are estimated to be 32 MIM production operations, ranging from major 3C specialists producing notebook hinges and other 3C components through to niche producers of dental brackets, automotive components and novel copper heat-sinks.

The types of MIM components are diverse with the heaviest parts weighing up to 1000 g and high aspect ratio components with longest dimensions reaching 20 cm. The origins of the MIM industry in Taiwan can be traced to US technology, and it is based predominantly on proprietary wax polymer formulations (75%) and more recently POM feedstock (25%) produced by BASF at its facility in Taoyuan. Annual MIM powder consumption in 2016 was estimated at 1,990 tonnes, mainly based on water atomised powder from Japan, more than double the volume consumed in 2012 at 860 tonnes.

Taiwanese companies surveyed by Prof. Kuen-Shyang Hwang of National Taiwan University (NTU) on behalf of the Taiwan Powder Metallurgy Association (TPMA) indicated that the industry employs approximately 3600 workers, operating 529 injection moulding machines, 160 batch furnaces and 13 continuous furnaces [8]. The MIM industry is supported by a significant number of highly qualified staff (16 PhDs and more than a hundred MScs), with a significant number of these being ex-students of Prof Hwang.

The MIM industry survey in Taiwan for 2016 indicated that a small majority of businesses (55%) saw an improvement compared to 2015 and the outlook for 2017 is split, with half of companies expecting growth, 10% remaining the same and the rest expecting a decline in fortunes. Taiwan's MIM factories are now facing tough competition from Mainland China for 3C business where project life cycles are typically limited to two or three years at most, resulting in a cyclic revenue stream. In this climate, it is easy to understand why speculative investment can lead to overcapacity in preparation for the next big volume project. In turn a number of smaller, satellite operations have developed, offering swing capacity for sub-contract manufacture of parts at peaks in demand. This presents some challenges to maintain consistent quality among sub-contractors.

Japan

The MIM industry in Japan has endured at least six years of gradual decline with 2015 sales amounting to JPY ¥10.5 billion (approx. $93 million), down from the peak in 2010 of ¥11.9 billion. However, early results from the JPMA, presented by Dr Hideki Nakayama at the APMA 2017 conference suggest that sales recovered to ¥11.2 billion in 2016 and a further increase is anticipated in 2017 with a forecast of ¥11.7 billion [10,11].

In general, the demand for MIM components in traditional sectors for Japan, such as industrial machine components, medical, automotive and consumer products, especially camera parts, has been reported by the JPMA as steady, with some signs of expansion in motorcycle parts, for example. There have been some notable increases in production capacity in Japan of late, led by Iwaki Die-Cast Co., Ltd. whose Kodaira factory development creates one of the largest MIM facilities in Japan. There is little sign of improvement in the Japanese economy and, despite years of economic stimulus, growth in Japan's economy remains modest (~1% GDP). Nevertheless, Japan's government continues to support industrial investment at home, aiming to stimulate exports.

The development of aerospace applications, including compressor vanes and vane holders, led by IHI Corporation, has created high value-

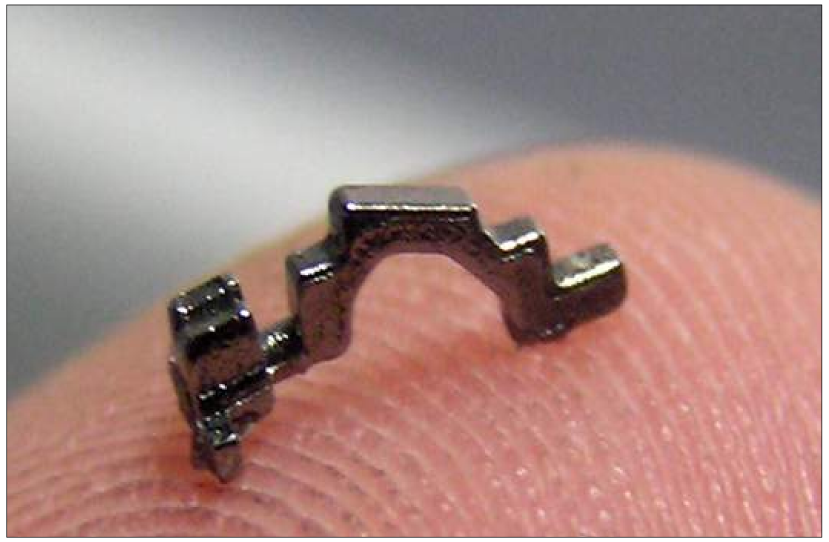


Fig. 12 An example of a component produced by Taiwan Powder Technologies Co., Ltd. and used in smartphones. This 'hanger' part is produced using an ultra-high strength (>1500 MPa) patented sinter-hardened material. Designed by HTC. As published in [9]

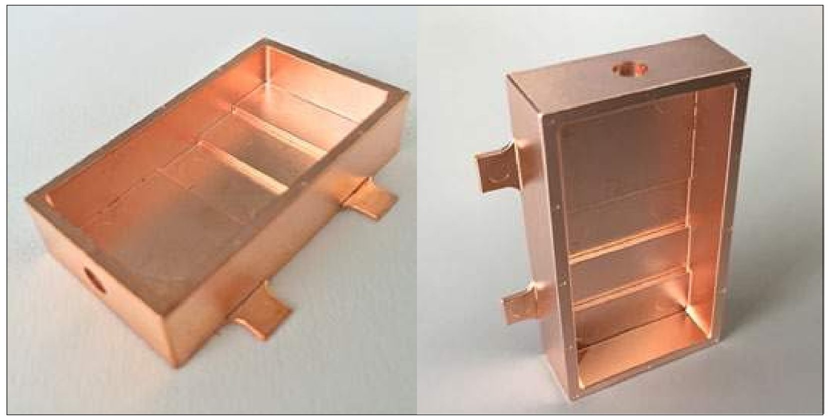


Fig. 13 Japan's MIM industry is noted for its use of innovative and advanced MIM materials and processes. In this application example from Epson Atmix Corporation, sintering is carefully managed to control oxygen content. High thermal conductivity equivalent to that of oxygen-free copper has been achieved. The external dimensions of this part are 45 × 25 × 10 mm with a fin thickness of 0.6 mm, side thickness 2.0 mm (Courtesy Epson Atmix)

Fig. 14 Nippon Piston Ring's development of rocker arm parts represents an early success in the Japanese MIM industries efforts to penetrate the automotive sector

Fig. 15 A MIM component for instrumentation equipment produced from 316L by Singapore's Dou Yee Technologies. The component replaces what was previously an assembly of two parts (Courtesy of Dou Yee Technologies)

added opportunities for MIM, based on nickel-based superalloys applied to the very latest aero-engines [12]. Similarly, ATECT, a specialist MIM and CIM component and feedstock producer focusing on turbocharger components and titanium parts with enhanced surface finish, was reported to be moving from Osaka into larger production facilities in Shiga prefecture in April 2017. Other MIM companies in Japan include Epson Atmix (Fig. 13), a famous watch manufacturer as well as water atomised powder producer, Nippon Piston Ring, focusing on automotive components (Fig. 14) and Sumitomo Heavy Industries subsidiary Sumiju Precision Forging Co., Ltd.

Mitsubishi Steel published an Annual Report earlier this year highlighting progress on a mid-term business plan aimed at creating added value from materials, including an entry into a turbocharger assembly business and MIM component production by acquisition. Mitsubishi Steel has an existing automotive business, which includes a precision casting plant in Thailand making nozzle, vane and turbine wheel turbocharger components that could be threatened by MIM technology. Therefore, leveraging their existing MIM powder production, with the possibility of introducing new lines at the Chiba Works, Mitsubishi intend to enhance assemblies of both cast and MIM parts in turbocharger applications.

The production of titanium MIM components features prominently in Japan compared with other geographies. While volumes remain modest, there is some growth, though this is slow because of limited availability of good quality and affordable titanium powder. Supply of relatively fine pure titanium and titanium alloy powders, is mainly from Vacuum Induction melting Gas Atomising (VIGA) plants operating with refractory free crucibles and nozzles to minimise contamination by impurities. Further development of fine titanium powder production facilities, targeting a higher yield of powder with size less than 30 microns, will be required to stimulate new applications.

South East Asia

Singapore

The MIM industry in Singapore is well established, dating back to the involvement of Motorola, who prompted significant expansion in the industry based on sourcing MIM components, including hinges for classic mobile handsets such as the PEBL and RAZR. The MIM market in Singapore was assessed by Chee Hoo Liang of Advance Materials Technologies (AMT) at the APMA 2017 conference, with an estimated turnover of $52 million and a 5-10% growth rate [13].

While AMT has relinquished their interest in 3C after declining sales to Motorola, supply to the 3C industry has been embraced by other companies in Singapore. These include Dou Yee Technologies (Fig. 15), which has production plants in Singapore and China, Solidmicron and, more recently, Dynacast. The latter, which is headquartered in the US, also has MIM related facilities in Singapore as well as Batam (Indonesia) and Vietnam. All MIM components produced in Singapore are exported, with markets in 3C (62%), General Engineering (16%), Automotive (15%), Medical (5%) and Energy (2%). Materials are dominated by stainless steels (62%), FeNi and low alloy steels (25%), copper (5%) and a balance of other materials.

Thailand

Thailand has two Japanese company transplants, including Castem, who have recently expanded their production, and the microMIM specialist company Taisei Kogyo, both supported by National Science and Technology Development Agency of Thailand.

Malaysia

Medical research at the University of Kebangsaan, Malaysia, has produced some interesting developments in implantable alloys based on enhanced biocompatible titanium alloys.

Philippines

Precision Foundry of the Philippines has a newly installed MIM capability, producing general engineering components and parts for small arms manufacture. MIM is a natural extension of its extensive casting expertise, which also includes dental and medical devices and implants.

Australia and New Zealand

Australia has an emerging presence in the MIM industry with Advanced Metallurgical Solutions (AMS) focusing on titanium components and sintered metallic membranes (filters etc.). Research by the University of Auckland in New Zealand on titanium MIM is also expanding knowledge in this field.

Fig. 16 Quality inspection of MIM turbocharger parts at PIM Korea Co., Ltd. As published in [15]

Fig. 17 A selection of turbocharger components produced by PIM Korea Co., Ltd. As published in [15]

South Korea

The South Korean PIM industry, which combines both ceramics and metals, was reviewed by Prof Seong Jin Park on behalf of the Korean Powder Metallurgy Association (KPMA) at the APMA 2017 conference. He reported annual revenues of $80 million, with three MIM companies having a turnover greater than $10 million, including PIM Korea ($25 million), Amphenol ($21 million) and KR MIM ($18 million) [14].

Other significant MIM companies include Inway ($3.4 million) and Hansuh ($3.3 million), with the majority of small operations reporting revenue less than $1 million, along with some relatively new MIM companies established in Korea, including MTIG ($0.8 million), who specialise in titanium components including dental implants. The MIM industry in Korea, which is mainly based on exports, has experienced a drop in sales in the last ten years due to competition from both China and India, but a gradual recovery is evident in recent years

Fig. 18 A selection of metal injection moulded parts manufactured by Indo-MIM, showing the size range of parts processed. As published in [16]

with a stronger automotive sector including PIM Korea (Figs. 16-17) and KR MIM. Here, producing engine and turbocharger components, on time, to the exacting standards of the global automotive supply chain is critical.

The potential for growth in MIM technology has been acknowledged by blue chip companies such as Samsung, who have set up a new R&D team, further supported by government funding of $2.5 million for ten projects split equally between academic and industrial research, including prominent work at POSTECH, Pohang University of Science and Technology, Hanyang and Andong Universities.

India

The MIM industry in India has an estimated revenue of $125 million and at least four companies operating, but is dominated in volume and revenue by Indo-MIM Private Limited, which provides a full service product offering from part design, accelerated tool manufacture and post-process finishing including polishing and plating (Fig. 18). Indo-MIM has two manufacturing plants in the Bangalore free trade zone focusing almost exclusively on export markets with a diverse market sector approach, from 3C to automotive, including diesel and gasoline turbocharger components, medical and aerospace. The company is opening a new, custom-built factory this summer in San Antonio, Texas, USA. This will focus on serving the substantial North American market (small arms production, medical, automotive and aerospace), addressing the preference for domestic manufacturing and sourcing in the US.

The Indian economy is growing at a rate of ~6% GDP per annum and, as a growing affluent middle class is established, demand for new vehicles and low cost smartphones will drive the emergence of a domestic MIM market. Smartphone handset assembly in India is growing rapidly, as highlighted by new production facilities earmarked by Apple and Google and other established foreign producers led by Samsung, complementing strong domestic brands such as Micromax and Celcon. The new production investments proposed by Tier 1 suppliers including Wistron and Foxconn, including the possibility of reopening the vast Nokia plant in Chennai, may also provide new opportunities for the MIM industry, especially as Indian government policy dictates that 30% of the components are sourced locally.

Summary

In conclusion, the MIM industry in Asia is large and expanding and presents some excellent growth opportunities, from turbocharger parts and aero-engine components to what could perhaps be the ultimate MIM component, the smartphone middle frame. Adapting to the rapidly changing 3C market has highlighted the maturity of the MIM market and it is clear that the continuing support of the whole supply chain including powders, equipment and technical expertise is needed to sustain further market growth.

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Ceramic Injection Moulding: Baselworld 2017 sees luxury watch brands launch new offerings

Baselword 2017, held in Basel, Switzerland, from March 23-30, was the 100th anniversary of this, the most important marketplace for the global watch and jewellery industries. Over 106,000 visitors came to see the latest collections from the crème de la crème in watchmaking, including the most recent offerings in watches using Ceramic Injection Moulded cases, bezels and bracelet parts. Bernard Williams reports on some of the launches from leading players.

Over the past twenty years Ceramic Injection Moulding has become a key driver in contemporary watch design, with its adopters ranging from the most celebrated luxury manufacturers to more affordable mainstream brands. Many watch-makers now use CIM for their watch cases, in full or in part, as well as for bracelets and other components largely due to the allure of highly polished or striking matt ceramics, with their extreme hardness offering superior scratch resistance. The cool touch and hypoallergenic properties of ceramics are of course further positive considerations. However, it is the world's leading luxury brands that continue to push the boundaries of what can be achieved with CIM and create iconic new editions of ceramic watches such as Rado's Ceramica, Omega's Seamaster Planet Ocean Big Blue and Hublot's Big Bang, to name just a few.

Ceramic watch components have, in the main, been produced using ultrafine tetragonal zirconia powders, first developed by the Tosoh Corp in Japan in the early 1980s, although other types of ceramic powders, including silicon nitride, titanium nitride and boron carbide, have also been used. The ceramic powders are blended with a binder before being homogenised and granulated to produce the feedstock for injection moulding to net shape. Following injection moulding the components then go through binder removal stages. Significant progress has been made in debinding technology for ceramic watch parts in recent years; in addition to the catalytic debinding approach originally developed by BASF SE, which offered excellent performance in terms of extremely

Fig. 1 An exhibition like no other - the TAG Heuer stand at Baselworld (Courtesy Baselword)

Fig. 2 Following the success of the original matt Ceramicas, two models in grey ceramic were on show (Photo Rado Watch Co. Ltd.)

Fig. 3 Rado has added this grey/brown high tech polished plasma ceramic case to its DiaMaster Grande Seconde family (Photo Rado Watch Co. Ltd.)

Fig. 4 The True Thinline Colours from Rado features polished plasma CIM cases available in grey, blue, green or brown (Photo Rado Watch Co. Ltd.)

short debinding times, thermal debinding and solvent debinding are now widely used. The solvent debinding process has been widely adopted in the CIM sector where a portion of the binder is chemically removed using solvents such as acetone, trichloroethane or heptane. The open porosity created after solvent debinding allows the degraded products to diffuse easily to the surface of the parts.

After debinding, the ceramic parts are sintered in dedicated sintering furnaces at temperatures around 1450°C. Chemically derived ultrafine ZrO_2 powder shows very good sintering activity and, with appropriate powder processing, it can be readily sintered to practically theoretical density. The sintered material exhibits an unusual combination of several favourable properties; it shows high strength, high toughness, high hardness, low thermal conductivity, a high volumetric density and a high refractive index. The high strength of sintered zirconia is said to be associated with the very fine crystallite size of the sintered material, usually not more than 0.3-0.5 µm, allowing a four point bend strength of 1000 MPa or more. The sintered CIM parts can be polished to give a satin finish or sandblasted to give a matt finish.

Whilst black zirconia parts have become standard for many CIM watch parts, higher end watch producers have begun turning their attention in recent years to incorporating other colours and tones such as red, blue, orange, white, grey and brown. For coloured CIM zirconia parts, the material has to be pigmented with mixtures of several transition metal oxides such as iron, cobalt, nickel, manganese and chromium. The key to the selection of colouring pigments is that they must survive the high sintering temperature without evaporating or melting.

Rado

Rado of Lengnau, Switzerland, part of the Swatch Group, was one of the first of the luxury watch makers to turn to Ceramic Injection Moulding for its watch pieces in the 1990s and stated at the relaunch of its Ceramica brand in 2016 that high-tech ceramics offer an attractive combination of lightness and scratch resistance. Seven ceramic colours – black, white, plasma, grey, brown, green and blue – are now featured in Rado's collections. The launch of the grey Ceramica (Fig. 2) at Baselworld 2017 marks the first time that this advanced ceramic shade has been featured in the Ceramica family.

Grey ceramic debuted in the Ceramica collection with two finishes: a subtle, earthy sandblasted matt and a perfect high-gloss polish, a testament to the versatility of this remarkable material. The polished grey version features the same Super-LumiNova® indexes as its matt black counterpart, while the dial of the matt grey version features a vertically brushed finish and concave dots that function as indexes. This collection marks the first time that automatic movements have been used in the Ceramica family.

Konstantin Grcic, a leading international industrial designer, stated in relation to his work on

Fig. 5 Omega's Seamaster Planet Ocean Big Blue ceramic watch, launched at Baselworld 2017 (Photo Omega SA)

Fig. 6 The Speedmaster Racing model from Omega has a polished ceramic bezel with a brushed Liquidmetal® tachymeter scale (Photo Omega SA)

Rado's watches that colour functions as a form of coding, stating, "Applied to an object, colour is both functional and emotional. For example, a black watch is perceived to be elegant, but also quite masculine and professional. A grey watch, in comparison, is less gender specific. The colour has a contemporary connotation. It feels younger, less classical."

Rado also added two new timepieces to its distinctive DiaMaster Grande Seconde family. The 43 mm case in the DiaMaster Grande Seconde (Fig. 3) is manufactured using one of Rado's signature materials, plasma high-tech ceramic. To create this material, finished white ceramic components are fired in a plasma furnace, where gases activated at 20,000°C give rise to a metallic shine on the surface. This gives the DiaMaster Grande Seconde the look of a classic metal wristwatch while offering the benefits of ceramic construction.

Rado's thinnest-ever Ceramica timepieces, designated the True Thinline and launched at Baselworld 2017, come in four colourful new ceramic variations – inky blue, forest green, lunar grey or chocolate brown. This combination of colour and material in the new collection was, states Rado, allowed to become the key focus of the series thanks to the True Thinline's restrained design and extremely thin 4.9 mm profile (Fig. 4).

The True Thinline Colours watches feature alternating matt and polished ceramic surfaces. The grey and blue models are almost entirely polished, but their shine is offset by contrasting matt middle links in the bracelet, while the green high-tech ceramic model is fully polished and the brown entirely matt.

Omega

Omega SA, based in Biel/Bienne, Switzerland, is also part of the Swatch Group and the luxury watchmaker unveiled some noteworthy new ceramic models at Baselworld 2017. These included the new Seamaster Planet Ocean Big Blue, which the company claims breaks new ground in ceramic watchmaking.

In the Planet Ocean colours of blue and orange, Big Blue signals the first time that Omega has delivered a case made entirely from blue zirconia ceramic (Fig. 5). As well as the solid blue case, the watch features a blue ceramic dial with an orange GMT track. Adding sparkle to the blue dial are hands and indexes in 18 carat white gold with a white Super-LumiNova coating. The blue ceramic bezel features a diving scale with Liquidmetal® numerals. A blend of orange rubber and ceramic covers the first fifteen minutes. The reverse side of the Big Blue is equally impressive, with its alveol pattern screw-in caseback, which features a unique Omega innovation: a patented ceramic Naiad Lock that keeps the engraved wording in position.

The company stressed that creating any new colour of ceramic demands an extra level of expertise and understanding. With the new Seamaster Planet Ocean Big Blue, the colouring begins with pigmentation at the early stage of preparing the ceramic powder. However, it is

Fig. 7 TAG Heuer unveiled its very first proprietary men's chronograph made almost entirely from ceramic, including the bracelet, at Baselworld 2017 (Photo TAG Heuer SA)

the careful steps which follow that are key to producing the final result.

Omega first embraced Ceramic Injection Moulding around eight years ago, largely thanks to the pioneering efforts of the Swatch Group in Powder Injection Moulding. The first Ceramic Injection Moulded part was a small triangle on a piece of jewellery in its Seamaster Planet Ocean collection. From this point onwards, ceramics became an important part of the brand's future creations.

Going much further than that first small triangle, Omega has now integrated ceramics into many more of its designs and the material can be found from bezels to dials and full case bodies. However, this success requires the mastering and rigorous control of the CIM production process. For a ceramic Speedmaster today, the shape of the case body is first injection moulded from a special zirconia-based powder. The case bodies are then debound followed by a sintering process at temperatures reaching in excess of 1400°C, making the zirconia ceramic hard and scratch-resistant. For such a tough material, it then takes machining with diamond tools to add any defining edges and grooves. A three-hour plasma treatment in a 20,000°C furnace then paves the way for precision laser engraving.

Omega's Speedmaster Dark Side of the Moon was the first of the brand's models to receive this full ceramic case body. Others, such as the White Side of the Moon and Grey Side of the Moon have followed. The latest Speedmaster Racing Master Chronometer shown at Baselworld 2017 (Fig. 6) sees two models featuring a polished ceramic bezel with a brushed Liquidmetal® tachymeter scale, and another using a blue ceramic bezel with a Ceragold™ tachymeter scale. Ceragold™ is a special method of decorating ceramic watch parts with 18 carat gold.

TAG Heuer

TAG Heuer SA, based in La Chaux-de-Fonds, Switzerland, first presented its Carrera Heuer 01 chronograph at Baselworld 2015, where it formed the cornerstone of its new collection. At this year's event, the company showed a new version of Carrera Heuer 01 where the 45 mm case, bezel, lugs and case middle are produced using matt black ceramic (Fig. 7) The company states that its zirconia ceramic offers unparalleled scratch resistance and that the black ceramic bracelet, with its H-shaped links and matt finish, gives this huge ceramic watch a new contemporary and sleek look. The ceramic parts are micro-blasted to achieve the matt black finish.

Hublot

Hublot SA, of Nyon, Switzerland, first introduced zirconium oxide ceramic materials for watches in its Big Bang series, launched in 2005, featuring satin black and white as well as bright red and yellow. At that time, ceramics had not yet been widely accepted as a watch case material, with the majority of black watches made from stainless steel or other metals with a black coating that would chip and fade over time. In 2012, Hublot introduced a new material for its Big Bang Ferrari Limited Edition timepieces, where 24 carat gold is fused with boron carbide to create a 'Magic Gold' alloy. To produce watch parts from this new alloy, the boron carbide powder is first injection moulded to produce the required shaped part and, after debinding and sintering, a 24 carat gold alloyed with 3% molten liquid gold is injected at high pressure and high temperature into the porous ceramic. The gold fills the pores in the ceramic creating the Magic Gold effect (Fig. 8)

At Baselworld 2017, Hublot introduced ceramic designs for the 'Click Italia Independent' women's luxury range, developed in partnership with the Italian design company Italia Independent. The 39 mm diameter timepiece (Fig. 9) comes in three different combinations using scratch resistant polished black ceramic cases and black plated steel deploying clasps on velvet straps. The black ceramic case features ten diamond indices on the dial and a diamond studded dial.

Fig. 8 Hublot's Magic Gold watches are produced from injection moulded porous boron carbide impregnated with gold (Photo Hublot SA)

Fig. 9 Hublot's new ceramic 'Click Italia Independent' womens luxury watch shown at Baselworld 2017 (Photo Hublot SA)

Seiko

In 2016, Seiko Watches Corp. of Japan expanded its Grand Seiko range into the sports realm by presenting the Black Ceramic Limited Edition for Spring Drive watches using a combination of a zirconia ceramic outer case and a titanium inner case. Seiko stated that zirconia ceramic is stronger and tougher than any other fine ceramic and seven times harder on the Vickers scale than stainless steel. The new Grand Seiko, launched at Baselworld 2017, comes in three forms, all of which have the same sports design as well as a new hybrid titanium-ceramic bracelet construction (Fig. 10). The flat shape of the case was developed with the aim of making the most of the unique characteristics of zirconia ceramic. Despite the difficulties of polishing ceramics, the ceramic edges on the polyhedral shape are polished to a mirror finish and produce the intricate overlapping reflections that are the characteristics of the Grand Seiko design. Ceramic does not typically have reflective properties, but multiple polished surfaces on the Grand Seiko case reflect light even in dim conditions, creating a sharp, crisp visual impression. The watch is said to be comfortable to wear, primarily because of the lightweight

Fig. 10 The limited edition Grand Seiko Spring Drive Chronograph GMT has enhanced timing accuracy and features a combination of ceramic and titanium in the case and bracelet (Photo Seiko Watches Corp.)

Fig. 11 Rolex launched its new Yacht-Master II with blue ceramic bezel at Baselworld 2017 (Photo Rolex SA)

Fig. 12 The Intemporal Keramik from Lehmann Schramberg (Photo Lehmann Präzisionsuhren GmbH)

hybrid titanium-ceramic case and bracelet. As the zirconia ceramic parts are raised slightly above the level of the titanium, the bracelet is virtually impervious to scratches and will retain, states Seiko, its as-new appearance just as long as the watch case itself. Remarkably, given the technical difficulty of polishing ceramics, the ceramic parts in the centre of the bracelet are polished to a mirror finish and the signature Grand Seiko sharpness of the angles on each component has been retained.

Rolex

Rolex, of Plan-les-Ouates near Geneva, Switzerland, adopted black ceramic bezels in 2005 using its Cerachrom process, developed and patented by the company, which allows this watch component to be produced as a single piece in two distinct colours. In 2010, the company developed a Monobloc Cerachrom bezel, rather than a bezel insert, for the Cosmograph Daytona model and, in 2014, introduced a red and blue Cerachrom bezel for its Oyster Perpetual GMT-Master II having found a way to locally modify the chemical composition and hence colour of each ceramic grain to the core of the material. In this way, the colour on the bezel changes from red to blue from one half to the next. ensuring a sharp delineation between the two colours.

Rolex introduced a number of new timepieces at Baselworld 2017, many with the now popular black or two-coloured Cerachrom bezels. Included in the new line-up were the Cosmograph Daytona, Oyster Perpetual Sea Dweller, Explorer II, GMT-Master II and the gold Yachtmaster I and Yachtmaster II. The Rolex Oyster Perpetual Yachtmaster II's Cerachrom bezel features well-defined minute markers and polished, raised graduations on the ceramic inlay, which stand in relief against a sandblasted, matt black background.

Lehmann Schramberg

Uhrenmanufaktur Lehmann has been producing watches in Schramberg, a centre for watchmaking in the Black Forest area of Southern Germany, since October 2011, utilising the high precision manufacturing skills of its parent company Lehmann Präzision, located just a few kilometres away. The watches are characterised by their round cases and slim bezels which culminate in closed horns that form a distinctive frame to the wrist-band (Fig. 12). The German watch-maker recently expanded its range of timepieces and, at Baselworld 2017, introduced its new Intemporal Keramik. Markus Lehmann said that, whilst the fabrication of the elaborately crafted ceramic case was genuinely challenging, it was worth all the extra effort. The dark ceramic surface of the watch case has a striking matt shimmer that changes from black to grey, depending on the lighting conditions.

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Titanium MIM moves into the mainstream with plasma atomised powders from AP&C

When it was announced earlier this year that Canada's AP&C, a GE Additive Company, had received an order for 30 tons of plasma atomised titanium powder for a Metal Injection Moulding application, it became clear that titanium MIM had reached the mainstream. In the following article AP&C explains the attraction of MIM for titanium components, outlines the company's plasma atomisation process and presents its growing range of products specifically suited to the MIM process.

Product designers in a wide range of industries are carefully eyeing titanium due to its unusual combination of high strength, low weight and excellent corrosion resistance. The primary factor limiting the more widespread use of titanium and its alloys is the high cost of raw materials and processing relative to competitive materials. These costs are particularly high for geometrically complex parts. Metal Injection Moulding (MIM) provides an attractive method of producing small, complex titanium components at a lower cost using processing techniques that are similar to those used in plastic injection moulding.

Expanding the usage of MIM to new applications requires a ramping up of the supply of titanium powders with the required tailored size distributions and consistently high quality. The plasma atomisation process used at AP&C has demonstrated the ability to provide the precise control of powder properties necessary to satisfy the demands of a broad range of current and potential MIM applications. This article will survey the continuing evolution of the plasma atomisation process as it evolves to deliver the large quantities of high quality fine powders required to fully develop the potential of MIM technology.

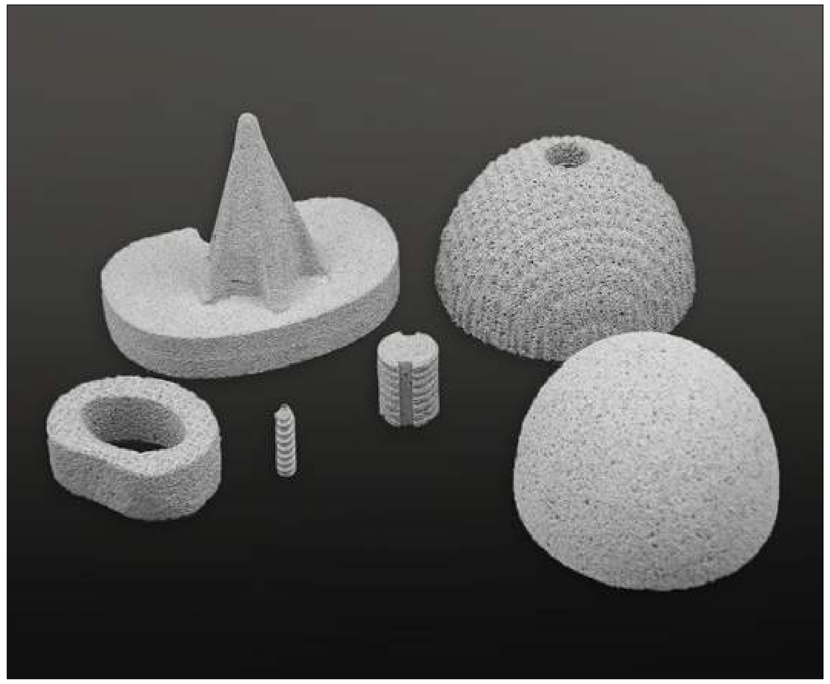

Fig. 1 Titanium hip joint replacement parts made by MIM

The attraction of titanium

Titanium is one of the strongest and most durable materials on the planet and has the highest strength to density ratio of any metallic

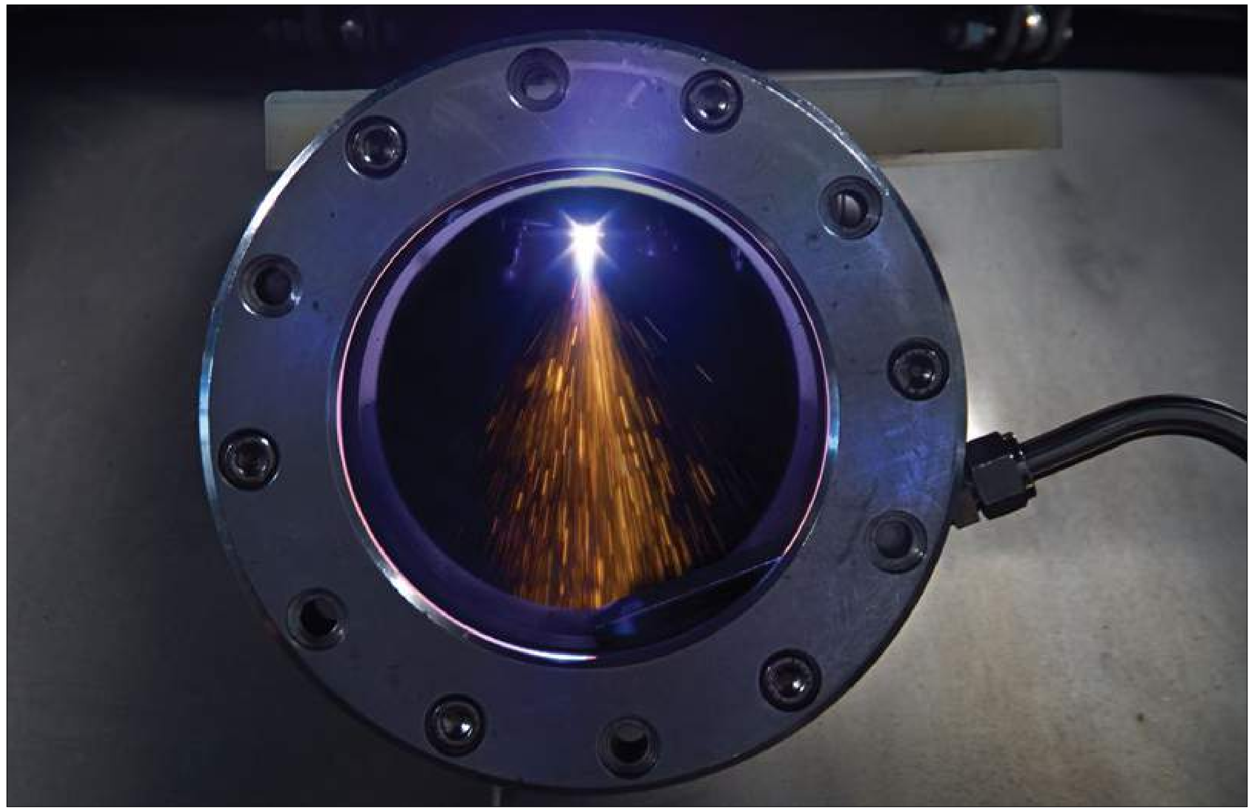

Fig. 2 Plasma torches during an atomisation run at AP&C

element. Bulk titanium is also relatively inert, which means it can survive exposure to unfavourable conditions far better than other materials. Titanium's biocompatibility, which means it is not toxic and not rejected by the body, has led to many applications in the medical industry such as artificial knees and hips, surgical instruments, body piercings and even dental implants (Fig. 1). Titanium's high strength-to-weight ratio means it can also be used to reduce the weight of an aircraft while maintaining structural integrity. The result is a substantial reduction in fuel consumption that can provide enormous savings over the lifetime of the aircraft.

The primary limiting factor in the proliferation of conventional titanium parts is their relatively high cost, which results from their raw material costs, fabricating costs and metal removal costs. The largest expense is typically the machining processes required to bring the part to its final shape. Titanium is recognised as a difficult to machine material, which often raises the costs of cutting tools, fixtures and machine tools compared to conventional materials. However, an even greater factor in most cases is the large proportion of the initial material that ends up as chips on the machine shop floor. It is not uncommon for the weight of the material that is removed from the workpiece during machining to exceed the final part by a factor of 20 to 1; this waste material is generally sold as scrap for a small fraction of the original material cost.

The titanium MIM process

The titanium Metal Injection Moulding (Ti-MIM) process has the potential to substantially reduce the cost of producing many titanium parts at high levels of quality. A key advantage of the Ti-MIM process is that it combines Powder Metallurgy and plastic injection moulding methods to produce parts to net shape without any material waste. High purity spherical titanium fine powder is used in Ti-MIM and this is mixed with a thermoplastic binder and heated to melt the binder and achieve the right level of viscosity for injection moulding. After moulding, the binder is removed either by heating and/or chemical reaction and the part is then sintered at a high temperature to fuse the metal particles into a dense solid.

MIM has the advantage of being able to produce intricate shapes at a relatively low cost because it eliminates material waste and machining expenses. It is considerably faster and can achieve much closer tolerances than investment casting. It is, however, usually limited to small parts below 200 g. The MIM process is also used to manufacture parts made of many other materials, including various types of specialty steels and non-ferrous alloys.

A major challenge in scaling up the production of titanium MIM parts is producing the needed quantities of fine titanium powder that provide the specific characteristics required by the MIM process. One of the most critical requirements is the particle

size distribution (PSD). Another important requirement is the particle shape – spherical particles are preferred for most MIM processes because they provide high loading which minimises the shrinkage and ensures consistent mould filling and reduced tool wear. Finer PSD provides a better surface finish and sinters at lower temperature, reducing the grain growth during the heating stage. Purity is also important, with the major concern usually being interstitial elements - impurities found in nominally pure metals that are small enough to fit between normal crystalline lattice locations.

Oxygen is typically the major concern in titanium, so common practice involves specifying the maximum oxygen impurity level, with each impurity counting against this limit based on its effect on the properties of the finished part relative to oxygen. Oxygen content is even more critical with fine PSD powder because of its high specific area and native oxide layer. Porosity, which refers to the presence of entrapped gas pockets, must also be held to very low levels to achieve good mechanical properties, but the use of fine PSD minimises such risk.

The plasma atomisation process

Several different methods are used to produce powder for Ti-MIM including inert gas atomisation, plasma spheroidisation, Hydride-Dehydride (HDH) and other chemical reduction processes. Plasma atomisation is a relatively new process that has gained Ti powder market share rapidly because of its ability to produce highly spherically shaped particles in accurate size distributions with low oxygen content and low internal porosity (Fig. 2, 3). In this process, titanium wire (Fig. 4) is fed into a plasma torch which converts the wire into droplets that subsequently solidify to powder form.

Plasma atomisation production has been evolving ever since its initial conception in the 1990s. At that time,

Fig. 3 A plasma atomisation production unit

Fig. 4 Titanium wire feedstock used in the plasma atomisation process

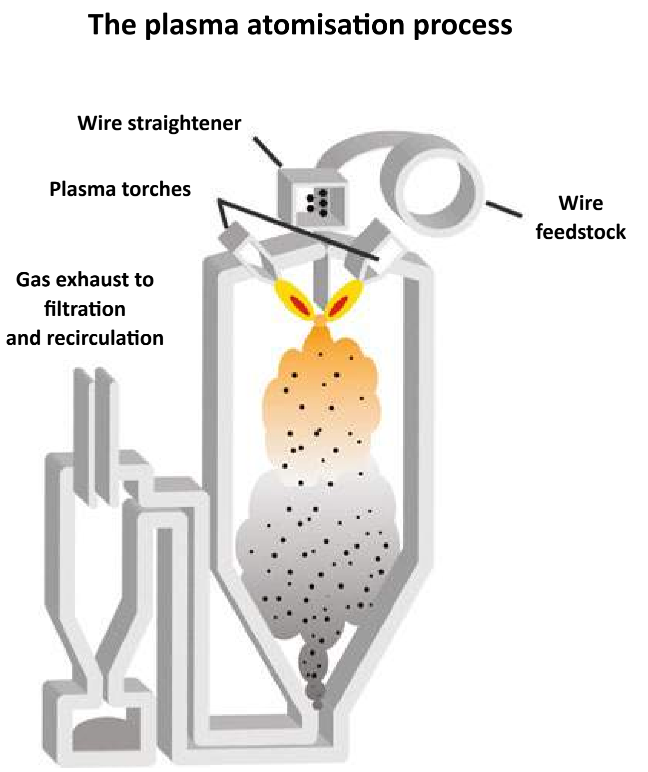

Fig. 5 Schematic of plasma atomisation process

problems were experienced with throughput and poor yield of fine PSD which resulted in high production costs. Over the last few decades, these problems have been overcome, resulting in the development of large capacity production units that consistently deliver high-purity spherical metal powders. AP&C has been at the forefront of the technology's development for more than ten years and has become the world leader in the industrialisation and optimisation of the plasma atomisation process.

The first production step is to straighten the feed wire to ensure its optimal positioning at the apex of one or several plasma torches. The speed of the wire also needs to be monitored to control and adjust the resulting particle size distribution. In a typical case, three DC plasma torches, each delivering about 30 kW, are placed so that their jets converge on the metal wire. The supersonic nozzles installed at the exit of the torches ensure a maximum gas velocity to successfully atomise the metal wire. A schematic of the process is shown in Fig. 5.

The argon gas used as the atomising medium is heated to a high temperature to prevent the metal particles from rapidly freezing together into irregular shapes. Heated argon gas has a higher velocity and thus applies a stronger atomisation force at a lower temperature without increasing the gas flow rate. The plasma superheats the melt and subsequent cooling ensures complete spheroidisation. A low concentration of suspended atomised particles prevents the formation of satellites that reduce flowability.

The importance of minimising agglomerates in powder collection and sieving

Breaking up agglomerates is critical to maintaining the flowability of the feedstock, which helps ensure the right moulding behaviour. Agglomeration is also detrimental to the feedstock preparation because of its impact on the compounding with the polymeric binder. Very small PSD powder has high interfacial adhesion energy, making it difficult to break up agglomerates during the high shear mixing process used in compounding. AP&C has developed methods to reduce the formation of agglomerates in the powder production process, improving the flowability of the powder.

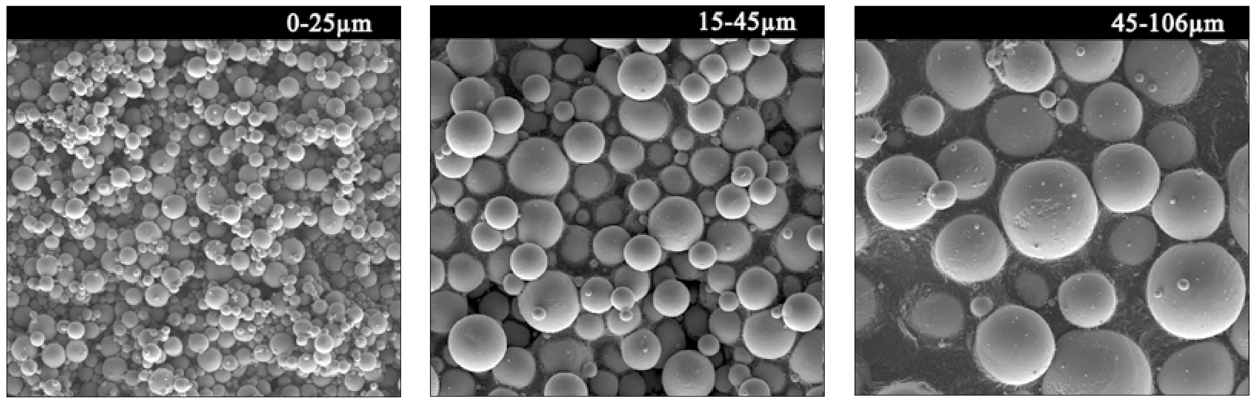

Fig. 6 Various sizes of highly spherical titanium powder produced by AP&C using the plasma atomisation process.

Fig. 7 Alain Dupont, President of AP&C, at the construction site of AP&C's new state-of-the-art titanium powder factory in St. Eustache, Montreal, Canada, in February

Powder collection is done via a typical cyclonic device and the powder is carefully passivated to enable safe manipulation in open air and reduce oxygen content. After the passivation stage, the powder is sieved with an ultrasonic resonator according to the final customer's size distribution requirement. The plasma atomisation process typically delivers powders with sizes up to 150 µm. The most common grades are 0-25 µm, 0-45 µm, 15-45 µm and 45-106 µm (Fig. 6). For cut sizes smaller than 25 µm, a gas separation apparatus, based on saltation velocity theory, is used to ensure the effective removal of the smaller particles.

The melt source can be chosen from unalloyed titanium grades (for example grades 1, 2, 3 or 4); titanium alloys modified with palladium or ruthenium (for example grades 7, 11, 16, 17, 26 or 27); alpha and near-alpha titanium alloys (for example grades 6, 9, 12, 18, 28); alpha-beta titanium alloys (for example grades 5, 23 or 29); near-beta and beta titanium alloys (for example grades 19 or 20). The primary titanium powders used in the MIM process are commercially pure titanium (CpTi) and titanium alloys including Ti-6Al-4V, Ti-6Al-2Sn-4Zr-2Mo and Ti-5Al-5V-5Mo-3Cr.

Almost any metal can be atomised with the plasma atomisation process, although it is best suited to reactive materials and materials with high melting points that cannot easily be processed into spherical powders by other methods. Materials that have been successfully atomised with the plasma atomisation process include niobium (Nb), molybdenum (Mo) and nickel-titanium alloy (nitinol). This last material is a super elastic memory alloy that is extremely difficult to process given its sensitivity to any crystallographic modification. Customers can provide the metal wire feedstock for atomisation in quantities as small as 100 kg.

The particle size distributions of different Ti-6Al-4V ELI (Extra Low Interstitial) powders produced by plasma atomisation were measured by laser diffraction. The apparent densities of these powders were about the same at somewhat over 2.50 g/cm^3 but their flowability was very different. The 0-25 µm powder did not flow at all. It is primarily used in cold spray or surface finish applications. The 0-45 µm powder did not flow under normal conditions of temperature and humidity but in a controlled low-humidity, low-static environment it flows well. The 15-45 µm powder was specially engineered to flow in under 35 s in the Hall flowmeter according to ASTM-B213. Finally, the 45-106 µm powder flowed in less than 25 s in the Hall flowmeter according to ASTM-B213. The powder demonstrated high sphericity and very few satellites were present in every size distribution.

Fig. 8 AP&C's management team on the site of AP&C's new titanium powder factory

Sintering Temperature (C)	Part Density (g/cm³)	% of Bulk Density (4.408 g/cm³)
1100	4.36	98.9%
1200	4.38	99.4%

Table 1 Effects of MIM sintering temperature on part density

A typical atomisation run

A typical example of a plasma atomisation run is analysed in which 0.125" diameter Ti-6Al-4V (grade 23) wire is used as the raw material, with three converging plasma jets oriented at about 30° with respect to the vertical axis. The plasma contacts the metal wire less than 2.5 cm from the plasma torch nozzle outlet. Each plasma torch operates at a power of 30 kW with a 150 standard litre per minute (SLM) argon gas flow. A background sheath gas was used to ensure the proper transport of metal droplets. The sheath gas flow is in the range of 550 SLM. An electric current of about 180 A at 45 V DC was used to preheat the wire and this is fed at 13 kg/h through a gas-cooled, adjustable guide to maintain the wire position at the apex of the plasma torch jets. Wire is typically run in batches of approximately 100 kg. The gas to metal ratio in this production run was 8.7. The resulting PSD obtained was determined according to ASTM B214 'Standard Test Method for Sieve Analysis of Metal Powders'. Despite the low gas-to-metal ratio, this application yielded over 90% of 0-106 µm and almost 60% of 0-45 µm powder.

Investing for the future

AP&C has the world's largest production capacity for spherical titanium powder. The company has production capacity of 500 tons per year in its first plant in Boisbriand, Canada. The company's second plant will start production in the third quarter of 2017 at St. Eustache, Montreal, Canada, providing an additional 250 tons per year of production capacity (Fig. 7, 8). AP&C plans to invest up to US $25 million in the new facility. The production capacity of the second plant can rapidly be increased to 750 tons per year. AP&C is investigating the possibility of adding further production capacity at different locations to locally serve strategic markets.

AP&C has developed a new grade of powder that combines very fine PSDs (0-20 µm), low oxygen content and minimal agglomeration. This new powder grade enables low MIM sintering temperatures ranging from 1100°C to 1200°C, high part density and excellent surface finish (Table 1). AP&C recently received a 30-ton order for MIM powder to be delivered in 2017 that is believed to be the largest titanium powder for MIM contract ever. AP&C has worked with the National Research Council (NRC), the Canadian government's premier research organization, to develop a new MIM feedstock containing 1% carbon. This formulation minimises grain growth which improves mechanical properties. The new feedstock's finer microstructure and low porosity translates into better fatigue resistance and fracture toughness.

Conclusion

Titanium powders are now used across many industrial sectors, especially biomedical and aerospace, to manufacture complex structures with properties such as higher strength, high biocompatibility, high resistance to metal fatigue and desired surface morphologies. Precise control of powder properties is necessary to satisfy the demands of individual applications. The plasma atomisation process enables the production of high purity spherical titanium metal powders that meet the requirements of MIM and many other applications. Powder manufacturers are continuing to push the limits to deliver larger quantities of higher quality titanium powder to enable net shape forming of ever more complex products at higher levels of quality and lower cost than conventional manufacturing methods.

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APMA 2017: MIM strengthens its competitiveness with novel technologies and new applications

Advances in MIM applications, materials and processing featured prominently at APMA 2017, the 4th International Conference on Powder Metallurgy in Asia, held in Taiwan, April 9-11 2017. In this report Prof Jai-Sung Lee, Hanyang University ERICA, focuses on developments which will strengthen the competitiveness of MIM and broaden its applications. These include the MIM of an innovative IGBT cold plate, a modified PEG/PMMA binder system for Ti-MIM, the simulation of surface defects and advances in the Catamold® feedstock system for new applications in the consumer electronics sector.

Forming innovative Insulated-Gate Bipolar Transistor (IGBT) cold plate design by MIM

Larry Lin and colleagues at Amulaire Thermal Technology, New Taipei City, Taiwan, reported on the Amulaire® innovative cold plate design feature of U-cup Fin™, which primarily targets high-end liquid cooling systems, particularly those with limited thermal dissipation space [1]. These devices, such as EV/HEV power modules, generally have a compact structure with little thermal dissipation space and, thus, have difficulties dissipating the heat they generated. Amulaire employed Metal Injection Moulding technology to achieve a complex geometric design that provides both high thermal performance and low pressure drop. The U-cup Fin™ was incorporated to reduce the wake flow arising from the obstacles encountered in the flow path.

The shape of the U-cup Fin™, which the company designed and fabricated by MIM, is very similar to that of the conventional pin fin, but with an extra round cavity at the base of the pin fin (Fig. 1). Lin stated that the presence of the round cavity at the bottom of the pin fin generates a flow that is perpendicular to the direction of the inlet flow and acts, along with the pin fin, to hinder the accumulation of the wake flow, reducing the pressure drop with improving thermal performance.

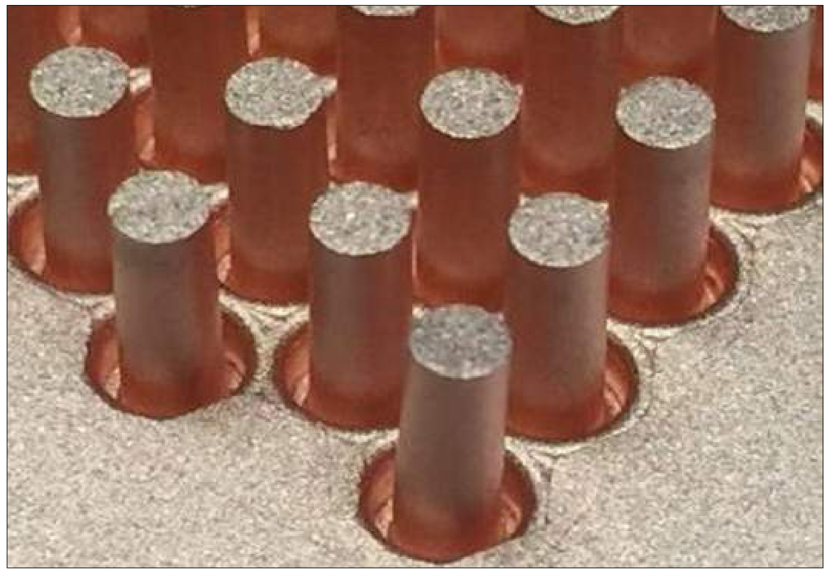

Fig. 1 U-cup Fin™ designed by Amulaire Thermal technology [1]

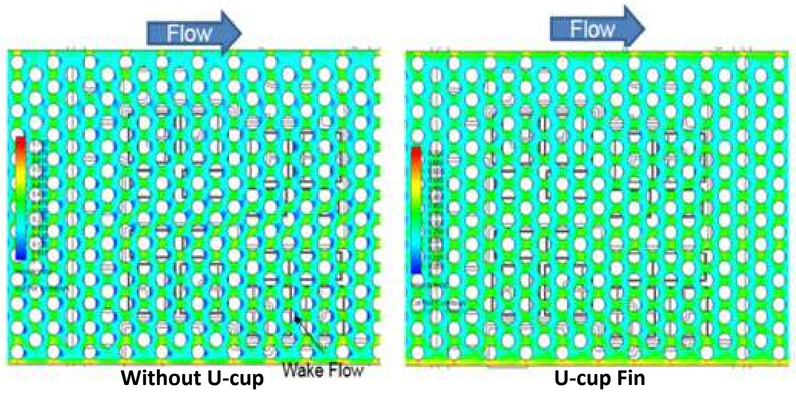

Fig. 2 CFD result of flow velocity in conventional design (left) and U-cup Fin™ (right) [1]

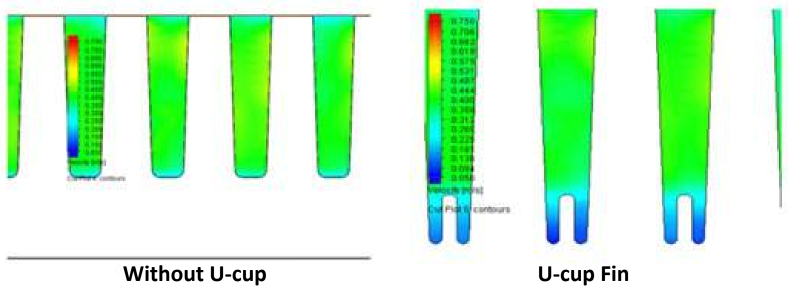

Fig. 3 CFD result of cross-sectional flow rate in conventional round pin fin (left) and U-cup Fin™ (right) [1]

Lin summarised the advantages of using the U-cup Fin™ based on the computational results as follows: Firstly, it reduces wake flow by creating a perpendicularly oriented flow field. He compared the Computational Fluid Dynamics (CFD) results of the flow velocity in the conventional design (left) and the U-cup Fin™ design (right) (Fig. 2).

The results clearly indicated that the stationary flow surrounding each pin fin was significantly decreased in the U-cup Fin™ due to the decrease of the wake flow.

Secondly, the U-cup Fin™ was found to enlarge the overall cross-sectional area that the fluid passes through. This implies that a greater cross-sectional flow area leads to a lower pressure drag and eventually reduces the overall pressure drop in the system. The CFD result of the cross-sectional flow rate in the conventional design (left) and the U-cup Fin™ (right) of Fig. 3 represented this remarkable result.

Thirdly, apart from increasing thermal performance by means of lowering stationary flow, the U-cup Fin™ MIM part was found to have lower thermal resistance. It is seen in Fig. 4 that T1 and T2 represent the minimum distance (thickness) between heat source and cooling fluid in the conventional design and the U-cup Fin™, respectively. It follows that R1, the thermal resistance in the conventional design, is greater than R2, the thermal resistance in the U-cup Fin™. As a result, the U-cup Fin™ was proven to have less heat accumulated near the heat source than the conventional design does.

Furthermore, Lin emphasised that the MIM part with the U-cup Fin™ had less part weight and, at the same time, still retained high thermal performance. This characteristic is essential for the IGBT power module market. Achieving high thermal performance and lightweight together was an urgent goal for the IGBT power module market. The authors also examined the performance of the U-cup Fin™ MIM part in comparison with the conventionally designed part by using computational simulation and an actual experiment. From Table 1 and Table 2, the U-cup Fin™ MIM part was found to have better performance in all areas than the conventionally designed part. It was also notable that the simulation results were very close to the experimental results.

In conclusion, he forecast that the U-cup Fin™ MIM part has the potential to achieve the goals of the IGBT power module market that has an increasing demand for thermal performance and light weight.

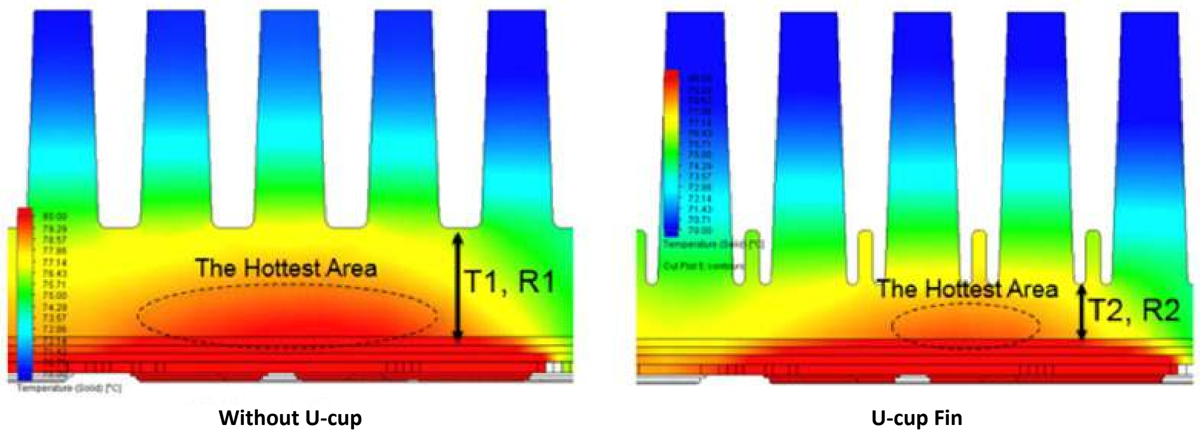

Fig. 4 CFD result of cold plate temperature in conventional design (left) and U-cup Fin™ (right) [1]

	CFD analysis		
	Conventional design	U-cup Fin™	Improvement
Flow rate (L/min)	6.82	6.82	n/a
Thermal resistance (K/W)	0.0214	0.0210	1.87%
Pressure drop (Pa)	14167.2	13152.5	7.16%
Weight (g)	540.93	422.38	21.92%

Table 1 CFD results in conventional pin fin and U-cup Fin™ [1]

	Empirical results		
	Conventional design	U-cup Fin™	Improvement
Flow rate (L/min)	6.82	6.82	n/a
Thermal resistance (K/W)	0.0216	0.0212	1.85%
Pressure drop (Pa)	20246.1	18635.3	7.96%
Weight (g)	551.98	435.95	21.02%

Table 2 Experimental results in conventional pin fin and U-cup Fin™ [1]

Modified PEG/PMMA binder system for Ti-MIM

The polyethylene glycol/polymethyl methacrylate (PEG/PMMA) binder system has not seen significant success in the Metal Injection Moulding (MIM) industry, despite being one of the cleanest and environmentally friendly binder systems. Muhammad D. Hayat and Peng Cao at University of Auckland, New Zealand reported on the modification of the PVP-PEG/PMMA binder system to be used for titanium MIM (Ti-MIM) through a complete analysis of rheological and mechanical properties, aiming at solving the problem associated with this binder system; 'Void Formation' upon solidification [2].

For their experiments, they used argon gas atomised spherical CP Ti powder (OSAKA Titanium Technologies Co., Ltd.). Using four different binder compositional feedstocks with an overall solid volume loading of 67%, they investigated the effect of incorporating varying amounts of PVP on final properties. The feedstock compositions were as follows:

- Feedstock A (15 wt.% PVP of PEG)
- Feedstock B (20 wt.% PVP of PEG)
- Feedstock C (25 wt.% PVP of PEG)
- Feedstock-D (Zero wt.% PVP of PEG–unaltered PEG/PMMA binder).

Sequence	%PVP wt./wt. % of PEG	Heat absorption (J/g)	Energy of crystallisation (J/g)
Feedstock D	0	-13.9	12.3
Feedstock A	15	-12.5	8.3
Feedstock B	20	-9.2	6.9
Feedstock C	25	-8.7	6.2

Table 3 DSC data of feedstock formulations with varying amounts of PVP [2]

In order to test the hypothesis that "incorporation of PVP into the binder mixture results in the inhibition of PEG crystallisation" for Ti-MIM, they confirmed from Table 3, based on DSC analysis, that, as the PVP content in the binder mixture was increased from Feedstock A to C, there was a reduction in the heat of melting and energy of crystallisation. Above Feedstock B composition (20 wt/wt % PVP of PEG), however, additional PVP in the binder mixture was found to inhibit PEG crystallisation negligibly (-9.2 to -8.7 J/g), stating that PVP is more expensive than PEG; hence the amount used should warrant a corresponding crystallisation inhibition.

The authors explained the simplest mechanism for PVP inhibiting PEG crystallisation as follows: As PVP is incorporated into the binder mixture with PEG, the PVP molecules encapsulate the PEG molecules. This obliterates the molecular conformity and, thereby, restrains the PEG molecules from packing together. Subsequent additions of PVP increase this restraining force, hence PEG crystallisation decreases as the PVP content in the binder is increased. They also stated that the interactions

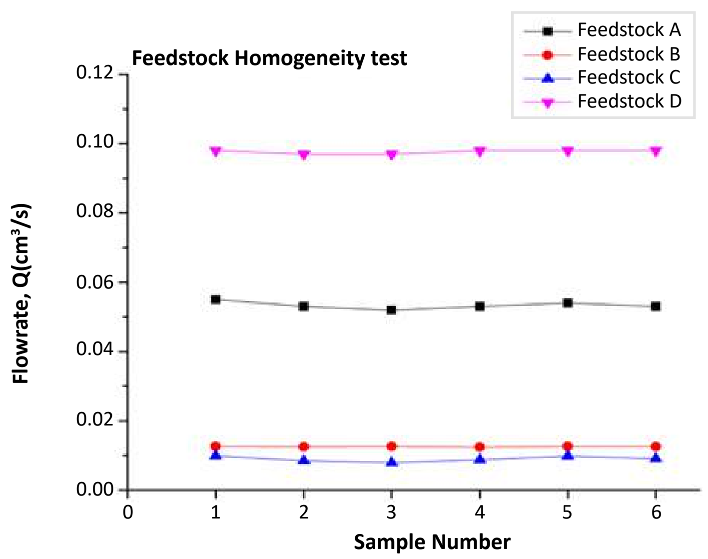

Fig. 5 Homogeneity behaviour of the feedstocks as verified by capillary rheometer [2]

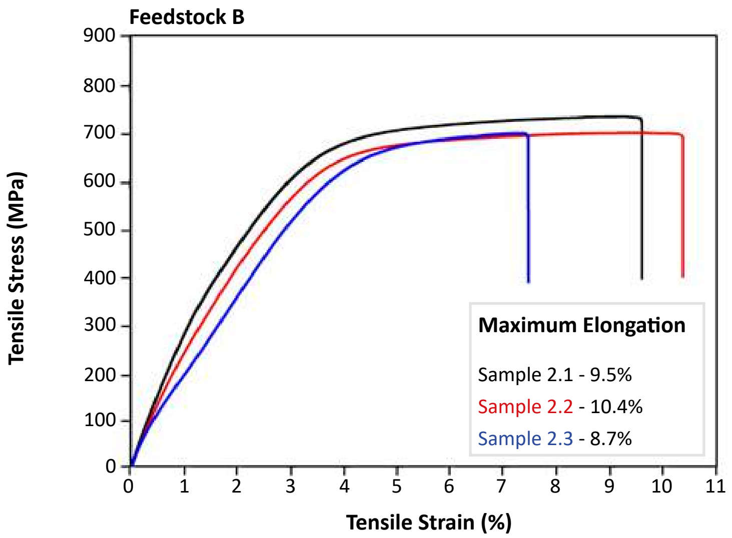

Fig. 6 Tensile property curve for Feedstock B [2]

Sequence	Mechanical properties			Relative Density (%)
	0.2% YS (MPa)	UTS (MPa)	Elongation (%)	
Feedstock B	680	760	9.5	98
Feedstock D	386	410	3	94

Table 4 Results of tensile tests for the MIM parts prepared with Feedstock B and D (average values) [2]

between the powder and binder have been proven to be a significant factor contributing to desirable final mechanical properties and excellent shape retention. For Feedstock C, having PVP 25 wt./wt.% of PEG, positive interactions between PVP and PEG did result in the inhibition of PEG crystallisation. However, the flowability was minimal (Fig. 5).

For the economical reason that PVP is relatively more expensive than PEG, the authors indicated that both the PVP and PEG amounts in the binder should not be chosen primarily on the basis of crystallisation inhibition requirement, stating that there should be sufficient PVP in the binder mixture to inhibit PEG crystallisation; however, the relative amount of PEG should not reduce so much that feedstock flowability is negatively affected.

Based on the results above, they chose Feedstock B, having PVP 20 wt./wt.% of PEG, as an optimal feedstock. Using this feedstock and, for comparison, Feedstock D, they carried out MIM experiments including injection moulding, debinding, sintering and tensile testing. From the stress-strain curve for Feedstock B (Fig. 6), they listed the results of the mechanical tests with those of sintering property in Table 4.

The authors indicated that the sintered density of the MIM sample of Feedstock D was lower, despite its better rheological properties, resulting in excellent injection moulded samples. They confirmed that this lower sinterability was attributed to the presence of voids inside the samples. However, the MIM sample of Feedstock B showed improved mechanical properties. They explained that such an improvement is due to its higher sintered density as well as an absence of void formation.

Finally, they summarised their results as follows: Through an extensive study on the addition of PVP into the water soluble PEG/PMMA based binder systems for titanium MIM, it was confirmed that the addition of PVP resulted in a decrease in PEG crystallisation, thereby minimising the solidification defects. In addition, they found that PVP was successfully removed during water debinding along with PEG, without shape distortion, emphasising that the optimal feedstock B showed considerably improved mechanical properties of the MIM part with an average elongation of 9.5%.

Simulation of surface defects in Metal Injection Moulding

Black lines are one of the most critical MIM problems, especially with regards to surface quality. Many companies using MIM technology are hoping to overcome this challenge with an efficient tool. Now, the CAE tool for plastic injection moulding, Moldex3D, has not only extended its capabilities to simulating the MIM process, but also providing powder concentration prediction to help understand the phenomena of powder dispersion and powder-binder separation. In this presentation, Shun-Tian Lin (National Taiwan University of Science and Technology), Chao-Zong Ruan (Shin Zu Shing Co., Ltd.), and Huan-Chang Tseng (CoreTech System Co., Ltd / Moldex3D) demonstrated a strong correlation between the low powder concentration areas and the real-life black line regions based upon the simulation of surface defects in MIM and using a real experiment [3].

According to the validity of the assessment of powder concentration, the authors used the suspension balance model for the concentrated suspension fluid simple flow channels, including both plaque and contraction-expansion geometries for presenting the powder-binder phase separation during flowing. In the case considered, the average volume fraction was 60 vol.% and the powder diameter was 10 µm. The simulation result showed the powder concentration pattern in the plaque flow in Fig. 7. The appearance of a powder concentration gradient is obvious. As a whole, near a wall, the concentration was relatively low, whereas the central concentration was high. For this reason, such a representation clearly indicates the powder-binder phase separation.

The authors applied the simulation result to a real MIM part of interest in Fig. 8. The part volume is about 4 cm^3. The MIM powder feedstock used had a solid powder loading of 60%, consisting of a POM (Polyoxy-

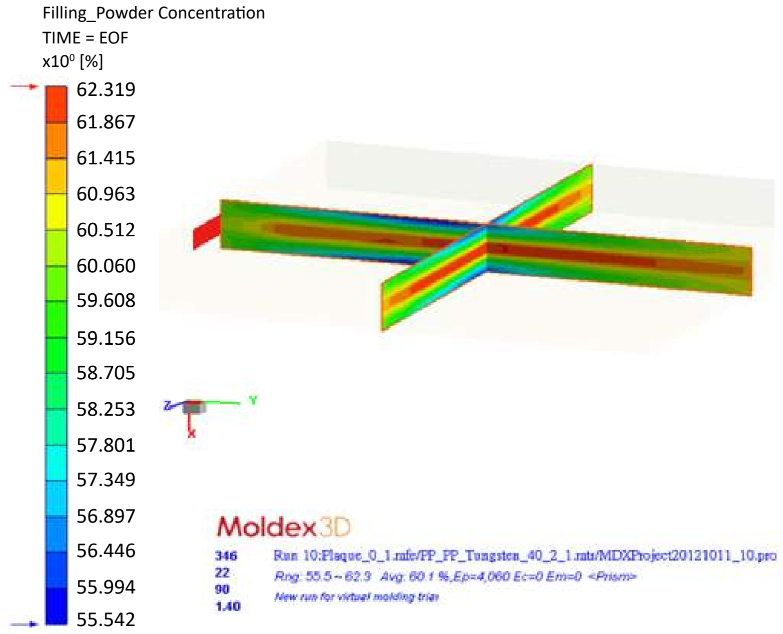

Fig. 7 Powder concentration pattern for the plaque filling with the average volume fraction of 60 vol.% [3]

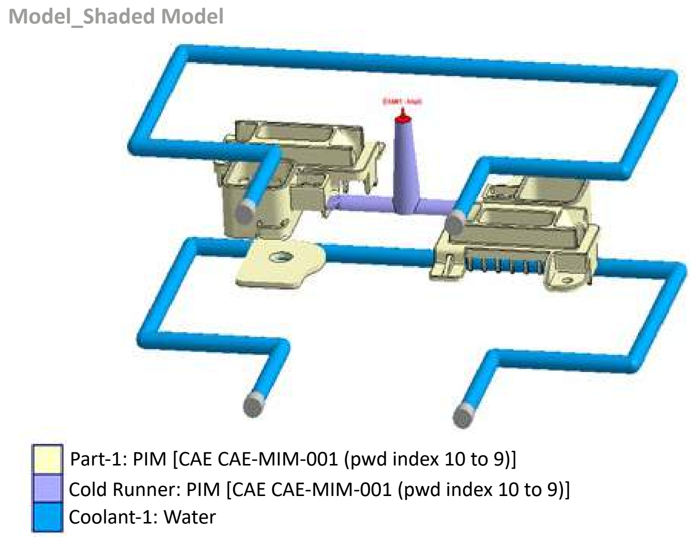

Fig. 8 Geometry of real MIM part [3]

methylene) binder and 17-4PH steel powder. The process conditions were as follows: The mould temperature was approximately 100°C, while the inlet temperature was 200°C. The filling time and packing time were about 0.3 sec and 2.3 sec. It is noted that the mass of the green part was about 23 g and the sintered part was about 21 g.

As a result of the MIM experiment, the MIM part (Fig. 9) showed that the surface defect on the sintered part, marked by blue lines, exhibited some dark areas among the larger light areas. The authors explained that this is generally called a black line in MIM industrial fabrication, or is known as powder-binder phase separation for the academic community.

Furthermore, they predicted the surface powder concentration distribution by using Moldex3D's PIM package, as shown in Fig 10. It was

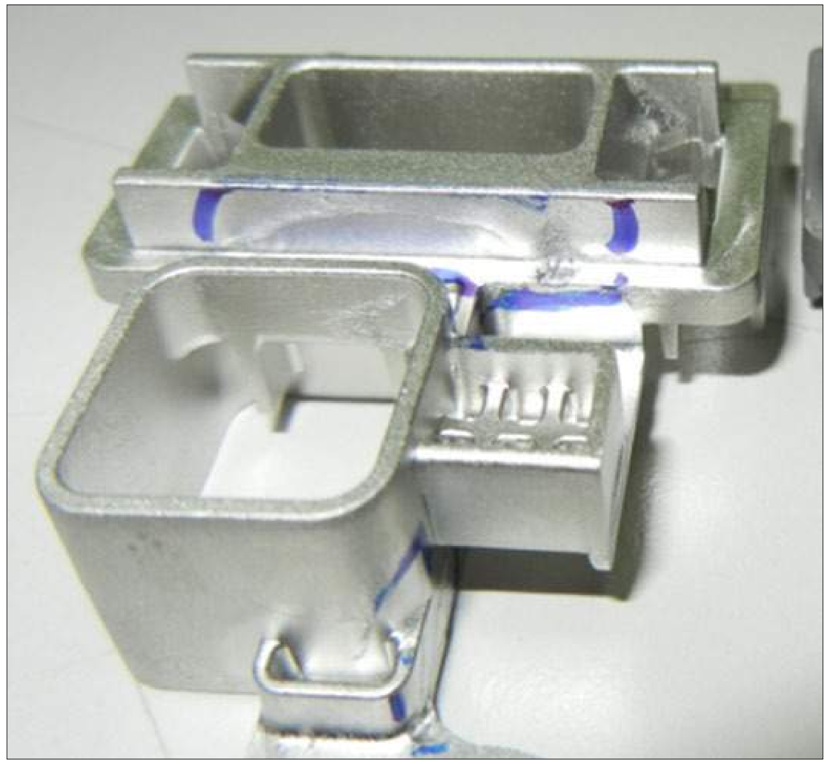

Fig. 9 The black lines of the real sintered part are marked by blue lines [3]

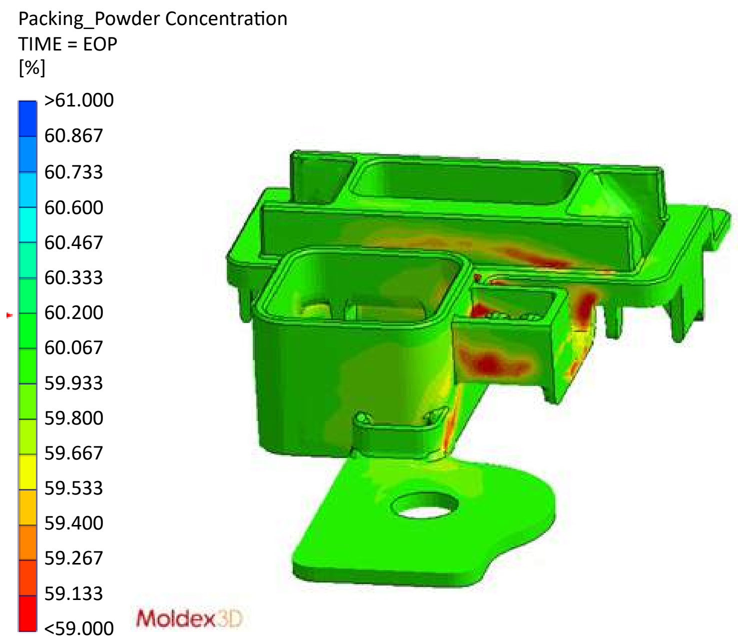

Fig. 10 Powder concentration distribution prediction [3]

clear that the overall distribution was uniform, or was close to the average concentration (60 vol.%). Obviously, some lower concentration areas were noted. From the comparison of a relationship between Fig. 9 and Fig. 10, surprisingly, the authors found that the black lines are related with low concentration. Therefore, the black lines from the sintered part in the MIM process might indicate a high binder concentration or a low powder concentration in the green parts. This is helpful to suggest black lines via the powder concentration prediction, especially concerning the surface defects in MIM parts.

In summary, the authors demonstrated the importance of performing powder concentration simulation of the concentrated suspension fluids. Based on the powder concentration simulation, they could predict black lines or powder-binder phase separation of the green parts in MIM processing, particularly near gate locations. There was a good correlation between the numerical and experimental results, indicating that the powder concentration scheme successfully simulates black lines for the final sintered products. Therefore, they concluded that the simulation system, including the suspension balance model and Moldex3D, could be a useful tool for MIM mould designers.

The Catamold® solution for challenging applications

Information from the consumer electronic market indicates that the 5G era is coming very soon and the request for the signal connection for the new generation cell phone is much higher than before. The metal mid-frame for cell phones would play an important role in maintaining good strength. The potential for this application is huge. However, the process control for MIM technology is a challenge, since the part is quite large for MIM and the manufacturing process is too long to control. Currently, the yield rate is quite low, which means that cost is higher than competing technologies. In the presentation, Bor Yuan Chen and colleagues at BASF SE, Ludwigshafen am Rhein, Germany demonstrated that Catamold® feedstock from BASF provides a solution to overcome the distortion and dimension control [4]. Another challenge for MIM is the high gloss surface quality that diminishes the porosity of the part.

They introduced the target application (Fig. 11) for cell phone middle frame, (size: 150 x 75 x 6 mm, weight: 34 g, materials: 304 and 316L stainless steels). It was noted that the material requested should be non-magnetic, have sufficient strength and good surface quality. Thus, material candidates are austenitic steels. The most important representative of the Cr-Ni steels, 316L, has better corrosion resistant than 304 (1.4306, X2 CrNi 19 11) due to the presence of 2-3% of Mo. The material 304 could also be a candidate for the mid-frame application due to low cost and relative higher strength.

In the presentation, Chen introduced the Catamold® 316L G Plus feedstock which was developed for the middle frame, back cover and high gloss surface and complex structure applications. He showed two excellent properties of Catamold® 316L G Plus: the good flowability represented by the higher melt flow index (MFI) over 1000 g/10 min (Fig. 12) and tighter oversizing factor of 1.164–1.170 (Fig. 13).

Using the Catamold® feedstock, they performed the MIM experiment including the entire MIM processes of mould design, injection, debinding, sintering, sizing and post treatment. Since the viscosity of Catamold® is relative higher than that of most thermoplastic materials, the pressure drop in the gating system should remain as low as possible. For this reason they adopted the hot runner for the part, as shown in Fig. 14.

After injection moulding, debinding was carried out catalytically using the BASF process and by secondary thermal debinding. Through subsequent sintering and sizing processes, the authors achieved outstanding sintering properties in terms of microstructure (Fig. 15). This shows that Catamold® 316L G Plus has 200 µm surface dense layer and sintered density of 7.96 g/cm³, showing less porosity and a fully austenitic structure in the sintered condition. It is conducive to achieving a high quality and high gloss surface after post treatment.

Fig. 11 Mobile phone middle frame demonstration component showing the highly polished finish that can be achieved with the new Catamold® feedstock [4]

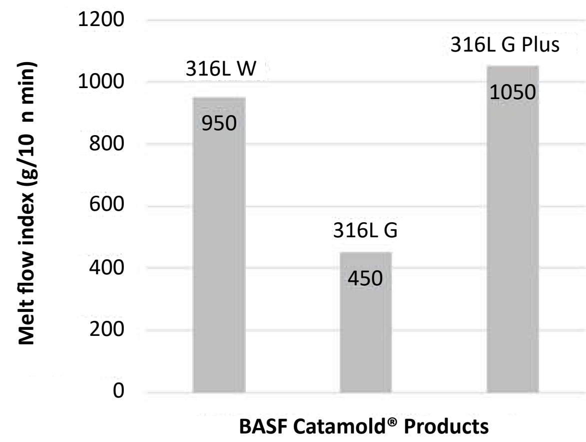

Fig. 12 Melt flow index of BASF Catamold® 316L W, G, and G Plus grades [4]

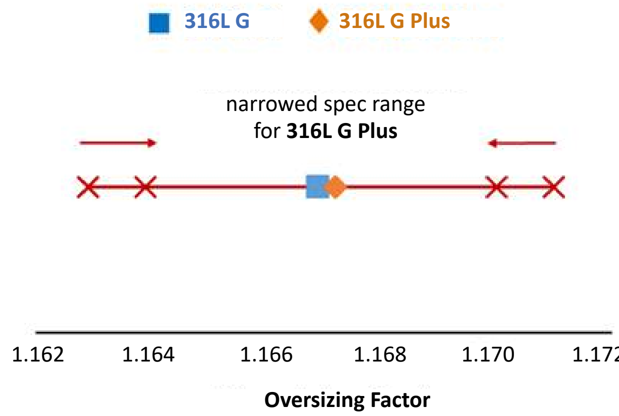

Fig. 13 Oversizing factor of BASF Catamold® 316L G and G Plus grades [4]

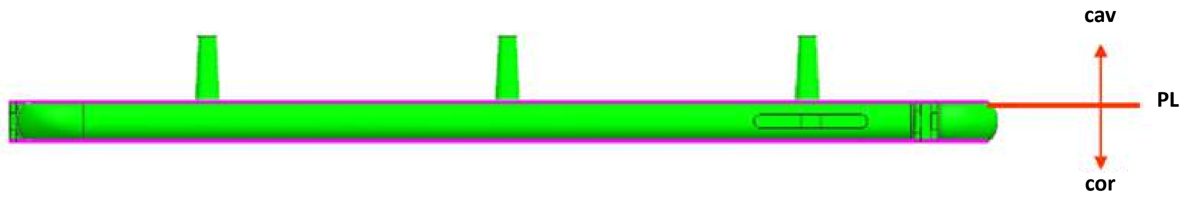

Fig. 14 Mould design [4]

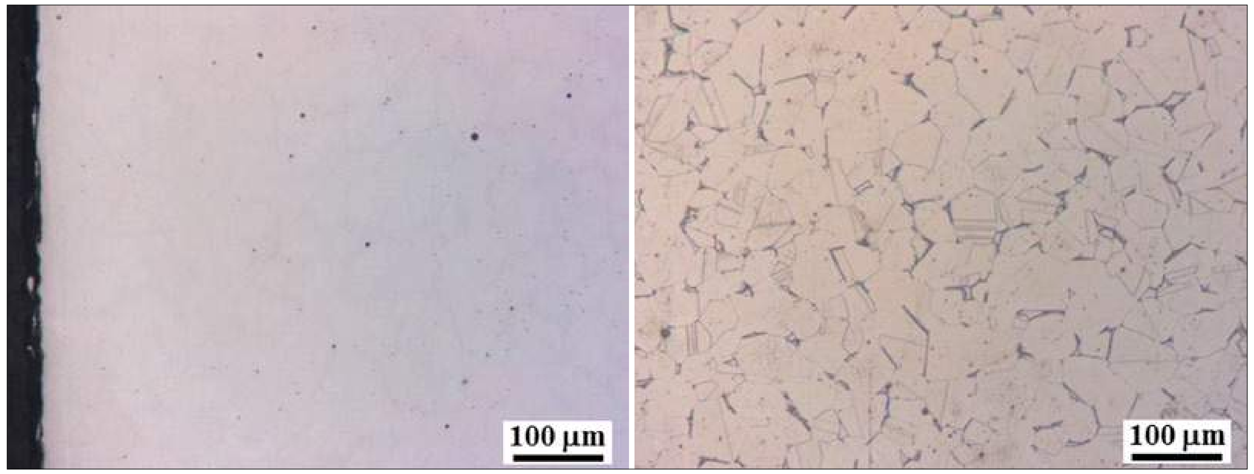

Fig. 15 Surface area and metallography of Catamold® 316L G Plus [4]

In conclusion, the authors stated that Catamold® technology is a reliable way to produce a challenging MIM component, such as the large sized middle frame, in very high numbers at a reasonable yield rate, indicating that the key points are to control material selection, mould design, sintering and polishing. Thus, Catamold® technology provides an essential contribution in rationalising and standardising the MIM production process for the mid-frame application and this has given an additional impetus in competitiveness.

Further MIM highlights from APMA 2017

Three papers highlighted in the previous issue of *PIM International* (Vol. 11 No. 1) were also introduced at APMA 2017 and are therefore only reviewed in brief in this report.

Advances in PIM of tri-modal type iron micro-nano powder

Jai-Sung Lee and colleagues at Hanyang University-ERICA in Ansan, Korea, presented an invited paper entitled 'Advances in Powder Injection Moulding of tri-modal type Fe micro-nano powder' [5]. They introduced this work mostly based upon their previous paper presented at the World PM2016 Congress and reported in *PIM International*, Vol. 11, No. 1, January 2017, pp 83-84. In this invited presentation, Lee introduced a new result on the improvement of mechanical properties in the tri-modal powder PIM part. The test results showed that the tensile specimens were fabricated by isothermal sintering at 1250°C for 3 h. It was found that the tri-modal powder sample showed higher UTS and elongation compared to the micro powder sample owing to its higher sintered density and smaller grain size. Lee stated that such an improvement in mechanical properties basically results from two factors; lower porosity arising from enhanced densification and grain refinement by the slow-down of grain growth.

Metal Injection Moulding of tungsten and its alloys

Yang Yu and colleagues Jiupeng, Wei Wang at China National R&D Centre for Tungsten Technology in Xiamen, China reported on 'Metal Injection Moulding of tungsten and its alloys' describing the MIM of an ultrafine oxide dispersion strengthened (ODS) W-Y_2O_3 powder, W-alloys of submicron W-Cu and W heavy alloys using wax-based binders [6]. They introduced this work mostly based upon their previous paper presented at the World PM2016 Congress and reported in *PIM International*, Vol. 11, No. 1, January 2017, pp 85-86, stating that MIM is a promising route for producing ODS-W and W-Cu shape charge liners with enhancing sinterability, reducing sintering temperature, increasing final density and providing a homogeneous microstructure.

| contents page | news | events | advertisers' index | contact |
MIM highlights from APMA 2017

Powder Injection Moulded thin-walled structure for heat dissipation

Recent advances in mobile electronic devices have become increasingly multi-functional with faster processors leading to increased heat generated by the internal components. Thus effective heat dissipation in these electronic devices is a critical issue for their good performance. Heat pipes are a relatively simple thermal management device comprising evaporator, adiabatic section and condenser. Hanlyun Cho and Seong Jin Park at Pohang University of Science and Technology (POSTECH), in Pohang, Korea presented a paper entitled 'Powder injection moulded thin-walled structure for heat dissipation' [7]. They introduced this work basically based upon their previous paper presented at the World PM2016 Congress and reported in *PIM International*, Vol. 11, No. 1, January 2017, pp 86-87, stating that PIM is a promising route for producing micro copper heat pipes because of its ability to achieve the required total pipe thickness of less than 0.6 mm with a wall thickness of around 0.1 mm ~ 0.2 mm.

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The proceedings of the technical sessions and poster programmes from APMA 2017 were published in digital format by the Taiwan Powders and Powder Metallurgy Association (TPPA) by endorsement of the Asian Powder Metallurgy Association (APMA), www.apma.asia.

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[2] Modified PEG/PMMA binder system for Ti-MIM. Muhammad D. Hayat, et al. As presented at the APMA2017 (International Conference of Powder Metallurgy in Asia), Hsinchu, Taiwan, April 9-11, 2017, and published in the proceedings by the Asian Powder Metallurgy Association (APMA).

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Prototyping for Metal Injection Moulding: 3DEO's AM solution matches the density and chemistry of MIM parts

The nature of Metal Injection Moulding technology means that creating functional prototypes that match the density and chemistry of the final parts can be both expensive and time consuming, whilst machined or AM alternatives simply do not allow for a realistic assessment of how a component will function. In the following article 3DEO's Matt Sand presents a new service that promises to deliver prototype and low to medium volume runs of components that match the performance of MIM parts.

3DEO, Inc., based in Los Angeles, California, USA, has launched a novel, low-cost Additive Manufacturing technology that is uniquely suited to help accelerate component development in the Metal Injection Moulding industry. The technology was created in part to address the MIM market's need for a true prototyping technology. Existing technologies used for MIM prototyping often include subtractive manufacturing and laser sintering processes, but neither produce parts with material properties analogous to MIM. 3DEO's new AM process uses existing MIM infrastructure and materials to create prototype parts that are held to the same density and chemistry specifications as MIM parts, based on MPIF Standard 35. Leveraging MIM in this way has allowed the company to reduce final cost of parts by 60 to 80% when compared to conventional metal AM technologies.

According to PriceWaterhouse-Coopers, the single biggest barrier to implementing metal AM is cost. High-end metal AM machines cost on average over $700,000. Lower cost options are now coming to the market, but even the lowest cost machines are priced at $120,000. One of the biggest advantages of 3DEO's new process is the low cost of the machines. With laser sintering, for example, machine amortisation can be as much as 60% of the final part cost. 3DEO's machine cost is so low that its amortisation in part cost is negligible.

Beyond MIM, 3DEO is also able to produce complex metal parts for a wide variety of industrial customers. Since the process is not constrained by a mould, additional design freedom

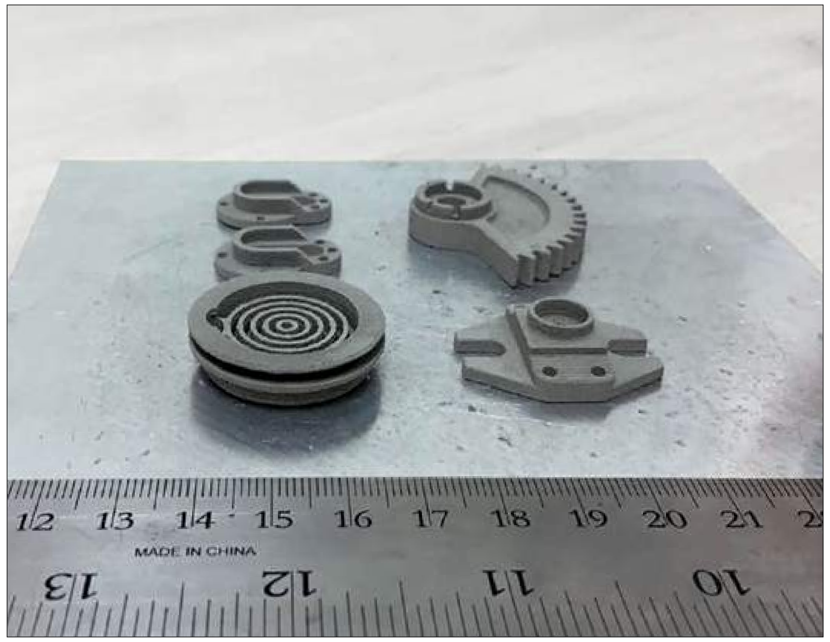

Fig. 1 Green parts after printing using 3DEO's process

Fig. 2 A selection of prototype MIM parts manufactured using 3DEO's Additive Manufacturing technology

and larger part size is possible. For example, conformal cooling channels in injection moulds are features that can only be achieved through Additive Manufacturing. Since 3DEO's technology has the design freedom of AM, there are many additional possibilities beyond MIM.

As part of its business strategy, 3DEO is not selling machines, but intends to become a parts supplier and subcontractor to other manufacturing companies. Given the low cost of 3DEO parts and established industry standards, the company is in a unique position to manufacture volumes of 100 to 10,000 pieces or more, something rarely seen in metal Additive Manufacturing.

Industry partnership with PolyAlloys

When launching the company, the 3DEO founding team quickly realised the importance of establishing strong industry connections. After exploring possible collaborations with a number of potential MIM companies in the United States, 3DEO partnered with PolyAlloys, also located in the Los Angeles area. PolyAlloys is a leading MIM manufacturer on the West Coast of the US and a division of PSM Industries, a Powder Metallurgy based parts production company with multiple facilities across the US. With its supportive team and available infrastructure, PolyAlloys has been a critical partner to 3DEO, incubating the new technology and helping the technical team understand the perspective of MIM manufacturers.

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The challenges facing MIM manufacturers

There are four main steps in MIM manufacturing: feedstock compounding, injection moulding, debinding and sintering. The homogeneous mixing of the metal powder and binding agent takes place in a large industrial mixer and creates the final pelletised feedstock. The feedstock is then injection moulded under elevated temperature and pressure to create what is known as the 'green part'. This green part is then debound via a solvent or through thermal processes, which leaves a 'brown part'. The final step is to place the brown part into an atmosphere-controlled furnace to sinter the respective metal base material. As the metal powder sinters in the furnace, the part begins to isotropically shrink 15-25% as it increases in density. After several hours in the furnace, the part is removed and cooled to its final finished state.

Due to the high cost of the mould and setup, MIM as a manufacturing process is only economical in very high volumes – typically tens or hundreds of thousands of pieces and higher, depending on complexity. This creates a number of problems for MIM manufacturers. Not only can moulds cost tens of thousands of dollars, but because of the complexity of their manufacture the first parts can take weeks or months to be delivered. Many prospective customers are simply not willing to make the capital or time investment before knowing that MIM parts will meet the fit and functional requirements of their application. Given this dilemma, MIM prototype parts will help prospective customers evaluate MIM as a manufacturing option without incurring high entry costs or delays typically associated with MIM.

A further challenge for MIM manufacturers is the difficulty of building accurate moulds that will deliver net shape parts. Even for the most experienced practitioners, there are many unknowns associated with the moulding and sintering processes. When a mould does not work as intended, either the mould needs to be re-worked or the parts need to be fixed in secondary operations. Both options cut into a MIM manufacturer's bottom line. A proper MIM prototyping technology will enable MIM manufacturers to evaluate various geometric compensations, in order to drastically increase the accuracy of the mould and decrease the need for secondary operations.

Fig. 3 A gear (top) and heat sink (bottom) produced by 3DEO (Courtesy PolyAlloys)

Traditional MIM prototyping and its limitations

There are a number of prototyping options currently used by MIM manufacturers, but none are able to produce truly analogous MIM parts. One possibility is a temporary mould approximating the part, which can be used to deliver a limited number of MIM parts. Unfortunately, with the limited output and high time investment required to engineer and produce the mould, this can be a prohibitively expensive option.

Other metal part fabrication technologies have also been employed to make prototypes that customers can use for testing. These processes include both subtractive and additive manufacturing. The main issue with using either route is that the parts produced by these processes are not reflective of MIM part performance. Customers may be able to test the fit of the part, but the function of a MIM part can be drastically different compared to the function of a metal AM part. The same goes for parts made through CNC machining.

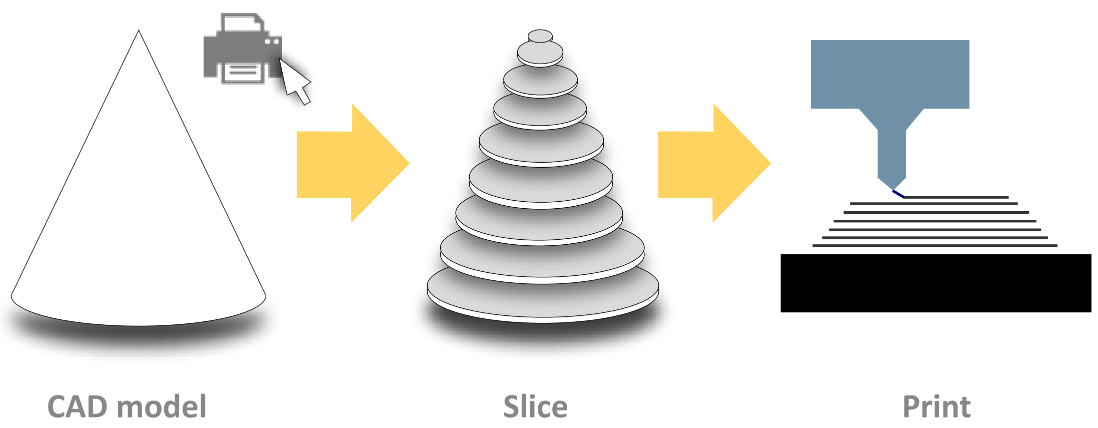

Fig. 4 The primary process steps in the conversion of a CAD object into an additively manufactured component

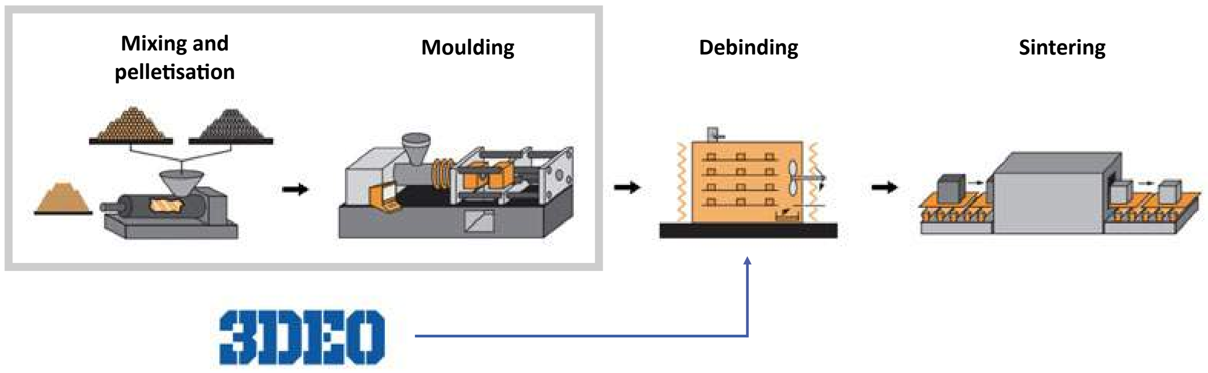

Fig. 5 The Metal Injection Moulding process. 3DEO's process shares the debinding and sintering steps as well as the metal powders

Customers correctly point out that while the dimensions of the part may be accurate, the performance of the parts will very likely be different. Ultimately, in the vast majority of cases, these subtractive and additive approximations of MIM parts will not help the customer evaluate MIM as a viable manufacturing option for high volume production. The MIM industry therefore needs the ability to create actual MIM parts in low volumes.

The opportunities presented by AM

Additive Manufacturing is a part fabrication process by which a real-world physical object is made from a three-dimensional digital model. This three-dimensional digital model is first created in a CAD software package and is then 'sliced' into two-dimensional layers (Fig. 4). Each of these layers is a thinly sliced horizontal cross-section of the eventual object. Each layer is manufactured in the AM process one at a time and stacked on top of previous layers. After all the 2D layers have been constructed, the final 3D part is complete.

There are a variety of existing metal AM processes, such as laser sintering and binder jetting, and each has its own advantages and disadvantages. In the end, AM is by no means a panacea for manufacturing. According to GE's Kirk Rogers, "Additive Manufacturing is not a replacement, but merely another method to complement other technologies on the factory floor." Regardless of the process, AM is a breakthrough manufacturing technology that will become industry standard and complementary to existing manufacturing processes.

There are a variety of benefits for AM. Design freedom is perhaps the main benefit, as parts that were previously impossible to build using traditional manufacturing techniques can be made with AM. Other benefits of AM include the elimination of tooling costs, immediate production on demand and drastically shorter lead times.

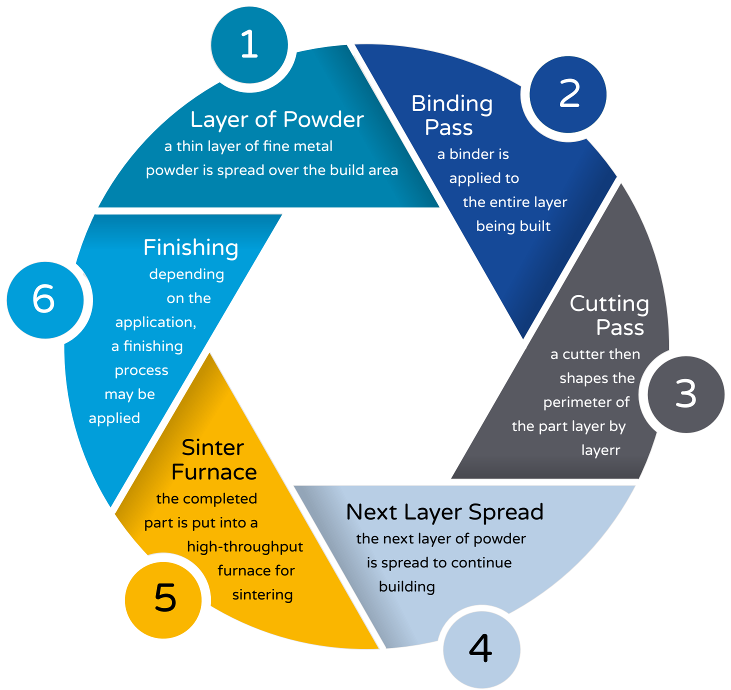

Fig. 6 Diagram of the 3DEO process steps

Creating the MIM analogue

3DEO set out to develop a rapid prototyping technique to produce truly analogous parts for the MIM industry. The team first approached this challenge by looking at the most widely recognised industry standard for MIM material properties, MPIF Standard 35. They evaluated whether green parts could be produced through Additive Manufacturing, as opposed to moulding, while still attempting to keep processing as close to MIM as possible.

This led to the creation of a process which replaces the first two steps of MIM (mixing and moulding, Fig. 5) with a single additive step, wherein a green part is created one layer at a time. This allows for green parts to be created with complex geometries and features associated with metal AM. The green part then undergoes the same sintering process as in traditional MIM. The result is a rapidly prototyped part that looks, feels and performs just like a MIM part.

There are six steps to 3DEO's Intelligent Layering® process, outlined below and in Fig. 6. The parts are built layer-by-layer in a 20 cm (8 in) by 20 cm bed of loose metal powder.

Step 1: Spread a layer of powder
The first step in the process is to spread a thin layer of spherical metal powder particles over the entire build platform. The layers can be very thin or relatively thick, depending on the geometry of the part and the features that are being built in that layer. The average layer thickness is 100 µm.

Step 2: Bind the layer
A low-cost spray head covers the entire layer with a proprietary binder. This binder is carefully applied to ensure it penetrates to an appropriate depth. The binder is cured so the part can then be defined in the next step.

Step 3: Cut the layer
A CNC end-mill is used to 'cut' the boundaries and internal features of the part. These cuts create channels that define the part as it is being built layer-by-layer (Fig. 7).

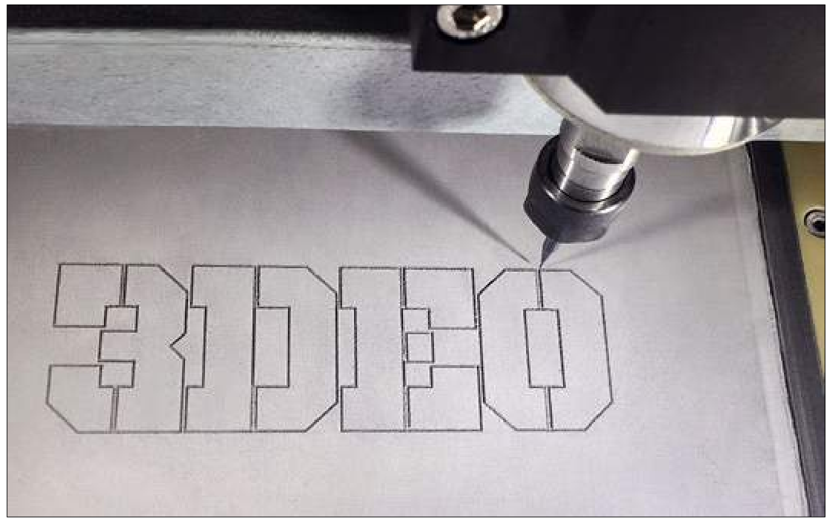

Fig. 7 The cutting set in action on a 3DEO machine

Step 4: Spread the next layer
Steps 1-3 are then repeated for every layer required to build the final green part. The height of the part determines how many layers need to be spread. For very tall parts, hundreds of layers may need to be spread. Most MIM parts require 50-100 layers.

Step 5: Sinter the green part
The green part created through this process is then inserted into a standard MIM debind and sinter furnace. Thermal debinding is, however, much more efficient due to the low binder content of 3DEO green parts.

Step 6: Finishing the part
Depending on the application and customer requirements, the parts can then be finished with a variety of options for secondary operations. Any secondary operations applied to MIM parts can also be applied to 3DEO's parts.

The metal powders used

Spherical fine MIM powders (D_{50} < 10 µm) are used in the 3DEO process. Currently, the company is making parts in 17-4PH. There are, however, many additional materials on the horizon. In theory, any spherical powder that is used in MIM today will also be able to be used in 3DEO's process. Future materials that are planned for development include:

- Inconel, nickel alloys
- Stainless steels
- F75 – cobalt chrome
- Titanium
- Tool steels
- Low alloy steels
- Soft magnetic alloys
- Controlled expansion alloys
- Tungsten carbide
- Tungsten heavy alloy
- Bronze, copper and brass

Part specifications

3DEO is currently working with MIM and non-MIM customers to further development this process. The parts being produced today meet the industry specifications of MPIF Standard 35, which is a chemistry and density specification.

- Component mass: 1 g to 2000 g
- Dimensions: 1 mm (0.08 in) to 200 mm (8 in)
- Tolerance: +/- 0.005 in/in
- Density: 97%
- Production Quantities: 10 to 10,000 units

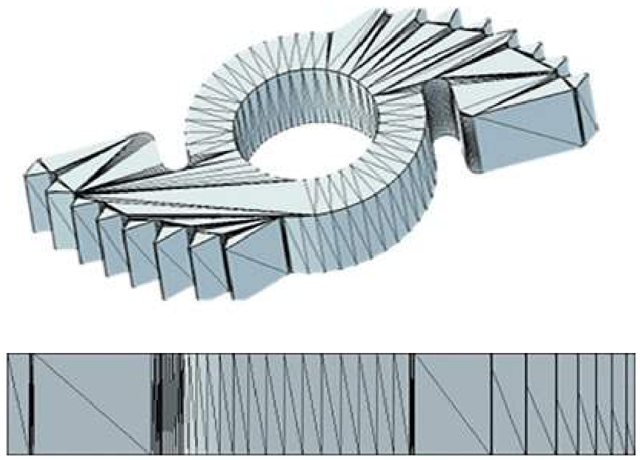

Fig. 8 An example of a 2.5D part

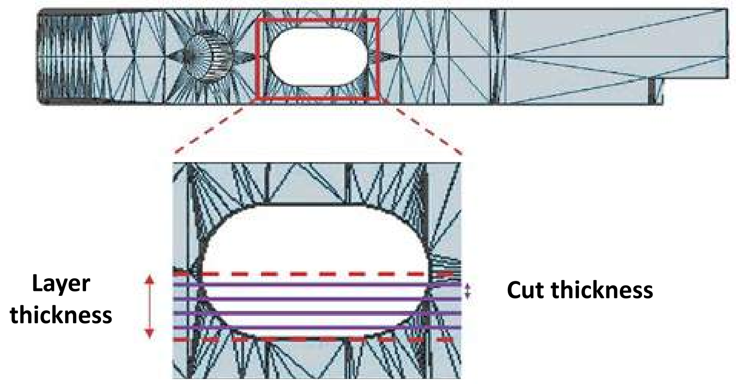

Fig. 9 Example of intra-layer cutting

3DEO's Intelligent Layering® process

There are several technical innovations in the Intelligent Layering® process used by 3DEO. The first is the ability to delay cutting on vertical sections so that multiple layers can be milled at the same time. This results in significant time savings and optimises the cutting process by only focusing on sections as needed. This is particularly useful on 2.5D parts (Fig. 8), or shape extrusions, where the CNC mill can cut down through the several layers at a time. Another highlight is intra-layer cutting, which is the ability to make multiple cuts within each individual layer to increase resolution (Fig. 9). In the 3DEO process, the cutting tool depth dictates the z-axis part resolution. For example, with each layer measuring 100 µm, this translates to cutting up to five times per layer at a thickness of 20 µm per cut. Finally, Intelligent Layering® also utilises a top down CNC process that allows for additional milling of the green part to smooth any layer lines and create high quality surface finish.

MIM prototype parts

3DEO is working with MIM manufacturers by providing prototype parts. The company states that for $2,500 it can deliver ten MIM prototype pieces with a fast ten-day turnaround. After this initial order, the per-part cost drops significantly and parts are quoted on a per-piece basis. Up to 10,000 pieces can be ordered. 3DEO intends to deliver prototype, pre-production and low-volume production orders to MIM manufacturers.

Conclusion

The strategic business advantages provided by 3DEO for the MIM industry arise from its ability to create truly analogous prototypes and low volume order fulfilment for existing customers. As a sales tool, the Intelligent Layering® system provides powerful value not only in fulfilling smaller orders, but also in the ability to reach the customer earlier in the sales process. This creates a new pipeline to grow business and funnel the higher quantity follow-on orders directly into the typical MIM process. Prototype parts can also help reduce operational costs by predicting shrinkage issues before investing in a production mould.

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ARCMIM	36
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BASF	4
Carpenter Powder Products	31
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formnext powered by TCT	82
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MIM2018	64
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PM Titanium 2017 Conference	90
PolyMIM GmbH	32
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POWDERMET2018	72
Renishaw plc	28
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Silcon Plastic	40
Sintex	33
Sintez CIP	42
TAV S.p.A.	24
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Winkworth	32
Wittman Battenfeld	29
World PM2018	63

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