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It was only by chance this summer that it occurred to me that it is forty years since Parmatech won two prizes for components produced by its new MIM process in the 1979 MPIF PM Design Excellence Awards. This was, of course, the first time MIM parts had won such an award and, as such, launched the technology to the wider Powder Metallurgy and engineering communities.

Whilst the story of the forty years that followed these awards is known to many within the MIM industry, in this issue we have taken the opportunity to present the story of MIM to a new audience of engineers and product designers who are more likely to be in tune with the opportunities presented by Additive Manufacturing (page 5). Of course, only the briefest of reviews of MIM’s short but highly successful history can be offered in fifteen pages of a magazine, but it is hoped that it will nevertheless encourage further exploration of both MIM and CIM in new quarters.

So who will read this review? Rather than risk ‘preaching to the converted’, we have an ambitious distribution plan that will see Powder Injection Moulding continue to reach new audiences, both in its print and digital formats. As highlighted on page 7 of this issue, we are excited to be organising a major showcase of PIM parts at this year’s Formnext exhibition in partnership with Mesago Messe Frankfurt GmbH, from which thousands of copies of this issue will be distributed to highly relevant visitors. This will be supplemented by an expansion of the ambitious social media campaigns that promote our digital edition to a targeted audience of new readers.

As to what the next forty years will bring, our report on Rolls-Royce’s use of MIM superalloy vanes (page 69) gives hope for a bright and ambitious future, not least in the aerospace sector.

Nick Williams,
Managing Director & Editor
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In this issue

53 Metal Injection Moulding: Celebrating forty years of innovation

Forty years ago, in 1979, Metal Injection Moulding arrived on the global stage thanks to two groundbreaking award-winning components from the technology’s pioneer, Parmatech Corp. Since then, the industry has gone from strength-to-strength, with MIM parts used in a highly diverse range of applications that we all rely on – often unknowingly – on a daily basis. These range from automotive, watch, smartphone and consumer electronics applications, to firearms, cutting tools, precision surgical devices and high-temperature jet engine components. Nick Williams reports on the industry’s evolution and highlights a number of ‘milestone’ applications.

69 MIM: An alternative manufacturing process for aerospace applications?

The aerospace sector has long been recognised as an important potential market for the Metal Injection Moulding industry. However, extended application development cycles, combined with a lack of fundamental process understanding and rigorous validation requirements have, until now, held back the technology. In this article, Rolls-Royce’s Enrico Daenicke and Schunk Sintermetalltechnik GmbH’s Ingolf Langer report on the development of a new generation of high-performance MIM components that are now flying in Rolls-Royce aero engines: IN713LC superalloy stator vanes.

77 Successful high-volume part production with HP Metal Jet 3D Printing: A guide for MIM professionals

While commercial plastic Additive Manufacturing (AM) has been a reality for nearly thirty years, metal AM is largely still in its infancy. This is due to the difficulty of using metal AM to produce cost-effective parts to the high quality and high volumes necessary to make it attractive for broader applications. Uday Yadati explains how, with its Metal Jet system, HP Inc. hopes to change this.

85 The effect of sintering conditions on magnetic and phase characteristics of X15 CrMnMoN 17-11-3 MIM nickel-free stainless steel

There is a growing market demand for non-magnetic MIM stainless steels, in particular from the 3C sector. Stainless steel alloy X15 CrMnMoN 17-11-3 is one widely known option; however, when using this material abnormal ferromagnetism can occur as a result of improper sintering profile design. Researchers from Chenming Mold Ind. Corp. (UNEEC), Taiwan, consider the root cause for this correlation between sintering parameters and final abnormal magnetic property.

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The NEW formulation

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Industry News

PIM showcase to promote MIM and CIM technology at Formnext 2019

A major showcase of more than a hundred components manufactured by Metal Injection Moulding (MIM) and Ceramic Injection Moulding (CIM) will be held at Formnext 2019, taking place in Frankfurt, Germany, November 19-22. These processes, which come under the umbrella of Powder Injection Moulding (PIM), enable the high-volume production of net shape, high-precision components from a diverse range of materials, including stainless steels, superalloys and titanium alloys.

Organised by PIM International in partnership with Mesago Messe Frankfurt GmbH, the showcase is designed to highlight the capabilities of PIM technology and its broad range of application areas. These include the automotive, aerospace, consumer electronics, medical and general engineering sectors.

Sascha F Wenzler, Vice President of Formnext at Mesago Messe Frankfurt, stated, “As the leading global exhibition and conference on Additive Manufacturing and the next generation of intelligent industrial production, Powder Injection Moulding fits perfectly into the scope of Formnext. We are delighted to be able to showcase the capabilities of MIM and CIM to our international visitors.”

“Since its launch, Formnext has seen visitor numbers increase dramatically, from 9,000 visitors in 2015 to nearly 27,000 in 2018. Made up of product designers, management, engineers, technicians and entrepreneurs from an impressive range of end-user industries, this is an ideal audience to present with this group of dynamic technologies, to the benefit of both our visitors and the industries we represent, added Wenzler.

Nick Williams, Managing Director of Inovar Communications Ltd, Shrewsbury, UK, stated, “The success of the metal Additive Manufacturing industry since the inaugural Formnext exhibition in 2015 reflects a growing acceptance of the use of metal powders for the production of high-performance end-use components for both general engineering and critical applications.”

“As technologies that have much in common with metal AM, both in terms of the starting powders and also, in the case of metal Binder Jetting and Fused Filament Fabrication, the binders and the sintering equipment used, MIM and CIM are a natural fit. Through our publication PIM International, we are excited to be able to cooperate with the Formnext team to promote the technology on such an important stage.”

The showcase, located in Hall 11.0, stand A51, will feature parts from Europe, North America and Asia and includes award winning parts from the European Powder Metallurgy Association [EPMA] and Metal Powder Industries Federation’s [MPIF] Metal Injection Molding Association [MIMA] along with numerous application examples from Germany’s MIM Expert Group [MIM Expertenkreis] and CIM Expert Group [Expertenkreis Keramikspritzguss].

www.formnext.com
www.pim-international.com

Since its launch, Formnext has seen visitor numbers increase dramatically, from 9,000 visitors in 2015 to nearly 27,000 in 2018, and ‘MIM-like’ technologies are a core focus of the event (Courtesy Mesago Messe Frankfurt)
Paper submissions now open for WorldPM2020 in Montréal

Paper submissions are now open for the 2020 World Congress on Powder Metallurgy & Particulate Materials (WorldPM2020), to be held in Montréal, Quebec, Canada, June 27–July 1, 2020. The congress is being organised by the MPIF and APMI International in conjunction with Additive Manufacturing with Powder Metallurgy (AMP) 2020 and the Tungsten, Refractory and Hardmaterials Conference 2020.

WorldPM is held every two years and in 2018 took place in Beijing, China. At WorldPM2018, more than one-hundred international exhibitors attended the exhibition, while the conference programme saw the presentation of more than 400 technical papers, including invited talks.

The 2020 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 PM processes.

In addition to the conference, there will be a major exhibition featuring a wide range of international exhibitors and providing the opportunity for visitors to network with material and equipment suppliers, part producers and end-users. Paper submissions are invited in the following categories:

- Design & modelling
- Particulate production
- General compaction & forming processes
- Powder Injection Moulding
- Pre-sintering & sintering
- Secondary operations
- Materials
- Refractory metals, carbides & ceramics
- Advanced particulate materials & processes
- Material properties
- Testing & evaluation
- Applications
- Management issues

Those wishing to submit papers should do so no later than November 15, 2019. Further information on the event and on paper submissions is available via the conference website www.mpif.org/events/worldPM2020.aspx.

New consultancy to drive MIM application development in China

A new MIM industry consultancy service has been established serving the Greater China area with the aim of supporting the growth of MIM technology in the region. Under the brand ‘You neeD Technology’, Kunshan Yaode Enterprise Consulting Co., Ltd’s founder, Dr Chiou, commonly known as Dr Q, has more than thirty years of experience promoting MIM technology in the region. He is joined in the enterprise by Y D (James) Cho.

The business focuses on MIM consultancy and training for MIM powder manufacturing companies, MIM equipment suppliers and MIM producers. “Our classes include part design, design for manufacturability, tooling design, material and powder selection, feedstock production and adjustment, injection moulding, the arranging and deburring of green parts, debinding, sintering and post-treatment,” Dr Chiou told PIM International.

The consulting business started earlier this year and now has a number of clients. “Every day of our month is very busy with customers in both Taiwan and mainland China. In the future, the number of consultant lecturers will gradually increase, with each having more than ten years of MIM industry experience.”

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**Micro MIM Japan succeeds in production of 0.03 mm diameter micro nozzle by MIM**

Micro MIM Japan Holdings Inc., a division of Tasei Kogyo Co., Ltd., based in Osaka, Japan, reports that it has succeeded in the mass production of a micro nozzle with a hole diameter of 0.03 mm and an aspect ratio of 5 using Metal Injection Moulding.

Using conventional technology, i.e. machining, it is currently not possible to produce a hole with a diameter smaller than 0.05 mm. By using MIM with very fine metal powder and its µ-MIM technology, Micro MIM Japan was able to realise a 0.03 mm diameter nozzle with a dense and smooth surface and roughness of Ra=0.3, without post-processing.

In the micro-fabrication of a nozzle, it is difficult to achieve this surface quality even using Laser Powder Bed Fusion (L-PBF) Additive Manufacturing, due to the problem of dross deposits or residual thermal stress. By using micro Metal Injection Moulding, it is possible for Micro MIM Japan to produce ultra-small nozzles with complicated flow paths and good surface quality.

![Micro MIM Japan nozzle](image)

**Melrose announces 2019 half year results, GKN on track to achieve targets**

Melrose Industries PLC has announced its interim financial results for the six months ended June 30, 2019. The company reported half year revenues of approximately £6 billion, a significant rise from £2.97 billion in the first six months 2018. Operating profit was reported at £539 million, up from £284 million in the first six months 2018.

Melrose acquired GKN plc, including GKN Powder Metallurgy, the world’s largest producer of Powder Metallurgy components, for £8.1 billion in April 2018. In its 2019 half year results, the company stated that the three main divisions of GKN are on track to achieve previously announced targets.

Of particular note was that Automotive and Powder Metallurgy divisions were maintaining profit well in an automotive industry downturn, due it was said to Melrose’s decisive cost reductions. It was also stated that many operational improvement programmes and capital investment projects were underway to help improve performance further, while good progress is being made on resolving the GKN loss-making contracts.

Justin Dowley, Melrose Chairman, commented on the results, “These results show the initial fruits of the ‘improve’ stage of Melrose’s ownership of GKN and, with the overall GKN margin increasing positively, we are excited about what is possible. The performance is in line with expectations and leverage is better than expected. At the same time, this has been a year of record investment in aerospace technology and substantial eDrive development.”

www.melroseplc.net
www.gkn.com
AMP appoints Chris Chapman as its new Vice President of Sales and Marketing

Advanced Metalworking Practices Inc. (AMP), a manufacturer of feedstock for Metal Injection Moulding (MIM), headquartered in Carmel, Indiana, USA, has announced the appointment of Christopher M Chapman as its new Vice President of Sales and Marketing. Chapman will be responsible for developing new business opportunities for AMP’s wax/polymer (Advamet) and catalytic (Advacat) MIM feedstock binder systems. He is also expected to maintain the company’s existing business while expanding market development efforts globally.

Chapman previously worked as the Vice President of Sales and Marketing for Sun Star Inc., Latrobe, Pennsylvania, USA. In that role, he was responsible for maintaining and growing Sun Star’s medical and general industrial client base in North America. He also served in the role of Engineering and Technical Design Support. Prior to that, he worked as a Sales and Marketing Manager at Allegheny Performance Plastics and a Technical Engineer at James Walker & Co. Ltd. Chapman holds a Higher National Certificate in Mechanical and Production Engineering from Guildford College of Technology, Surrey, UK, and is a member of the Society of Plastic Engineers (SPE) and a past section president.

“Chris’s wide-ranging experience in both selling and servicing the needs of clients in the plastic and Metal Injection Moulding markets puts him in a strong position to help increase demand for our numerous feedstock offerings,” stated Lane Donoho, AMP’s President. “As a seasoned professional who has spent more than three decades in the industry, Chris has both the technical skill and the market end-use acumen to bridge between application quality attributes and raw material configuration requirements.”

www.amp-llc.net

AMP appoints Chris Chapman as its new Vice President of Sales and Marketing (Courtesy AMP)

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New project focuses on sustainable reprocessing of rare-earth magnets

A new EU-funded research and innovation project has launched focused on the Sustainable Recovery, Reprocessing and Reuse of Rare-Earth Magnets in a Circular Economy (SUSMAGPRO), with funding from the Horizon 2020 programme of the European Commission and consisting of nineteen project partners and one associated partner from nine European countries. The project’s partners represent stakeholders from industry, academia and technology transfer organisations.

SUSMAGPRO’s ambition is to dramatically change how magnets are recycled, addressing the challenge of recovering and reprocessing rare earth elements (REEs) from performant magnets, which currently have a recycling rate in Europe of less than 1%. These materials are critical components of several high-tech industries, such as automotive, aerospace, e-mobility, wind power generation, and consumer goods.

Each year, such industries require the import of 2,000–3,000 tonnes of REEs to be imported, since Europe does not have rare earth resources of its own. This puts permanent magnet manufacturing in Europe in a vulnerable position; the SUSMAGPRO project will attempt to rectify this by enabling the reclaiming of the tens of k-tonnes of magnets already imported into Europe in millions of devices as they come to the end of their useful life.

Instead of going to landfill sites or being exported to other parts of the globe, SUSMAGPRO will reportedly use the latest technology to extract the REEs from magnetic scrap, and will use short-loop circular economy routes to re-integrate the metals into new products for the European market.

SUSMAGPRO’s Coordinator is Pforzheim University, Germany, represented by Prof Carlo Burkhardt of the Institute for Precious Metals and Technology.

A previous EU project on the Resource Efficient Production of Magnets (REProMag) was covered in depth in the Winter 2017 issue of PIM International. In the article, Prof Burkhardt and colleagues reported on an initial evaluation of the Metal Injection Moulding of magnets using fully-recycled raw materials. Find the full article in our archive to learn more about the challenges facing permanent magnet production in Europe.

To learn more about SUSMAGPRO, visit the following page:
www.linkedin.com/in/susmagpro-project-8a287a184/
Jonas Zimmer appointed Managing Director of the Zimmer Group’s Process Technology division

The Zimmer Group, Rheinau, Switzerland, has appointed Jonas Zimmer the new Managing Director of its Process Technology division, which produces Metal Injection Moulding components and has capabilities in handling, damping, linear, machine tooling and systems technologies.

Jonas is the eldest son of Günther Zimmer who founded the Zimmer Group along with his brother, Martin Zimmer, in 1980. According to the group, Jonas Zimmer is an industrial engineer and has worked for more than ten years in the company. He was most recently assistant to the management of the Process Technology division.

The family-run business states that it aims to transfer the company’s management step-by-step to the next generation. Seven of the ten children of the shareholders are already employed by the group.

www.zimmer-group.de

MIM2020: It’s not too late to submit a paper

Presentation submissions will close on October 4, 2019, for MIM2020: the International Conference on Injection Molding of Metals, Ceramics and Carbides. The event will be held in Irvine, California, USA, March 2–4, 2020.

The conference is sponsored by the Metal Injection Molding Association (MIMAI), a trade association of the Metal Powder Industries Federation and its affiliate APMI International. Highlights of the 2020 event are set to include:

- A full conference programme of both high-level technical research and commercially-oriented presentations
- A tabletop exhibition & networking reception
- The annual PIM Tutorial, presented by industry veteran Randall M German

Authors wishing to present a paper at MIM2020 should submit an abstract via the submission form, which can be downloaded via the conference website. All accepted abstracts will require a PowerPoint presentation to be submitted for review prior to the conference.

Presentations are invited on the topic of manufacturing innovations in part design, tooling, moulding, debinding, sintering, and materials advancements in metals & alloys, ceramics and hard materials.

www.mim2020.org
Two MIM-focused Special Interest Seminars to take place at Euro PM2019

The Euro PM Congress & Exhibition 2019, organised by the EPMA, which will take place at the Maastricht Exhibition Congress Centre (MECC) in Maastricht, the Netherlands, from October 13–16, 2019, will feature two MIM-focused sessions as part of its programme of Special Interest Seminars (SIS).

The MIM-focused SISs will feature presentations and discussions on the current state of and developments in the MIM industry. Chaired by Georg Breitenmoser, Parmaco Metal Injection Moulding AG, Switzerland, and Prof Frank Petzoldt, Fraunhofer IFAM, Germany, the sessions will include the following presentations:

### MIM & Additive Manufacturing

- Impact of Powder-Binder-Based Additive Manufacturing on MIM
  Dr Animesh Bose (Desktop Metal, USA)
- Strategic partnership of GKN-HP-VW for Binder Additive Manufacturing
  Dr Simon Höges [GKN Sinter Metals Engineering GmbH, Germany]
- MIM and the chances of AM processes
  Dipl. Ing. Vera Friederici [Fraunhofer IFAM, Germany]

### The Future of MIM

- Update on Metal Injection Moulding and future prospects
  Benedikt Blitz [SMR Premium, Germany]
- Simulation of the process chain
  Dr Götz Hartmann [MAGMA GmbH, Germany]
- Road to Digitalisation – Digital Process Data Analysis
  Marc Kleider [Arburg, Germany]

### EuroMIM agenda

The EPMA has also released the full programme for the EuroMIM Open Meeting, taking place on October 15, 2019, during Euro PM2019. The programme includes:

- Welcome and Introductions
- Activities within the EPMA and EuroMIM in 2019 and 2020
  Bruno Vicenzi [EPMA]
- MIM trend survey data from 2018
  Georg Breitenmoser, Parmaco
- Market analysis
  Luke Harris [Sandvik Osprey]
- Interactive discussion on MIM topics
  Frank Petzoldt [Fraunhofer IFAM]

Further information on the sessions and registration details are available via the event website.

www.europm2019.com
GKN Powder Metallurgy opens new customer centre in Bonn

GKN Powder Metallurgy has opened a new customer centre in Bonn, Germany, at which customers and partners can receive support and training in all aspects of Powder Metallurgy and metal Additive Manufacturing. The opening is the third in a year which has seen the company launch customer centres in Danyang, China, and Auburn Hills, Michigan, USA.

The customer centre is expected to allow GKN Powder Metallurgy to host tailored visits for customers and business partners to meet their specific interests. Visitors to the site can also explore the integrated innovation showroom, with showcases featuring the full range of GKN Powder Metallurgy’s technology strategy, and take advantage of its spacious conference and training rooms for hands-on workshops.

“Today, emerging countries can manufacture products of the highest quality. This means we have to further accelerate innovation in Germany,” stated Guido Degen, President Additive Manufacturing at GKN Powder Metallurgy. “Our experience centres are an ideal platform for intensifying partnerships with our customers and strengthening collaboration. By discussing specific business challenges and evolving industry trends, we can identify areas of growth potential together.”

“We have great confidence we’re heading in the right direction because we are working with the world’s most amazing companies,” added Peter Oberparleiter, CEO at GKN Powder Metallurgy. “We’re developing groundbreaking products with our customers, refining 3D printing processes with our partners like HP Inc. and EOS, and creating our own digital solutions driven by the collective ingenuity of our people. GKN Powder Metallurgy’s focus on innovation will allow us to strengthen our position in the market even more in the future.”

GKN Powder Metallurgy employs more than 500 people at its IATF 16949-certified production site in Bonn, which was founded in 1934. The facility currently produces 7.2 million parts per week using conventional Powder Metallurgy and metal Additive Manufacturing.

www.gknpm.com

GKN Powder Metallurgy’s new customer centre in Bonn, Germany (Courtesy GKN Powder Metallurgy)
Centorr Vacuum Industries ships its new Sintervac AM™ furnace for additively manufactured parts

Centorr Vacuum Industries, Nashua, New Hampshire, USA, has shipped its new Sintervac AM furnace for the debinding and sintering of additively manufactured parts to a leading company in the AM market.

The new furnace is rated for operation to 1600°C. The graphite furnace design reportedly includes graphite tube and block elements created for long service life, with a four-sided hot zone and integral graphite retort for temperature uniformity. The retort also compartmentalises residual offgassing from Binder Jet materials, allowing them to be caught in the dual trapping system. The graphite insulation design provides long-term service even in the presence of process off-gassing and residual binder contamination. The Sweepgas® debinding system allows for effective ‘sweeping’ away of the process contaminants. The Sintervac AM is available in 2, 4.5, 9, 12, and 16 ft³ volumes.

www.vacuum-furnaces.com

US MIM producer MPP announces Tom Lunsford as its new CFO

MPP, a Mill Point Capital portfolio company based in Noblesville, Indiana, USA, has announced the appointment of Tom Lunsford as its Chief Financial Officer. Lunsford is reported to bring over twenty years of experience to the position and will be responsible for development and execution of the financial strategy supporting MPP’s business plan.

MPP is a global provider of custom-engineered Powder Metallurgy and Metal Injection Moulding solutions for industrial application, including material formulation, sintering, densification and PM joining techniques.

The company produces various components such as custom-engineered gears and sprockets, complex structural parts, high-strength aluminium parts and components requiring unique mechanical and physical properties, for use in high stress, wear and magnetic applications. MPP operates nine production facilities in the US and China.

www.MPinnovation.com

MIMA launches new website to further support MIM end-users

The Metal Injection Molding Association (MIMA), a trade association within the Metal Powder Industries Federation (MPIF) that promotes Metal Injection Moulding powders, components and products, has launched a new, redesigned website. Users can now reportedly benefit from a modern design, improved functionality and resources.

According to MIMA, the new website also includes a design resource centre, a growing collection of case studies, and a member directory of parts fabricators, powder and equipment suppliers, to educate end-users about the benefits of MIM technology.

The association encourages visitors to explore the new website and to sign up for a free, digital copy of the most recent MPIF Standard 35, Materials Standards for Metal Injection Molded Parts.

www.mimaweb.org
Advanced Powder Products appears for fourth time in the annual ‘Inc. 5000’

Advanced Powder Products, Inc. (APP), a MIM specialist headquartered in Philipsburg, Pennsylvania, USA, has been included in Inc. magazine’s annual list of the top 5000 fastest-growing private companies in the US. This is the fourth time that APP has appeared in the list and, this year, it is ranked 3066 with a three-year revenue growth of 121%.

The ‘Inc. 5000’ represents the most successful companies in the American economy. Companies such as Microsoft, Dell, LinkedIn and more are said to have gained their first national exposure through the list.

“We are proud to be recognised for our hard work and accomplishments by Inc. for the fourth consecutive year,” stated Donald Heaney, APP President. “As we continue to grow, we are pushing industry boundaries to provide innovative MIM solutions to some of the most critical industries. At APP, we aren’t just shaping components, we are shaping American manufacturing.”

James Ledbetter, Inc.’s Editor in Chief, commented, “The companies on this year’s Inc. 5000 have followed so many different paths to success. There’s no single course you can follow or investment you can take that will guarantee this kind of spectacular growth. But what they have in common is persistence and seizing opportunities.”

www.advancedpowderproducts.com

Hagen Symposium 2019 technical programme out now

The 38th Hagen Symposium on Powder Metallurgy, organised by the Fachverband Pulvermetallurgie (FPM), will take place in Hagen, Germany, November 28 – 29, 2019. The German-language event will include presentations on a wide range of PM technologies, as well as discussions on how Powder Metallurgy is a key technology for innovative system solutions.

The winner of this year’s Skaupy Award, to be presented during the symposium, is Prof Dr-Ing Dirk Biermann, of the Technical University of Dortmund. In his opening Skaupy lecture, Prof Biermann will discuss PM hardmetals for machining applications.

www.pulvermetallurgie.com

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nick@inovar-communications.com
14th edition of Asiamold to take place in February 2020

Asiamold 2020, organised by Guangzhou Guangya Messe Frankfurt Co Ltd., will be held at the China Import and Export Fair Complex in Guangzhou, China, from February 26–28, 2020. The event will be held concurrently with SPS – Industrial Automation Fair Guangzhou (SIAF), and will bring together leading brands in the tool, die and moulding industries and cover a diverse range of metalworking technologies.

The 2019 edition of Asiamold, held together with SIAF, attracted over 98,000 visitors, and welcomed more than 988 exhibitors from twenty countries. A number of ‘thematic zones’ once again contributed to the 2019 show’s success. In line with China’s rapid development in the field of Additive Manufacturing, the 3D Printing Asia zone was said to have been a key highlight of the show, showcasing a series of cutting-edge AM technologies and solutions by prominent brands in the region.

Some of the exhibitors reported to have confirmed their attendance at Asiamold 2020 include: Beijing Tenyou 3D Technology, Dongguan Chuangyi Metal Product, Dongguan Gunri Precision Mold, Dongguan U-Light Mould, Guangzhou Sengxing Eletric, Hostar Hotrunner Technic and JK Mold. The organisers state that the event programme is still to be announced.

Asiamold forms part of a series of international events including Formnext, Intermold Japan and Rosmould. Formnext 2019 will be held from November 19–22, at Messe Frankfurt, Frankfurt, Germany. Intermold Japan 2019 will be held from April 17–20, in Tokyo, Japan, and June 19–22 in Nagoya, Japan. Rosmould 2019 will run from June 18–20 in Moscow, Russia. The first edition of Formnext + PM South China will be held from September 9–11, 2020, in Shenzhen, China.

Arburg breaks ground on expanded US headquarters

Arburg Inc., the North American subsidiary of Arburg GmbH + Co. KG, Lossburg, Germany, has broken ground on its new US headquarters in Rocky Hill, Connecticut, USA. A groundbreaking ceremony held by the company was attended by Friedrich Kanz, Arburg Inc.’s Managing Director, and Claude-Helene McIntyre, Arburg Inc.’s VP – Finance/CFO, as well as representatives of the city of Rocky Hill.

The new hall will add approximately 2,100 m² of floor space, an expansion of more than 80% on its original scale, offering more space for building and acceptance-testing of complete turnkey systems and adapting stock machines to customer specifications, as well as a significantly larger spare parts warehouse.

According to Arburg, the new building will be equipped with modern logistics and a gantry crane with a lifting capacity of 40 tonnes. Further rooms will be made available for customer training and technical seminars, while the showroom in the existing building will continue to serve as a demonstration area for seven Allrounder injection moulding machines.

While it operates out of thirty-four locations in twenty-six countries, Arburg stated that the USA is its most important foreign market. Arburg Inc. was founded in 1990 and, in addition to its newly-expanded facility in Rocky Hill, is represented by two Technology Centers in the US – ATC California, Irvine, California, and ATC Midwest, in Elgin, Illinois. The company has a user base of 13,000 installed machines in the US, Canada and the Mexican border region.

“In recent years, our business in the US has developed significantly better and faster than expected,” stated Kanz. “Thanks to this dynamic development, we now face the fortunate problem that our US headquarters, which was newly built as recently as 2015, is already reaching its capacity limits.”

www.arburg.com

Zhang Mingfu, General Manager of Hostar Hotrunner Technic Co Ltd, stated, “Asiamold is always a good platform for us to gain company exposure and to showcase our latest innovations in hot runner systems. We are able to meet a number of overseas visitors here, which is very crucial and beneficial for us to enter the international market, providing us the opportunities to export our products abroad.”

www.asiamold-china.cn.messe-frankfurt.com

Visitors at the Asiamold 2019 event (Courtesy Guangzhou Guangya Messe Frankfurt Co Ltd)

Groundbreaking for the expansion of Arburg Inc.’s Rocky Hill headquarters. From left to right: Jim Becker, Project Architect Tecton Architects; Claude-Helene McIntyre, VP – Finance/CFO Arburg Inc.; Friedrich Kanz, Managing Director Arburg Inc.; William O’Sullivan, Deputy Mayor of Rocky Hill; and Larrye deBaer, Chairman Economic Development Commission Rocky Hill (Courtesy Arburg Inc.)

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BASF to reshape organisation with a reduction of 6000 jobs

BASF, Ludwigshafen, Germany, has reported that it is reshaping its organisation to create conditions for greater customer proximity, increased competitiveness and more profitable growth. The organisation stated that it will streamline its administration, sharpen the roles of services and regions and simplify procedures and processes. As a result, the company expects to achieve savings of €300 million, as part of an ongoing programme expected to contribute €2 billion to earnings annually from the end of 2021 onwards.

According to BASF, in the course of the strategy implementation, it expects a reduction of approximately 6,000 positions worldwide until the end of 2021. This decrease results from the organisational simplification and from efficiency gains in administration and services as well as in the operating divisions. In addition, central structures are being streamlined in the context of the announced portfolio changes. It will continue to require additional employees in fields like production or digitalisation, depending on future growth rates.

Customer-focused operating divisions, service units and regions as well as a lean Corporate Center are reported to be the cornerstones of BASF’s new organisation. The Corporate Center is anticipated to consist of less than 1,000 employees, and will support the organisation’s Board of Executive Directors in steering the company as a whole. In addition, BASF reports that around 29,000 employees will be working in cross-functional service units.

'Global Engineering Services' and 'Global Digital Services' will in future offer their services either for individual sites or globally for business units of the BASF Group. 'Global Procurement' is expected to make purchasing more effective, and 'Global Business Services' will be newly established and form a worldwide network of about 8,000 employees providing end-to-end services. They will support the business units with services, among others from the areas of finance, human resources, communications and supply chain. The unit will be led by Marc Ehrhardt, currently head of the Finance Division. BASF reports that the first changes will take effect on January 1, 2020.

"We will set up the new organisation with a clear focus on leveraging synergies, reducing interfaces and enabling flexibility and creativity," stated Dr Martin Brudermüller, Chairman of the Board of Executive Directors of BASF. "We want our customers to experience a new BASF. To achieve this, we have to live a new BASF. We will therefore continue to develop our organisation to work more effectively and efficiently. In this way, we will ensure the success of our customers, strengthen our competitiveness, and grow profitably as a company."

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Australian dental manufacturer adds two Lithoz CeraFab Additive Manufacturing systems

3rdAxis, a small dental Additive Manufacturing company located in Australia, has purchased the new CeraFab 7500 Dental and CeraFab System S65 machine from ceramic AM company Lithoz GmbH, Vienna, Austria. Lithoz specialises in AM systems for the production of bone replacement and high-performance ceramics.

The CeraFab 7500 Dental is a further development of Lithoz’s CeraFab 7500 machine, and both the hardware and software of the new machine have been optimised for dental applications. The Ultra High Contrast system (UHC vat) is said to facilitate the manufacture of complex geometries including ultra-thin occlusal veneers, making it possible to produce edges as thin as 100 µm.

According to Lithoz, the CeraFab System is designed for the industrial series production of additively manufactured high-performance ceramics and bioreabsorbable materials. Having up to four production units per electronic unit increases productivity and minimises the risk of failure, while a server-based database for storing and editing process data facilitates the documentation of builds and allows real-time monitoring.

The new machine’s WQXGA projector provides a higher resolution of 2560 x 1600 pixels, helping to guarantee the precision of AM components, especially in the micro ranges. Further, the company’s CeraFab Control software enables unrestricted access to all parameters, while CeraDoc4Med allows for the simple and automated documentation of reports required for manufacturing medical products.

Lithoz will exhibit its systems at AM Ceramics 2019, to be held in co-operation with the Ceramtec Conference taking place in Munich, Germany, from September 19–20, 2019.

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Waste plastic proposed as a binder for Metal Injection Moulding

A team of researchers at SIRIM Berhad, Shah Alam, Malaysia, led by Dr Mohd Afian Omar, has found a way to make use of waste plastic as a binder in the Metal Injection Moulding process. The technique is described as an eco-friendly way to recycle waste materials, and has been successfully employed to produce high-grade stainless steel medical implant components.

“We call it the Eco-Friendly Binder System,” explained Dr Afian. “Our recipe uses waste materials such as waste plastic as a cheap and easily-sourced material for the binder in the moulding process.” For the research project, waste thermoplastic powder was obtained from waste polyolefin, such as that used in water bottles, shampoo bottles and milk bottles, by mechanical grinding. The powder was then sieved to achieve an average particle size of 200 µm.

“Because the binder is discarded during the moulding process, it is preferable for it to be made of something cheap and plentiful,” stated Dr Afian. “It is not a part of the metal itself, so why should it add to the cost of the product?”

Every company has its own binder formula, most of which are petroleum-based formulas such as polyethylene and polypropylene, which are not typically eco-friendly. By using waste plastic mixed with wax, Dr Afian stated that he has found a binder material that has zero ecological impact. “With our process, any recycled plastic will do: mineral water bottles, shampoo bottles, even toys,” he commented.

The project is a collaborative effort between researchers at SIRIM and additional researchers at the University Sains Malaysia (USM) and International Islamic University of Malaysia (IIUM). The eco-friendly binder has been shown to work with many other alloys in addition to stainless steel, and SIRIM is now continuing its research to improve the process while evaluating the suitability of the binder system with other types of metals such as high-speed steel, cobalt-based alloys and titanium.

The waste plastic binder composition is not only environmentally friendly and non-hazardous, but also enables moulding of feedstock at low moulding temperatures and pressures. This results in less wear on tooling and allows for the use of less expensive tooling materials, such as aluminium, for relatively low-volume production of green parts.

Contact: Dr Mohd Afian Omar, afian@sirim.my

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Researchers deliver biocompatible NiTi alloy for dental implants

Two researchers based at the Universiti Teknologi Mara (UiTM), Shah Alam, Malaysia, have reportedly developed an improved alternative for dental implants using biocompatible nickel-titanium (NiTi) alloy. As reported in New Straits Times, the researchers believe that the alternative dental implants are cheaper, more effective and easier to install.

The NiTi alloy was developed by Dr Muhammad Hussain Ismail, Associate Professor, Dr Rohana Ahmad, Associate Professor, and local medical device company, Nitium Technology Sdn Bhd. According to the researchers, the NiTi elements have similar properties to those found in human bone. Dr Ahmad told New Straits Times that her team hoped to use the new implant material to produce shorter implants to be used in areas of the jaw where there is bone deficiency, and added, “This especially applies to the back of the upper jaw. The upper jaw usually has lower bone quality and is associated with lower implant success rate. Hence, we hope our implants will be the solution to this problem.”

The idea for the implant material reportedly originated from the research of Dr Muhammad Hussain Ismail, Deputy Dean of the UiTM Mechanical Engineering Faculty, who formed a partnership with Muhammad Asif Ahmad Khushaini, the founder and chief executive officer of Nitium Technology, to commercialise the alloy. Nitium Technology then turned to Dr Ahmad for her expertise in this field.

To develop the material, the team first conducted a biocompatibility study to identify any adverse effects or biological risks to organic tissues posed by the new material. This study was conducted at UiTM, Universiti Kebangsaan Malaysia (UKM), Sirim QAS International and a clinical research organisation in India. Dr Hussain manufactured his first prototypes using Powder Metallurgy and told New Straits Times, “The Powder Metallurgy method used to make our implant has reduced the production cost by 60%. One of the most important aspects in Powder Metallurgy is particle size. When we first tried to replicate the formulation, things turned out not as we expected. We mixed the mould in UiTM.”

More than one hundred prototypes were then metal injection moulded in Sirim Penang, Malaysia, and underwent pre-clinical studies. After making some modifications to the powder size and binder characteristics to improve flow and pore distribution, a second prototype has now been tested in an animal study.

The team are still analysing the results of this study, the paper reported, but expect a positive outcome from the data analysed so far. Once completed, the new dental implant is expected to be launched in 2020.

www.uitm.edu.my

Maltese mining group to buy Metalysis out of administration

Power Resources Group (PRG), a mining company headquartered in Valletta, Malta, will buy Metalysis, Rotherham, UK, after the company entered administration following financial difficulties in June 2019. PRG will be the sole owner of Metalysis.

PRG mines tantalum and niobium in Rwanda, and has a refinery in North Macedonia. One of the challenges said to have been faced by Metalysis was its reliance on externally sourced materials, the prices of which can be volatile, for the metal powders it produced for the Additive Manufacturing industry.

Ray Power, CEO of PRG, told Reuters that Metalysis had been “just a whisper away from commerciality” when it went into administration, and that “the technology metals focus is a perfect complement to PRG’s existing vertically integrated mining and refining operations and customer base.”

Eddie Williams of Grant Thornton, joint administrator of Metalysis, said the sale had been “a very challenging process,” but that he was pleased that jobs had been saved.

www.metalysis.com | www.prgplc.eu

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SinteZ (Russian) [Image]
Sandvik reports high demand but fewer orders in Q2 2019

Sandvik AB, headquartered in Stockholm, Sweden, has reported its results for the second quarter of 2019. Revenues were said to have remained steady, but adjusted operating profit declined by 2%, adversely impacted by the negative earnings development in Sandvik Machining Solutions. In the period, order intake declined by 5% and the adjusted operating margin declined to 18.8%.

Björn Rosengren, President and CEO of Sandvik, stated, “In the second quarter, the level of demand was at a historically high level. Customer activity in the mining industry remained robust, while softer market activity in our early-cyclical businesses was noted toward the end of the quarter, most tangibly in the automotive and general engineering segments.”

“The adjusted operating margin declined to 18.8%. I am not entirely satisfied with this level,” he added. “After a long period of high focus on managing strong growth, we now further emphasise focus on efficiency measures. We will take further action in all business areas to deliver strong margins long-term. These activities will be promptly implemented and include a personnel reduction of approximately 2,000, which is on top of the 450 whom have already left during the first six months.”

“Consequently, cost of about 1.2 billion SEK will impact operating profit in the second half of 2019. I expect total savings of about 1.4 billion SEK, and these should start filtering through already toward the end of this year,” he stated.

Across the Sandvik Group, order intake decreased in the company’s main global markets, with Asia showing a decline of 6%, Europe a decline of 10% and North America a decline of 8%. Orders in South America remained stable, while orders in Australia saw a significant increase of 57%.

Sandvik Machining Solutions saw a slight decline in its Q2 operating profit, reporting a total Q2 operating profit of SEK 2,483 million, down 11% on the same period in 2018. The operating margin declined to 23.3%, compared to 26.8% in the same period in 2018. The company stated that underabsorption of fixed costs due to lower production volumes impact the operating margin by -2.7% points year-on-year. The operating margin was also adversely impacted by reduced profitability in the tungsten powder and blanks business as organic growth declined.

Sandvik Mining and Rock Technology saw a continued high order intake, earnings growth and margin expansion, and further expanded its digital offering. The division saw an operating profit improved by 13%, amounting to SEK 2,115 million (Q2 2018: 1,865). Organic growth was flat at 0%, with revenues improving organically by 3% year-on-year. In total, orders for equipment remained at a high level, positively impacted primarily by the mechanical cutting and automation divisions, while orders for underground mining equipment declined.

Sandvik Materials Technology saw a decline in organic orders of 20% year-on-year. Excluding the impact of large orders, the decline was reported to be 17% year-on-year. Operating profit excluding the effects of metal prices was SEK 454 million (Q2 2018: 338 million), implying an underlying margin of 11.3% (Q2 2018: 8.7%). Adjusted operating profit increased
President and CEO to depart in February

In August, Björn Rosengren, President and CEO of Sandvik AB, informed the Chairman of the Sandvik Board that he intends to resign and will leave the company as of February 1, 2020. He will now join ABB, a multinational automation corporation headquartered in Zurich, Switzerland.

Johan Molin, Chairman of the Board for Sandvik, stated, “Björn Rosengren has, since he joined Sandvik in November 2015, established a solid decentralised business model for the company and made the organisation more flexible and efficient.”

Björn Rosengren, President and CEO of Sandvik AB, is set to resign in February 2020 (Courtesy Sandvik AB)

“The board is very grateful for his and all the employees’ work during these years,” he continued. “We will initiate the process to assign a very experienced and competent industrial leader that can succeed Björn in the role as President and CEO and continue to develop the company even further.”

“This has not been an easy decision,” commented Rosengren. “Sandvik is a great company with a lot of future potential and I will continue to lead the organisation with a strong commitment until the end of January.”

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POWDERMET2019: State of the North American MIM industry 2019

The POWDERMET2019 International Conference on Powder Metallurgy and Particulate Materials was held in Phoenix, Arizona, USA, from June 23–26, 2019. Organised by the Metal Powder Industries Federation (MPIF), the event attracted over 850 participants and included three days of presentations accompanied by an exhibition and a range of social and networking events.

The Opening General Session included a presentation by MPIF President John F Sweet, PMT, who gave delegates a detailed overview of the state of the North American Powder Metallurgy industry. The 2019 outlook for Metal Injection Moulding was said to remain positive and firm, with estimated 2018 sales of MIM parts in the US increasing by a range of 5–10% ($440–460 million). Sales of MIM parts in China (including Taiwan) were estimated to exceed $1 billion, with European MIM parts sales said to track US sales closely or slightly higher. Total global MIM parts sales in 2018 were estimated at around $2.6 billion.

It was stated that MIM-grade fine powders consumed in the US (domestically produced and imported materials) increased by up to 10% in 2018 to 3,465,000 kg (7,623,000 lb). This amount also includes fine powders for metal AM applications. According to the MPIF PM Industry Pulse Survey, responding members of the Metal Injection Molding Association (MIMA) estimated stainless steel powders accounted for 48% of materials used by weight of MIM parts shipped (Fig. 1). Fig. 2 shows the MIM market mix according to weight of parts shipped. The medical and dental markets will continue growing along with MIM parts in vehicles. The firearms market flattened in 2018, with 2019 experiencing more of the same.

Optimism dominates market expectations for 2019, stated Sweet. The MPIF PM Industry Pulse Survey reports that 72% of MIMA respondents forecast sales increasing and 28% of MIMA members forecast more stable sales levels. The most important reported manufacturing/engineering challenges facing 2019 include reducing time-to-market, expanding capacity, reducing scrap and developing new materials. MIM companies are also actively considering potential manufacturing marriages with AM processes.

Metal powder suppliers, domestically and internationally, are expanding R&D programs and production capacities for a variety of metal AM-grade fine powders. They include: cobalt-chrome, titanium, aluminium, stainless steel, low-alloy steel, tool steel and copper, tungsten and tungsten carbide alloys, the Inconel family of materials, and aluminide alloys such as titanium aluminide and nickel aluminicides.

www.mpif.org | mimaweb.org ■

**MIM Materials Based on Weight of Parts Shipped**

![MIM materials based on weight of parts shipped (Courtesy MPIF)](image)

**MIM Market Mix According to Weight of Parts Shipped**

![MIM market mix according to weight of parts shipped (Courtesy MPIF)](image)
China’s largest PM and MIM exhibition, PM China 2020, set for Shanghai next March

PM China 2020, the 13th Shanghai International Powder Metallurgy Exhibition and Conference, will once again take place at the Shanghai World Expo Exhibition & Convention Center, China, from March 24–26, 2020. The event, organised by Uniris Exhibition Shanghai Co., Ltd, will include a number of forums and meetings focused on key Powder Metallurgy topics.

The three-day event will also include 2020 PM Industry Forum & Metal Injection Molding Symposium and will be held concurrently with the 2020 International Advanced Ceramics & Cemented Carbides Exhibition & Conference. The theme of PM China 2020 is ‘Convergence of Cutting-edge Technology & Products’.

The 2020 conference is expected to attract approximately 30,000 visitors from more than twenty countries, and over 500 exhibitors. The organisers state that the conference has maintained an average annual growth rate of 32%. Further information and pre-registration details are available via the event’s website.

en.pmexchina.com

ARC Group Worldwide announces voluntary delisting from NASDAQ

ARC Group Worldwide, Inc., DeLand, Florida, USA, has notified The Nasdaq Stock Market LLC of its intent to withdraw its common stock from listing on the NASDAQ Capital Market. The delisting will become effective on July 22, 2019. The company’s businesses include substantial Metal Injection Moulding operations in the US and Hungary.

On April 18, 2019, the company reportedly received notification from the Listing Qualifications Department of NASDAQ that for the previous thirty consecutive business days, the bid price for its common stock had closed below the minimum $1.00 per share requirement for continued listing on NASDAQ under NASDAQ’s listing rules.

Having reviewed and assessed possible actions to meet the minimum bid requirement, ARC’s company management determined to voluntarily delist from NASDAQ. The company expects its common stock to continue to be quoted and traded on the OTC Markets Pink Open Market, and does not expect the delisting from NASDAQ and SEC deregistration transitions to adversely affect its business operations.

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Indo-MIM achieves clean-sweep in MIM category in the MPIF’s Powder Metallurgy Design Excellence Awards 2019

The winners of the 2019 Powder Metallurgy Design Excellence Awards competition, sponsored by the Metal Powder Industries Federation (MPIF), were announced at POWDERMET2019 in Phoenix, Arizona, USA, in June 2019. Nine Grand Prizes and seven Awards of Distinction were given in this year’s competition, including five Grand Prizes and one Award of Distinction for components manufactured by Metal Injection Moulding. This year, and for the first time, all of the award winning MIM parts were manufactured by Indo-MIM Pvt. Ltd, headquartered in Bangalore, India. The six MIM component awards made by the MPIF reflect the diverse range of markets for MIM products and, in particular, the technology’s ongoing success in the automotive sector.

Automotive: Engine – Turbocharger Vane

In the Automotive-Engine Category for MIM components, a Grand Prize was awarded to Indo-MIM for a turbocharger vane. The part complexity includes a thin-walled, curved profile with a thick lug on top. A two-drop hot runner tool is used to produce twelve parts per shot without any slide involvement.

Automotive: Chassis – Roof Latching Plate

In the Automotive-Chassis Category, a Grand Prize was awarded to Indo-MIM for a MIM-17-4 PH latching plate used in a collapsible roof assembly for passenger cars. A solid-film lubricant coating is applied to the part to reduce friction during operation of the collapsible roof. Moulding was reportedly a challenge, as the part has two thin features joined by a thicker slotted section.

Hand Tools/Recreation – Ski Boot Bindings

The company received the Grand Prize in the Hand Tools/Recreation Category for MIM components for right- and left-hand bindings in ski boots. The parts are made from MIM-4605 that is zinc-blue passivated for corrosion resistance. Previously, the parts were cast and required many secondary operations to meet the desired configuration and dimensional tolerances.

Hardware/Appliance – Door Hinge Keeper/Ramp

A Grand Prize was awarded to Indo-MIM for two MIM-17-4 PH parts, a keeper and a ramp used in a door-
hinge assembly. The keeper has a thick but slotted curved profile that extends 79 mm. By using three slides, two to form the hole running along the length, and another to form the slot at the centre, two parts are produced per shot. Previously, the parts were cast and required considerable machining to achieve the desired dimensions.

Medical/Dental – Surgical Camera K-Mount

In the Medical/Dental Category, a Grand Prize was awarded to the company for a MIM-17-4 PH K-mount main part used in a digital surgical camera. The challenge in moulding was to develop a slide mechanism robust enough to form the y-section with ease and with precise matching to avoid flash. Previously, the part was made as two separate pieces that were subsequently welded. This created sharp edges that damaged the cable during use.

Automotive Engine – Valve Poppet

An Award of Distinction in the Automotive-Engine Category for MIM components was made to Indo-MIM for a valve poppet used in the fuel-injection system of a diesel engine for heavy trucks. The extremely small part has a tight tolerance on its outside diameter and the perpendicularity of the three legs. Part-specific forms were used during sintering to maintain part quality.

www.indo-mim.com | www.mpif.org
Metal Injection Moulding in the 5G era: Opportunities for growth

At the `Shenzhen International MIM and Additive Manufacturing Technology Summit’, to be held in Shenzhen, China, on September 26, 2019, leading MIM industry consultant Dr Y H Chiou, widely known as Dr Q, will report on opportunities for Metal Injection Moulding in the 5G era.

South China, in particular Guangdong, Hong Kong and the Macao Greater Bay Area, is China’s primary smartphone manufacturing area. It is for this reason that the Shenzhen and Dongguan have the highest density of MIM factories in the world. It is also the area where the operations of Chinese smartphone manufacturers such as OPPO, Vivo and Huawei (China’s top three producers), and overseas brands such as Apple and Google, are the most intensive. Here, the latest MIM smartphone parts are designed and mass-produced.

Dr Chiou told PIM International, “Since its advent in the 1970s, MIM technology has successfully taken a significant market share from conventional manufacturing technologies – such as investment casting, die casting, stamping and machining – in the production of small metal parts. MIM’s shrinkage ratio of more than 12% enables designers to create extremely small components with the finest of details, and the MIM industry’s ability to manufacture high volumes of small, light parts coincides with the consumer’s desire to carry and wear ever more electronic devices. MIM’s competitiveness is keeping pace with the demands of the smartphone industry and the technology continues to thrive.”

Today, significant activities are being undertaken to meet the demands of the coming 5G revolution. Dr Chiou stated that when looking at each generation of mobile networks and telecommunications technology upgrades, a corresponding proportional growth can be seen in MIM’s global gross product for the 3C sector (Fig. 1).

"As part of the development of a new generation of smartphones, Chinese manufacturers have been striving to improve the overall screen size of smartphones and avoid the ‘notch’ screen design that intrudes on the display of the current generation of Apple smartphones. This notch houses systems including sensors and the front camera modules. The production of smartphones that use a ‘micro-gear reduction module’ to enable the raising and lowering of a hidden ‘pop-up’ module, avoiding the need for the camera to intrude on screen space, began in the second half of 2018 [Figs. 2, 3],” stated Dr Chiou.

This module has become a highlight of Chinese smartphones in 2019. It is estimated that demand in...
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2019 will exceed 200 million units. Each unit includes micro-gears of less than 1 mm in diameter, micro-cylindrical gears, and internal gear modules. Each module has at least twelve MIM parts, requiring a total of more than 2.4 billion MIM components in 2019 alone for this single application. MIM has been used extensively on smartphone camera systems for many years. These cameras have many advanced functions, from features such as portrait mode to face ID systems for security authentication, and may require multi-lens systems and sensors to function. The correct positioning of these precise modules in relation to one another is vital (Fig. 4).

With the advent of new high-speed communication technology in the 5G era, MIM is also facing an important era of "hidden" needs in the wider 5G ecosystem. Physically, it is difficult to solve the challenges of 5G using conventional...
technology, because of the demand for electromagnetic compatibility, heat dissipation, current conduction and physical manufacturing tolerances. These problems are being solved through materials science and technology, resulting in a sharp increase in the demand for MIM parts made from a wider range of materials for specific applications in 5G communication signal receiving boxes, local servers and terminal devices.

Besides the use of conventional stainless steels as structural parts, the heat dissipation and electromagnetic isolation functions of copper-based alloys and the non-magnetic properties of cobalt-based alloys are required. The strength and magnetic conductivity of nickel-based alloys, the high specific gravity of tungsten alloy vibration parts, and even the inexpensive reinforcement function of iron-based alloys, constantly bring forth new and disruptive innovations to replace existing designs. It was also stated that there is an increase in the use of the sinter joining of ‘green’ MIM parts to make hollow, highly complex, or long structures.

Concluding, Dr Chiou told PIM International, “MIM will be the best partner for product design in 5G communications. With more than two hundred MIM factories in China, the technology is able to support the move to the 5G era.”

Contact: chiou_yh@yahoo.com.tw

Fig. 4 Lens protection rings manufactured with MIM technology ensure the relative positioning of lens modules and sensors, and include a variety of functional requirements that include a bright appearance, non-residual magnetism, conductivity, thermal conductivity, and even biocompatibility.
Developments in high-temperature nickel alloys for MIM applications

At POWDERMET2019, the International Conference on Powder Metallurgy & Particulate Materials, held in Phoenix, Arizona, USA, June 23–26, 2019, a presentation from Shu-Hsu Hsieh, Chung-Huei Chueh and I-Shuian Chen, Chenming Mold Ind. Corp. (UNEEC), Taiwan, and Martin Kearns, Paul Davies, Keith Murray, Mary-Kate Johnston and Szymon Kubal, Sandvik Osprey Ltd., UK, considered the effects of nitrogen atomised Inconel 713C powders / feedstocks on the microstructure and high-temperature performance via Metal Injection Moulding.

Sandvik Osprey and UNEEC’s presentation discussed the successful Metal Injection Moulding and sintering of a nitrogen gas-atomised 90% - 22 µm IN 713C pre-alloyed powder to high density. The as-atomised powder’s XRD and EBSD phase mapping demonstrated that the FCC crystal structure exists in the as-atomised state. Elemental analysis of the as-sintered material was found to be within the IN 713C specification. Analysis of the as-sintered product showed that 96.5% relative density can be reached by sintering above 1250°C. High density and uniform microstructure was achieved by sintering in the temperature range 1250–1270°C. Grain coarsening is not as pronounced within this temperature range, owing to the Zener pinning effect of MC carbides dispersed in the matrix. The sintering conditions adopted were able to control residual carbon, oxygen and nitrogen to quite low levels.

SEM images show the light contrast γ matrix phase and dark γ' segregated precipitates surrounded by the light γ network. The images also confirm the presence of a high volume fraction of cuboidal γ' precipitates, of around 0.5 µm size, in the as-sintered condition. TEM analysis reveals there is a semi-coherent interface between these phases.

Aside from primary MC metal carbides, EBSD phase mapping shows that no other secondary carbides (M6C, M7C3, M23C6) are stable within the temperature range 1250–1270°C. This implies that MC is stable in the temperature range 1250–1270°C. Nitride compounds, such as MN and M2N, are almost absent in sintered parts, even when nitrogen gas was used in the powder atomisation process.

Investigation of the oxidation behaviour of IN 713C MIM parts in the temperature range 900–1100°C for 100 h reveals that three distinct oxide layers exist. Proceeding from the inner to the outer oxide layer, these may be characterised as Al2O3, a mixed-oxide scale containing TiO2 and a spinel NiAl2O4 and NiO outer layer.

Hot tensile strength testing demonstrates that the material’s performance is comparable with data reported in other MIM studies. These results show that nitrogen-atomised powder is a suitable basis for the production of advanced industrial components by MIM. The atomisation process cost using nitrogen gas is significantly lower than that for atomising in argon gas.

UNEEC and Sandvik Osprey’s study, therefore, provides a promising and viable alternative for competitive MIM solutions for next generation high-temperature applications in automobiles, aero engines or stationary gas turbines.

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Fig. 1 HR-TEM image of 1260°C - sintered Inconel 713C

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MIM seen as alternative to casting for TWIP steels

Twinning-induced plasticity (TWIP) steel is a class of austenitic steel which has a unique combination of high mechanical properties (room temperature UTS up to 800 MPa) and ductility (elongation to failure up to 100%), based on a high work hardening capacity, which is attributed to the formation of mechanical twins during deformation. The TWIP steels have mostly high Mn content (above 20 wt.%) and small additions of C, Al and occasionally Si to promote the TWIP effect. Whilst TWIP steels have created growing interest, particularly in the automotive sector, because of their potential for the lightweight design of steel components, there are certain complications arising from their main production method – continuous casting. These include chemical interactions occurring in the mould, Mn losses during melting, strong segregation and high demands placed on hot and cold rolling machines.

Powder Metallurgy is considered an alternative production method to casting to eliminate segregation, and the potential of MIM is particularly interesting because of the possibility to achieve high sintered densities and, hence, a fully austenitic microstructure with equiaxed grains and annealing twins typical of high strength TWIP steels. Researchers at the Universitat Politecnica de Catalunya in Barcelona and at INEI-ETSII Universidad de Castilla-La Mancha in Ciudad Real, Spain, have been exploring the use of the MIM process to produce TWIP steels, and a paper on the results, by Karen-Adriana Garcia-Aguirre and colleagues, was published in Powder Metallurgy, Vol. 62, No. 3, 2019, pp. 205–211.

The researchers used a gas atomised, prealloyed Fe-22Mn-0.4-1.5Al-1.5Si powder, having particle size distribution D10 = 6 µm, D50 = 15 µm and D90 = 37 µm, with half of the powder being within the desired size range for MIM (20 µm). However, there were particles that were twice the maximum preferred size; results showed that a TWIP steel could still be successfully produced by MIM as an alternative production process, even when the prealloyed powder particle size was higher than recommended.

The prealloyed TWIP steel powder was mixed with high-density polyethylene (HDPE) and paraffin wax (PW) as binder, with the addition of stearic acid to improve the metal powder’s wettability for the binder in feedstock preparation. Feedstocks with metal powder loading of 60%, 62% and 64 vol.% were prepared and analysed for melt flow rate (MFR) (Table 1). The optimal powder loading in the feedstock was found to be 64 vol.%. Low Pressure Injection Moulding, using compressed air pressure (0.3 to 0.7 MPa) and mould temperature of 80°C, was investigated at feedstock temperatures of 150°C and 170°C to produce defect-free rectangular test bars.

Debinding was carried out first by the use of solvents to dissolve one of the binder components, and the remaining binder was then thermally extracted. The authors used TGA analyses and debinding thermal cycles previously defined for the binder system used to optimise the heating rates, isothermal tempera-

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>Temperature (°C)</th>
<th>MVR (cm³ per 10 min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2 kg load</td>
</tr>
<tr>
<td>T60</td>
<td>150</td>
<td>16.9 ± 0.3</td>
</tr>
<tr>
<td>T62</td>
<td>150</td>
<td>14.3 ± 0.5</td>
</tr>
<tr>
<td></td>
<td>170</td>
<td>21.5 ± 1.9</td>
</tr>
<tr>
<td>T64</td>
<td>170</td>
<td>21.1 ± 1.0</td>
</tr>
</tbody>
</table>

Fig. 1 Thermogravimetric analysis of the optimal TWIP feedstock – T64 (64 vol.% of metallic loading). (From paper: ‘Metal Injection Moulding (MIM) as an alternative fabrication process for the production of TWIP steel’, by Karen-Adriana Garcia-Aguirre et al, Powder Metallurgy Vol. 62, No. 3, 2019, pp. 205–211)

Fig. 2 Relative densification versus sintering temperature. (From paper: ‘Metal Injection Moulding (MIM) as an alternative fabrication process for the production of TWIP steel’, by Karen-Adriana Garcia-Aguirre et al, Powder Metallurgy Vol. 62, No. 3, 2019, pp. 205–211)

Sintering was carried out at 1200–1380°C for 1 h and the relative density evolution with the sintering temperature is shown in Fig. 2. Sintering at 1360°C for 1 h produced the highest relative density at 97.6% and the highest microhardness value of 187 HV. At higher sintering temperatures, a reduction in relative density, as well as geometric distortion, was observed, indicating an excessive sintering temperature.

The authors concluded that debinding and sintering conditions succeeded in producing a TWIP steel having a fully austenitic microstructure with equiaxed grains and annealing twins and with the proper amount of carbon in order to suppress the potential formation of martensite and carbides. Nevertheless, XRD patterns also revealed that manganese oxide formation had not been fully suppressed. This is said to be a common issue in sintering manganese steels, since manganese has a high affinity for oxygen.

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Ti6Al4V-wollastonite composites fabricated by PIM

Titanium and its alloys, such as Ti6Al4V, are often used in orthopaedics or dental applications because of their excellent biocompatibility properties and corrosion resistance. Wollastonite (WA) is a combination of calcium oxide and silica (CaSiO3) and, as a glass ceramic, is capable of forming strong chemical bonds with bone tissue and can promote the formation of apatite on bone. However, the mechanical properties of WA alone are not satisfactory so far and therefore it has limited use as an implant material.

Researchers at the Centre of Materials Engineering and Smart Manufacturing at the Universiti Kebangsaan, Malaysia, studied the combination of Ti6Al4V and the bioactive WA to produce a composite material for bone implant applications using Powder Injection Moulding. Mohd Ikram Ramli and colleagues reported on the results of their investigation in a paper published in Ceramics International (Vol. 45, [2019], pp. 11648–11653).

The authors reported that the combination of the two materials, i.e. Ti6Al4V and WA, can produce bioactive and biocompatible composite materials which can approximate the properties of human bone. However, no reports have been published to date on the use of Powder Injection Moulding to produce components from such composites. The researchers’ focus was therefore to determine the feasibility of the PIM process and the effects of sintering temperatures on the physical, mechanical and biocompatible properties of Ti6Al4V/WA composite.

The materials used in this study are 90 wt.% Ti6Al4V powder and 10 wt.% WA ceramics, having particle sizes of 19.54 µm and 10.10 µm respectively. The binder system comprises 60 wt.% of palm stearin (PS) and 40 wt.% of polyethylene (PE). Optimal powder loading was established at 67 vol.%, which is 2 vol.% below the critical powder volume percentage (CPVP) analysis established in ASTM D281-31 standards. Because the size and shape of the two powder materials differ, this will influence the dispersion of the powder in the feedstock mixing process, affecting rheological properties and shrinkage of the composite material during sintering. The authors therefore also evaluated the feedstock’s rheological properties, based on viscosity and shear rate sensitivity at temperatures of 130°C, 150°C, and 170°C. It was found that the Ti6Al4V/WA feedstock has the desirable pseudoplastic behaviour, which is needed during the injection moulding process. The Ti6Al4V/WA feedstock was subsequently injection moulded into green tensile test bars using a tabletop injection moulding machine.

The green composite parts were debound in two steps. Firstly, solvent extraction in heptane at 60°C for 6 h was used to remove the palm stearin (Fig. 1a), followed by thermal debinding of the remaining binder in argon at 500°C for 1 h. Fig. 1b shows an SEM micrograph of the Ti6Al4V/WA composite after the thermal debinding process. It can be seen that the binder system has been almost entirely eliminated. The debound parts were then vacuum sintered at 1100°C, 1200°C, and 1300°C for 5 h.

The authors stated that density of Ti6Al4V/WA composite was found to increase with increasing sintering temperature, reaching 4.12 g/cm³, or 97.5% of the theoretical density.
of the composite material, at 1300°C. They further stated that the remaining 2.5% porosity should be interconnected to allow for cell growth onto the Ti6Al4V/WA composite material, when used for medical implant applications.

The highest Young’s modulus value of 18.10 GPa was obtained at a sintering temperature of 1100°C, followed by 15.62 GPa at 1200°C and 14.57 GPa at 1300°C. The decrease in Young’s modulus, when the composites were sintered at higher temperatures, was attributed to grain growth. This degradation is also due to the transformation of β-phase (β-CaSiO₃) into α-phase (α-CaSiO₃) of wollastonite when the sintering temperature is above 1150°C. The authors stated that, even though the Young’s modulus decreases at the higher sintering temperature, it is still acceptable for bone implant applications as it is within the Young’s modulus range for human bones (10–30 GPa).

Cellular viability tests conducted on the sintered Ti6Al4V/WA composite showed that the cell absorbance increased from day 1 to day 7, as shown in Fig. 2, which indicates that the cells were proliferated and viable. It also confirmed that the PIM Ti6Al4V/WA composites are not cytotoxic and have good biocompatibility.

Fig. 2 Cell viability test for Ti6Al4V/WA composite sintered at 1200°C. (From the paper ‘Effect of sintering on the microstructure and mechanical properties of alloy titanium-wollastonite composite fabricated by powder injection moulding process’, by Mohd Ikram Raml, et al, Ceramics International Vol. 45, [2019] pp. 11648–11653)

Cellular viability tests conducted on the sintered Ti6Al4V/WA composite showed that the cell absorbance increased from day 1 to day 7, as shown in Fig. 2, which indicates that the cells were proliferated and viable. It also confirmed that the PIM Ti6Al4V/WA composites are not cytotoxic and have good biocompatibility.

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Silicon nitride bearing balls produced by optimised PIM process

Silicon nitride (Si₃N₄) is a ceramic material offering high strength, hardness, oxidation resistance, good thermal stability and creep resistance at elevated temperatures, plus reduced weight thanks to its low density compared to steels. It has, therefore, been widely used as bearings, engine turbines and valves and other structural components used in high-temperature environments. As a bearing material, the low density of Si₃N₄ reduces weight and centrifugal loading and allows an increase in operational speed. It also increases the rigidity or stiffness of the bearing due to a low elastic modulus, compared with a steel bearing, and the low friction characteristics reduce the heat generated within a bearing and the temperature rise during operation.

Powder Injection Moulding is a cost effective way to produce precision defect-free ball shapes, and researchers at the Pohang University of Science and Technology (POSTECH) and the Korea Electronic Material Co Ltd in Namdong-ro, Korea, have used conventional PIM technology in combination with pressureless sintering to produce Si₃N₄ ceramic balls. The results of the work by Chang Woo Gal and colleagues were published in Ceramics International, Vol. 45, (2019), pp. 6418–6424.

The researchers used a ball milled powder mixture (Si₃N₄ + 2 Y₂O₃), which comprises 93 wt.% silicon nitride (D₅₀ = 0.8 μm), 2 wt.% yttria (D₅₀ = 1.82 μm) and 5 wt.% alumina (D₅₀ = 0.24 μm). Yttria and alumina were added to improve the densification during sintering. The D₅₀ particle size of the Si₃N₄ + 2Y₅A powder mixture was 0.76 μm. This mixture was then blended with a wax-polymer binder system, comprising paraffin wax (PW) at 55 wt.%, polypropylene (PP) at 25 wt.%, polyethylene (PE) at 15 wt.% and stearic acid (SA) at 5 wt.%. The powder-binder mixture was mixed four times compared with three times for conventional metal-based PIM feedstocks, because of the small particle size of the ceramic powders; this was found to achieve a homogeneous Si₃N₄ + 2Y₅A feedstock. 48 vol.% powder loading was determined as the optimal solid loading in this study.

The rheological properties of the feedstock were evaluated using a capillary-type rheometer with the shear rate from 100 to 10,000 s⁻¹ and temperatures of 150°C, 160°C and 170°C. Table 1 compares the rheological values for the Si₃N₄ + 2Y₅A feedstock with other metal and ceramic PIM feedstocks. Optimum injection moulding conditions were established both for rectangular test bars and balls.

The injection moulded parts were subjected to a two-stage solvent and thermal debinding process. Solvent debinding was done in n-hexane at 50°C for 5 h to dissolve PW and SA. The thermal debinding cycle was done at a temperature up to 600°C in

<table>
<thead>
<tr>
<th>Rheological parameter</th>
<th>Si₃N₄ + 2Y₅A [In this study]</th>
<th>SUS316L</th>
<th>Gas-atomised titanium</th>
<th>PMN-PZT</th>
<th>Hypereutectic AlSi Alloy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow index (n)</td>
<td>0.318</td>
<td>0.425</td>
<td>0.278</td>
<td>0.510</td>
<td>0.570</td>
</tr>
<tr>
<td>Flow activation energy (E, kJ/mol)</td>
<td>12.97</td>
<td>26.63</td>
<td>10.40</td>
<td>18.85</td>
<td>40.65</td>
</tr>
<tr>
<td>Moldability index (αₚₚ, 10⁻⁴ Pa⁻¹ K⁻¹)</td>
<td>6.55</td>
<td>~10</td>
<td>~7.5</td>
<td>~3.6</td>
<td>~2.2</td>
</tr>
</tbody>
</table>

Table 1 Rheological values of Si₃N₄ + 2Y₅A compared with other PIM materials. (From the paper: ‘Fabrication of pressureless sintered Si₃N₄ ceramic balls by powder injection molding’ by Chang Woo Gal et al, Ceramics International Vol. 45, (2019), 6418-6424)
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Carbonyl Iron Powder
Atomized Stainless Steel Powder
Soft Magnetic Powder
MIM Feedstock
a tubular furnace in air with holding time at 250°C for 1 h and 2 h at 450°C. Final sintering of the debound samples was done in a non-oxide ceramic reaction furnace using a nitrogen atmosphere at 1750°C and 1800°C for 4 h. A packing powder (Si₃N₄:BN = 1:1) was used to reduce the thermal decomposition of Si₃N₄ due to the local gas equilibrium with silicon nitride solid. The final relative density of the Si₃N₄+2Y₅A was around 97%, when sintered at 1750°C, and 98% at 1800°C.

Examples showing the green and sintered test bar and balls can be seen in Fig. 1. Fig. 2 shows the mechanical properties obtained in the PIM Si₃N₄+2Y₅A material sintered at 1750°C and 1800°C. All mechanical properties were found to attain higher values at the sintering temperature of 1800°C, indicating that these properties greatly depend on the sintering densification, although the relative density showed very little difference between the two sintering temperatures. The authors conclude that optimising the entire PIM with pressureless sintering process allowed Si₃N₄ parts with high physical and mechanical properties to be fabricated.

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Fig. 1 Green and sintered PIM Si₃N₄+2Y₅A bodies [a] rectangular shape [b] ball shape. (From the paper: ‘Fabrication of pressureless sintered Si₃N₄ ceramic balls by powder injection molding’ by Chang Woo Gal et al, Ceramics International Vol. 45, (2019), 6418-6424)

Fig. 2 Mechanical properties of Si₃N₄+2Y₅A at two sintering temperatures [a] 3-point bending strength [b] Vickers hardness [c] fracture toughness. (From the paper: ‘Fabrication of pressureless sintered Si₃N₄ ceramic balls by powder injection molding’ by Chang Woo Gal et al, Ceramics International Vol. 45, (2019), 6418-6424)
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Binder system design

Characteristics required for Binder

- **High flowability at molding temperature**
  Binder design considering the viscosity at around the molding temperature.

- **High expansion property in the mold during injection moulding**
  Wide moulding condition range because of the Barus Effect. (Fig.1 and 2)

- **High thermal decomposition property in the de-binding process**
  There is no effect on the sinter quality, because there is no residue after de-binding. (Fig.3)

The flow amount $F$, when the load $S$ is applied to the thermoplastic fluid, is given as following equation.

$$F = aS^n$$

Here, $a$ is the flow characteristic at load=1, $n$ is Barus effect.

**Barus effect**

- $n=1$
- $n>2$

**Image of flow behavior**

- **Impact on the injection process**
  - Jetting (cause of welding)
  - Cloud, Sink (cause of dimensional error)
  - Good product

Fig.1 Schematic of the relationship between $n$ value and flow characteristic

※Since larger $n$ value, material expands in the mould, dense green part is obtained.

**Flow index (volume/Atom)**

<table>
<thead>
<tr>
<th>Stress (weight unit)</th>
<th>$n=1$</th>
<th>$n=2.33$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig.2 Flow characteristic compared with pellets using the other company’s binder

※With our binder, it is possible to obtain precise green part because material easily expands in the mould.

Fig.3 TGA Curve of Binder

※All components are vaporized at around 500°C.
Positive effects of adding carnauba wax to binders for MIM 4605 low alloy steels

Binders used in Metal Injection Moulding feedstock mostly comprise several polymers, each of which play an important role in MIM processing. For example, the primary component, or backbone, of the polymer binder helps to stabilise the shape of the injection moulded component during debinding and initial stage of sintering. Dispersants are added to the binder to improve homogeneity of the powder/binder mixture and increase powder loading; plasticisers are used to improve feedstock flow during injection moulding; lubricants such as a low-molecular weight polymer are added to the backbone binder to decrease friction between the powder particles, and thus decrease viscosity, and surfactants assist with dispersing the powder within the polymer matrix and prevent agglomeration.

Recent research by V Momeni and colleagues at the Mechanical Department and Center for Composite Materials at Malek Ashtar University of Technology in Lavizan, Tehran, Iran, has focused on the addition of carnauba wax (CW) to MIM binder systems. CW is a natural wax formed on Brazilian palm leaves and can act as a lubricant and mould releasing agent inside the feedstock. It is also said to help with particle wetting and gradual division of the debinding process.

The material is already an important part of many binder systems used for Ceramic and Metal Injection Moulding, with positive effects on the density and strength of the final sintered product. The work undertaken by the researchers covered the inclusion of CW in binders for feedstock used to process MIM parts from 4605 low alloy steels; the results of this work have been published in *Materials Science & Engineering Technology*, Vol. 50, 2019, 432–441.

The researchers used a gas atomised 4605 low alloy steel powder (Fe-2.15Ni-0.49Mo-0.42C-0.1Si) having D50 particle size of 6.44 µm and a width of size distribution S6 of 2.28, which is said to be optimum for MIM processing. They investigated the effect of using different percentages of carnauba wax in two series of binder compounds, which were then used to produce six batches of feedstock (Table 1).

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>PW (%)</th>
<th>PP (%)</th>
<th>CW (%)</th>
<th>SA (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Series 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F1</td>
<td>69</td>
<td>20</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>F2</td>
<td>65.15</td>
<td>18.9</td>
<td>15</td>
<td>0.95</td>
</tr>
<tr>
<td>F3</td>
<td>61.3</td>
<td>17.8</td>
<td>20</td>
<td>0.9</td>
</tr>
<tr>
<td><strong>Series 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F1</td>
<td>61.6</td>
<td>27.9</td>
<td>5</td>
<td>5.5</td>
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<tr>
<td>F2</td>
<td>55</td>
<td>25</td>
<td>15</td>
<td>5</td>
</tr>
<tr>
<td>F3</td>
<td>48.5</td>
<td>22</td>
<td>25</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Table 1 Weight percentages of the binder constituents used in this study. PW = paraffin wax; PP = polypropylene; CW = carnauba wax; SA = stearic acid. (From paper: ‘Effect of carnauba wax as a part of feedstock on the mechanical behaviour of a part made of 4605 low alloy steel powder using Metal Injection Molding’ by V Momeni et al. *Materials Science & Engineering Technology*, Vol. 50, 2019, 432–441)

*Fig. 1 Distribution of binder and powder of 4605 low alloy steel in S1F1 feedstock.* (From paper: ‘Effect of carnauba wax as a part of feedstock on the mechanical behaviour of a part made of 4605 low alloy steel powder using Metal Injection Molding’ by V Momeni et al. *Materials Science & Engineering Technology*, Vol. 50, 2019, 432–441)
The feedstocks containing the 4605 low alloy steel powder were injection moulded to produce MPIF 50 Standard tensile test pieces at an injection pressure of 140 bars and temperature of 170°C. Solvent debinding was carried out in n-heptane at 70°C for 5 h to remove most of the paraffin wax and stearic acid. This was followed by thermal debinding at different holding temperatures up to 600°C in argon and final sintering at 1200°C for 2 h, also in argon. Carnauba wax was found to degrade completely during thermal debinding at around 480°C with polypropylene degrading at 570°C, hence 600°C was used as the highest debinding temperature. The gradual degradation of CW was found to help maintain dimensional stability of the MIM parts during thermal debinding.

It was also found that increasing the amount of CW added to the feedstock led to an increase in sintered density which reached a maximum of 96.5% using feedstock S2F2, containing 15 wt.% CW. Average shrinkage occurring in the sintered and green samples was measured to be 17%.

The authors reported a high positive impact when adding CW to the feedstock binder, especially on mechanical and physical properties. However, a negative effect was found on the hardness of the sintered 4605 low alloy steel parts using CW in the binder. Improved part strength with an increase of CW in the binder was attributed to the fact that CW helps the backbone polymer in keeping dimensional stability of the MIM 4605 steel parts during the debinding process.

Table 2 compares the results of tensile testing and elongation of the MIM 4605 samples and all samples were reported to meet the requirements of MPIF Standard 35 for this material. Lower hardness values were attributed to the lower level of residual carbon remaining after debinding, leaving less carbon available to diffuse into the structure of the MIM 4605 steel parts during sintering.

![Table 2 Results of tensile strength and elongation tests for the developed MIM 4605 low alloy steel. (From paper: ‘Effect of carnauba wax as a part of feedstock on the mechanical behaviour of a part made of 4605 low alloy steel powder using Metal Injection Molding’ by V Momeni et al. Materials Science & Engineering Technology, Vol. 50, 2019, 432–441.)](image-url)
The company provides various types of structural material powders, magnetic material powders, and other alloy powders in a variety of particle sizes and tap density based on the demands of the customers. The product line includes 316L, 304L, 17-4PH, 4J29, F75, HK30, 420W, 440C, Fe2Ni, 4140, and FeSi. The customers have received the products with high acclaim.

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MIM & CIM Process
Metal and Ceramic Injection Molding
Metal Injection Moulding: Celebrating forty years of innovation

Forty years ago, in 1979, Metal Injection Moulding arrived on the global stage thanks to two groundbreaking award-winning components from the technology’s pioneer, Parmatech Corp. Since then, the industry has gone from strength-to-strength, with MIM parts used in a highly diverse range of applications that we all rely on – often unknowingly – on a daily basis. These range from automotive, watch, smartphone and consumer electronics applications, to firearms, cutting tools, precision surgical devices and high-temperature jet engine components. PIM International’s Nick Williams reports on the industry’s evolution and highlights a number of ‘milestone’ applications.

We live with components produced by Metal Injection Moulding (MIM) all around us. Our wristwatch may well have a MIM case and internal MIM components, while the glasses that we wear, with their ultra-compact sprung MIM hinge mechanisms, bring flexibility and comfort. Our smartphones, with their ten or more MIM parts, might be charged via ‘lightning cable’ connectors – of which billions have been made by MIM. On our laptop computer, MIM hinges deliver the perfect level of resistance when we close the screen. Our coats have MIM zip pull tabs, our houses are secured with tough MIM lock parts, and we might tune our car’s radio with a ‘cool to touch’ MIM rotary command dial before starting the engine, which may well contain high-temperature MIM turbocharger components, steel rocker arm parts and more besides.

One could go on, but the point is made. The above serves to highlight two crucial facts about Metal Injection Moulding: it is a technology that has permeated many areas of our lives, yet many people – engineers and production designers included – have never heard of it. The fact that it is so ubiquitous means, of course, that it must surely be regarded as a successful technology. But the reality is that a lack of awareness of MIM continues to limit its true potential. There are tens of thousands of applications out there that could benefit from being produced by MIM, taking advantage of its net shape capabili-

Fig. 1 A selection of MIM parts showing the range of shapes and sizes that can be manufactured by the technology, typically to net shape. The smallest part here is a 316L stainless steel locking device for a spectacle frame hinge, weighing 0.028 g and produced in volumes of more than 4 million parts a year. The largest part is a 316L tripod base which weighs 260 g and is 65 mm high.
ties, the ability to combine multiple components into one, superior mechanical properties and the ease at which it is able to deliver extremely high volumes of complex-shaped components with excellent batch-to-batch repeatability.

Whilst technology awareness may be low, success breeds success. Once a company has successfully adopted MIM technology for an application, others in the same industry quickly follow, and the technology comes to dominate. An example of this is the medical sector, where, following early groundbreaking applications in single-use surgical instruments in the 1990s, the technology has now become crucial (Fig. 2). The same can be said for firearms (Fig. 3), orthodontics and many more industries worldwide. So, whilst there are many industries where MIM has not yet made its mark, there are also many where it has brought new levels of profitability thanks to the benefits that it delivers (Fig. 4).

The above scenario does, of course, depend on companies championing their use of MIM rather than keeping it confidential in the hope of gaining a competitive advantage. The first thirty years of MIM’s evolution were in large part shrouded by a cloud of secrecy, both on the part of MIM producers protecting their technology and end-users protecting their newfound route to cost reductions and efficiency gains. When in 2006 we announced plans to launch PIM International – the first (and still only) magazine specifically focused on this industry – we were met with a mixture of enthusiasm and caution. “The industry is too secretive, nobody will talk,” was a common refrain. Thankfully, those companies who were willing to appear in our early issues led the way to the rest of the industry recognising that, in the end, they were all fighting the same battles, all facing the same technical challenges, and all shared a common goal.

Despite this, a level of secrecy remains engrained in the industry. Outside of Japan, getting detailed and accurate information on global MIM

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Fig. 2 MIM has become the preferred technology for many small, high-volume precision single-use medical device components such as these stainless steel jaws (Courtesy CMG Technologies)

Fig. 3 These stainless steel compensator brakes, which attach to Sig Sauer short barreled rifles, won a 2018 MPIF Award of Distinction for ARC Group Worldwide (Courtesy MPIF)

Fig. 4 This gas-tight flow block component is part of the specimen inlet module of a gas chromatography machine. Remarkably, MIM delivers a close to net shape part, with the only secondary operation needed being the tapping of threads in the pre-formed holes. The part won an MPIF Grand Prize in 2018 for AMT Pte, Ltd, Singapore (Courtesy MPIF)
statistics is a near-impossible task. Surveys of sentiment abound, but for hard figures on production in Europe, North America and much of Asia, we are left with regional trade associations doing their best to estimate industry size and health.

At a recent conference, a retired MIM company executive, who also happens to be a past president of a MIM industry trade association, recounted a conversation with a ‘finance guy’ at the time his company was up for sale. "Looks like the regional MIM market is reported as roughly $X million/year," said the finance guy. "Yeah, but don’t take that number as gospel, that’s a made-up number," commented the MIM executive. "Man, you are cynical! How can you say it’s a made-up number?" asked the finance guy, to which the MIM executive answered: "Because I’m the person who made it up!"

Of course, given the lack of hard data, analysts, observers and those in the industry have no choice but to make best guesses at the size and progress of the industry. In all probability, we do not even have the full picture from which to make our estimates. A few years ago, the famous Russian firearms manufacturer Kalashnikov announced that its new-generation military rifle would rely heavily on a MIM facility making a new range of parts, but we’re unlikely to get data on MIM production in Russia anytime soon.

Hesitation to share production and sales data with rivals is of course not unique to MIM; however, the diverse nature of MIM producers does not help. Firms involved in MIM range from small operators, with just one or two injection moulding machines, to ‘captive’ or in-house operations such as that of Taiwanese consumer electronics manufacturing partner Foxconn, where many hundreds of injection moulding machines are installed. As leading industry observer Prof Randall German recently stated in PIM International: “Over this industry, success is not uniform; 10% of the firms control two-thirds of the sales and enjoy 80% of the industry profits.”

How we got here

The story of MIM’s early development is the story of California-based firm Parmatech Corp. Founded in San Rafael in 1973 by four entrepreneurs; Karl Zueger, Peter Roth, Ray Millet and Ray Wiech, it specifically developed and commercialised what has become known as Powder Injection Moulding (PIM) technology, comprising Ceramic Injection Moulding (CIM) and Metal Injection Moulding.

Although the earliest forms of CIM date back to the 1930s and 40s, the process initially failed to gain acceptance and was limited by basic technology. Parmatech’s research efforts in the 1970s resulted in the development of a complex binder system that could be processed using a solvent debinding step followed by a second thermal debinding step in air. An initial patent application was filed in June 1972, with a continuation of application in 1974, and in 1980 the first MIM patent was
40 years of MIM innovation

awarded to Wiech, with Parmatech given exclusive manufacturing and licensing rights.

It was in 1979 that MIM hit the headlines – at least in some niche engineering publications – when Parmatech won two out of the five prizes awarded that year by North America’s Metal Powder Industries Federation (MPIF) (Fig. 5). The first of these award-winning parts was a 2-inch diameter ring-shaped screw seal used in the flap mechanism of Boeing 707 and 727 airliners and the German VFW 614 transport aircraft. Made of pure nickel, the part reached 96% density, offered excellent corrosion resistance and had a complex configuration featuring a unique internal discontinuous thread.

The second award was for niobium alloy parts used in a Rocketdyne rocket thrust system. The relatively large 6-inch chamber was moulded in one piece while the injector part, of an extremely complex geometry, was moulded in two pieces which were subsequently electron-beam welded together.

In 1981, the original founders of the Parmatech company separated and the wider dissemination of MIM began. Ray Millet took a licence to produce gun parts and established Millet Sights in Huntington Beach. Peter Roth returned to Switzerland with a general licence and established Moldinject, while Wiech established Witec in San Diego under a cross-licence agreement with Parmatech. Zueger remained as president and sole owner of Parmatech.

Licensing expanded the market for MIM products, increasing its geographic spread from the US and Europe to Asia. Early successes included electric typewriter heads and dot matrix printer parts developed by IBM and firearms components manufactured by Remington Arms – both licensees of the process.

One of the challenges for these early MIM producers was the availability of suitable metal powders, given the process’s specific requirements for particle size, chemistry and shape. Carbonyl iron powders were heavily relied upon, as atomisation processes at the time were not producing the necessary small-sized powders. Zero carbon Fe-Ni alloys also suited the thermal debinding in air used as part of the MIM workflow.

As both material availability and process sophistication improved, there was a move to higher performance stainless steels such as 316L and 17-4PH – materials that today have come to dominate the industry.

The industrialisation of MIM: Materials, production equipment and standards

The MIM industry’s success over the last two decades, in particular its spectacular recent growth in Asia, can be attributed in large part to...
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The commercial availability of MIM feedstock and the development of continuous debinding and sintering furnaces, in contrast to the use of batch debinding and sintering furnaces. The introduction of BASF’s Catamold® feedstock in the early 1990s was the driver behind the development of these continuous systems and, to this day, BASF remains the industry’s largest feedstock supplier.

BASF’s feedstock, based on an entirely new catalytic debinding process, allowed MIM to deliver fast and stable high-volume production and opened up new markets for the technology. In addition, the availability of a commercial feedstock system from such a recognised global company attracted new entrants into the industry.

The fact that BASF could use its own carbonyl iron powder was of course a driver behind this development; however, the industry’s growth also spurred companies such as Epson Atmix (Japan), Carpenter (USA) and Sandvik Osprey (UK) to develop MIM-tailored gas and water atomised powders, in particular 17-4 PH stainless steel.

This new era in MIM materials and production technology availability brought major new part producers into the industry. Swiss watch manufacturer The Swatch Group was one of the early adopters of Catamold for its Irony range dating back to 1994. Its ‘lights out’ continuous production facility in Grenchen, Switzerland, was held as an example of the potential of MIM production at the time, and is still in operation (Fig. 6).

By the mid-1990s, efforts were underway worldwide to create common standards for MIM. The Metal Powder Industries Federation (MPIF) first published its ‘Material Standards 35 for Metal Injection Molded Parts’ in 1993, covering a range of stainless steels and soft magnetic alloys. This standard has been revised a number of times, the latest published in 2017.

In 1997 the European Powder Metallurgy Association (EPMA) established a Thematic Network for...
European Standards on Metal Injection Moulding (MIMNet), which was financially supported by the European Union’s Standards, Measurement and Testing Programme. MIMNet published draft standards for MIM in 1999, which were later converted into the International Standard – ISO 2206: 2012. The Japan Powder Metallurgy Association (JPMA) also developed a MIM standard for Japan.

All of these early standardisation activities were important in underpinning the acceptance of MIM technology by design engineers, and have undoubtedly contributed to the continuing growth of the industry worldwide.

The MIM industry today

Global sales of MIM parts are today estimated to be in the region of $2.5 billion per year, with annual growth estimations varying by region but typically between 10–20% (Fig. 9). As manufacturing moved east, so did MIM, and today more than 50% of all MIM part production takes place in Asia. The remainder is estimated to be reasonably equally divided between the US and Europe.

There is now a wide selection of both feedstock and binder technology vendors, with MIM producers having the freedom to manufacture feedstock in-house, purchase from external vendors, or both. There has also been a proliferation of ‘Catamold alternatives’ since the lapse of BASF’s original patent.

Numerous types of binder system are available, with systems that allow debinding in water increasing in popularity in part because of their reduced environmental impact. With the evolution of binders came improved mouldability, higher green strength and the ability to mould ever more complex shapes. When this is combined with sophisticated hot runner systems, thermal management of the mould, and injection moulding simulation tools to optimise part design and mould development, previously unthinkable designs can now be manufactured by MIM.

In terms of metal powder supply, the rapid rise of AM technology has also brought a significant expansion in the number of metal powder producers that are able to offer MIM-grade powders. The rise of MIM-like AM processes, such as Binder Jetting and Fused Filament Fabrication (FFF), is expected to bring further players into the market and have a downward impact on powder prices.

A report published in PIM International in March 2019 stated that, of part designs reaching production, a typical component consists of 200,000 pieces per year, with a wall thickness of 1–3 mm and a median design mass of under 10 g. The report also emphasised that, based on the number of parts in production rather than number of designs, 6 g is a typical MIM part weight. This lower mass is influenced by the incredibly large number of smartphone components.
Regional considerations

Asia

Within Asia, Greater China leads the way, with annual sales now estimated to be around $1 billion. The major driving force for growth in the Chinese MIM industry is the consumer electronics (3C) sector, with 2017 data from the Powder Metallurgy Branch Association of the China Steel Construction Society citing mobile phones as the largest application area (65.7%), followed by wearable devices (6.9%) and computers (4.9%). Other application areas for MIM include automotive (7.2%), hardware (6%) and medical devices (3.9%).

The total shipment of materials (powders and feedstock) for MIM in China in 2017 was reported at between 8,000 and 8,500 tons. The market share for MIM materials remains relatively equally divided between domestic (55%) and foreign (45%) material producers. Of imported feedstock, BASF’s Catamold is reported to account for 90% of the market.

Around 80% of Chinese MIM firms have the capability to produce feedstock in house, although many use a combination of ready-to-use and self-manufactured feedstocks. In 2017, the most widely used MIM materials in China continued to be stainless steels (70%) and low-alloy steel (20%). Tungsten-based materials accounted for an estimated 8% of production, with hardmetals and copper, titanium and aluminium alloys making up the remaining 2%.

Elsewhere in Asia, India’s MIM industry, dominated by US Indo-MIM Pvt Ltd, tripled its revenues from $50 to $150 million between 2014 and 2016, with most of its products exported to North America, Europe and Japan.

According to the JPMA, Japanese MIM producers were expected to achieve sales of around $120 million in 2018, with a growth rate of 5–6%. The Japanese MIM market is primarily based on industrial machinery, medical and automotive applications. Other important suppliers of MIM products are South Korea and Singapore.
Asia’s MIM industry is expected to continue to experience strong growth, particularly in the automotive and medical markets. Whilst the 3C sector has brought huge production volumes (Figs. 10, 11), diversification is a priority at many Chinese MIM firms. Smartphone designs can be short lived, and some models may fail to sell whilst others become runaway successes. Unpredictable production volumes result in MIM producers struggling to balance the need to keep their operations busy whilst ensuring production availability for a short-notice, short-lead time order for a million smartphone parts.

North America
Based on data presented by the MPIF at this summer’s POWDERMET2019 conference, the outlook for MIM in the US is described as ‘positive and firm.’ Estimated 2018 sales of MIM parts in the US increased by 5–10%, with an estimated sales value of $440–460 million.

It is estimated that MIM-grade fine powders consumed in the US (domestically produced and imported materials) increased by up to 10% in 2018 to 3,500 tons. This figure includes fine powders that are suitable for ‘MIM-like’ Additive Manufacturing applications, but currently volumes for this new sector are low.

According to the MPIF’s PM Industry Pulse Survey, responding members of the Metal Injection Molding Association (MIMA) estimated that stainless steel powders accounted for 48% of materials used by weight of MIM parts shipped, with low alloy steels (20%) and soft magnetic materials (21%) accounting for much of the balance.

In terms of the MIM market mix according to weight of parts shipped, 2019 estimates are that the medical and dental markets now account for 30% of production, whilst MIM parts in vehicles have risen to 11% of production. The firearms market flattened in 2018 and is estimated to account for 33% of MIM production. Other markets highlighted include general industrial (12%), electronics (7%) and dental (3%). Bear in mind that whilst dental is only estimated to be 3% by weight of US production, the parts - which can weigh as little as 0.02 g - command a high price. Globally, the dental sector has been estimated to account for around 16% of MIM sales, by value.

Optimism dominates market expectations for 2019, states the MPIF. The MIMA survey reported that 72% of respondents forecast sales increasing and 28% forecast “more stable” sales levels. The survey also indicated that the most important reported MIM-related manufacturing/engineering challenges ahead include reducing time-to-market, expanding capacity, reducing scrap and developing new materials. MIM companies are also actively considering manufacturing marriages with AM processes.

Europe
Europe’s contribution to the global development of MIM has been significant for two reasons. Firstly, it is the leading provider of MIM technology to the world,
be it for MIM-tailored injection moulding machines (Arburg GmbH & Co KG is the leading global supplier), market-leading feedstock (BASF), or continuous furnaces for high-volume production (Cremer Thermoprozessanlagen GmbH pioneered continuous MIM furnaces, and the company’s MIM-Master remains the market leader). The solutions offered by this ‘Arburg BASF Cremer’ (ABC) grouping, as these three firms are often referred to, enabled the rapid rise of MIM in China. This combination gave confidence to OEMs such as Apple and Samsung that a MIM part design could be produced across multiple manufacturers to a consistent standard, even when production volumes reach tens of millions a year.

The second contribution that Europe made to MIM was in opening the technology up to the automotive industry at a relatively early date. This was thanks to the adoption of MIM technology by some of the leading ‘press and sinter’ Powder Metallurgy part makers, namely Sintermetallwerk Krebsoge GmbH (now part of GKN Sinter Metals) and Schunk Sintermetalltechnik GmbH, both located in Germany.

As major suppliers to the automotive sector, these companies were able to introduce their customers to what was, at the time, a completely unknown process to automotive designers. The current success of MIM in the European automotive industry – a success that is now spreading globally – is thanks to the early vision of these companies in embracing the technology.

Initial use of MIM in the automotive sector was for non-critical applications. However, a growing trust in the process gradually led to the technology’s use in a wide range of highly-loaded powertrain components. Although MIM rocker arm components had been produced in Japan by Nippon Piston Ring for a number of years, one of the most high profile MIM engine applications in Europe were the MIM rocker

![Fig. 13 MIM rocker arm components manufactured for BMW by Schunk Sintermetalltechnik GmbH, Germany](image1)

![Fig. 14 These 4605 low alloy steel MIM shock absorber components, used in the Chevrolet Camaro, won an MPIF award for Indo-MIM Pvt. Ltd. in 2017 (Courtsey MPIF)](image2)

![Fig. 15 This demonstration Hastelloy X swirler is designed for use in the combustion chamber of an aircraft engine and uses green machining to create the very small holes and sinter joining to create an assembly of multiple green parts (Courtesy Alliance-MIM, France)](image3)
arm components manufactured for BMW by Schunk Sintermetalltechnik GmbH (Fig. 13). This application brought significant exposure for MIM technology when it was announced in 2007.

These MIM parts were installed in BMW’s 6-cylinder engines, which used the company’s Valvetronic variable valve lift system. The MIM rocker arm was produced in volumes of around 4.5 million pieces annually using a hardenable 50NiCrMo2.2 alloy. The parts were injection moulded in a four-cavity mould before being debound and sintered in a continuous sintering furnace, followed by heat treatment. It was estimated that MIM brought cost savings of around 58% compared with wrought rocker arms. Alas even MIM technology isn’t immune to competition and eventually this part was replaced by a rival technology when a change in specifications reduced the process’s competitiveness.

Other automotive MIM applications include parts for fuel injection systems, turbochargers, transmissions, shock absorber parts (Fig. 14) hydraulic systems, actuators and sensor housings used in aggressive environments including exhaust gas applications where there are high temperatures and pressures. Heat dissipation systems for some hybrid vehicles have also adopted MIM technology.

Today, annual sales by Europe’s MIM producers are estimated by the EPMA to be in the region of $500 million. Estimates of the markets for MIM parts in 2017, based on an EPMA survey, suggest that the automotive industry now accounts for more than 40% of production. Other key markets include consumer goods, firearms, medical devices, construction, power tools and tooling. Stainless steels account for over 50% of parts production in Europe.

Future trends

Aerospace

In addition to ongoing improvements in productivity, materials and equipment, a key future task for the MIM industry is to improve on existing applications and develop new ones. As highlighted elsewhere in this issue, there is a growing demand for MIM parts in the aerospace industry, both in civil and military aircraft. Aerospace applications famously require a long time for development and qualification, but this is rewarded by long product lifecycles and attractive revenues.

Current applications include stator vanes, general mechanical parts, levers and connectors. Potential future applications include injectors and swirlers in the combustion chamber (Fig. 15), outer shrouds and more. Elevated temperature applications require nickel-base alloys such as Hastelloy X, Rene 77 and IN718 that are extremely well suited to
Two-material MIM

As reported in the September 2018 issue of PIM International, two-component (2C-MIM) products are now in commercial production. In this process, two different feedstocks are co-injected into a mould followed by sintering to form a two-material component with a strong join.

Schunk Sintermetalltechnik GmbH is now manufacturing 2C-MIM components for a turbocharger with a variable turbine geometry (Fig. 16). The pin must be weldable and have a wear- and corrosion-resistant surface, and the adjusting lever must also be corrosion-resistant and not wear at the point of contact with the pin. The solution developed features two MIM parts combining weldable stainless steel and a wear-resistant cobalt alloy.

Before these parts could be produced in large numbers at high quality, numerous technical challenges had to be overcome. Several feedstock variations with different binders and powders were tested. The runners of the different materials had to be separated, cycle times had to be increased and a common sintering regime had to be found for both alloys to produce parts with high densities and uniform shrinkage.

In the future, material combinations such as soft magnetic/wear resistant, soft magnetic/non-magnetic, weldable/wear resistant, wear resistant/heat resistant, low cost/high cost and metal/ceramic, are anticipated.

Titanium

Intensive R&D activity relating to the MIM of titanium and titanium alloys has not yet resulted in significant market penetration in key potential markets; namely the biomedical, aerospace and consumer products sectors. This is in part related to the challenges of controlling interstitial contamination, primarily oxygen and carbon content, and achieving consistent mechanical properties, in particular yield strength and elongation.

The high cost of MIM-grade titanium powders has also been a prohibiting factor behind the poor market penetration of titanium MIM to date. There are, however, some notable successes...
Slovak company GEVORKYAN finalizes investment in Additive Manufacturing and increases capacities in PM, MIM and HIP.

GEVORKYAN was established in Slovakia in 1996 by an Armenian immigrant. The family has a 50 year history in innovation, development and production of Powder Metallurgy components. It supplies PM and MIM parts to global customers in automotive, locks and security systems, hand tools, oil industry, agriculture, firearms, medical, cosmetics and many other industrial products.

With a total of 160 employees, including 14 engineers in the R&D department, developments have been made in robotic automation and digitalization of the company. A total of 21 robots were installed in the production and quality departments. There are plans to add a further 6 to 8 robots by the end of 2019. A special software developed by the company in co-operation with its suppliers enables managers to monitor production online via 30 video cameras that are accessed through mobile devices. These combined factors have increased the company turnover by 24%, whilst at the same time reducing staff by 15%.

Gevorkyan is positive about its future business development, with increased resources for R&D, Sales and Marketing, the company continues to attract new business with its strategy to diversify its customer base. Automotive is targeted to represent 40% of the business.

After several years of experience in 3D printing for non-metallic parts for internal company use, Gevorkyan has invested in metal AM machines for use in tool production (mainly MIM) in Gevorkyan’s tool-making subsidiary company, GPM Tools. Prior to founding this company, A. Gevorkyan worked as a military aircraft engineer specializing in materials. Later on, he established the first privately owned PM plant in Ukraine. He strongly believes that the company is capable to use Additive Manufacturing technology for aerospace applications. The company portfolio consists of 2000 various types of part, adding about 130 brand-new components every year.
and firms that specialise in Ti-MIM are enjoying steady growth – albeit typically in low- to medium-volume applications.

**Going big**

Whilst manufacturing large MIM parts poses technical challenges – particularly with regards to moulding and debinding – there are many examples of MIM parts in production that weigh more than 100 g. As previously mentioned, advances in feedstocks, process simulation and tooling technologies mean that MIM is being considered for ever larger parts. Barriers to the use of MIM in this way may include the relatively high cost of MIM-grade powder – something that is less important when making a part that weighs 5 g – and the coming challenge from metal Binder Jet Additive Manufacturing. Whilst Binder Jetting comes with its own design restrictions, it is of course free from the need for complex and expensive tooling.

**Going small**

Micro Powder Injection Moulding (MicroPIM) continues to attract attention as a unique process by which to manufacture metal and ceramic micro components in medium- to high-volumes. The technology is used for the production of both individual micro components, with typical dimensions of ≤1 mm, as well as larger components that feature micro or even nanoscale structures.

Success in this area is thanks to the technology’s high efficiency in medium- or large-series fabrication, the ability to create complex shaped pieces, and the wide range of processable materials. As the range of applications for microsystems technology expands, so will the use of functional or high-strength materials processed by Micro PIM. Application areas include electronics, medical devices, biosensors and others.

**Conclusion**

Such a brief overview can only hope to highlight a small selection of the MIM industry’s milestones and achievements over the past forty years. More detailed information on the process itself, specific markets, R&D activities and profiles of leading companies can be found in past issues of *PIM International* magazine, as well as the resources listed at the end of this article.

As with all manufacturing processes, potential users should be aware of the specific design guidelines that exist for MIM in order to maximise their success. Ideally, speak to a MIM producer at the earliest stage of a component’s design; guidelines are widely available online, but there is no substitute for an experienced eye when it comes to the adoption of a new technology.

At a time when interest in the production of components from metal powders is at an historic high, thanks
to the rise of metal Additive Manufacturing, MIM has the significant advantage of being a more mature process, with all the benefits this brings, such as its materials supply chain and established standards.

Metal Binder Jetting and Fused Filament Fabrication technologies, which have both borrowed heavily from MIM in terms of materials and technology, are only just moving towards industrialisation and it will take time for them to be accepted as proven processes.

"Metal Binder Jetting and FFF technologies, which have both borrowed heavily from MIM in terms of materials and technology, are only just moving towards industrialisation and it will take time for them to be accepted as proven processes."

what is possible, from the 'hot-zone' superalloy compressor vanes now used in Rolls-Royce aero engines (see next article) to the ultra-high volume production of complex micro-MIM assemblies for the smartphone industry. Certainly new technologies will bring strong competition, but the current renaissance in the use of metal powders for component production will bring a host of opportunities – after all, a rising tide lifts all boats.

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PIM International magazine archive
www.pim-international.com/archive

Metal Injection Moulding Association
www.mimaweb.org

European Powder Metallurgy Association
www.epma.com

MIM Expert Group (MIM Expertenkreis)
www.mim-experten.de

Asian Powder Metallurgy Association
www.apma.asia

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Metal Injection Moulding: An alternative manufacturing process for aerospace applications?

The aerospace sector has long been recognised as an important potential market for the Metal Injection Moulding industry. However, extended application development cycles, combined with a lack of fundamental process understanding and rigorous validation requirements have, until now, held back the technology. In the following article, Rolls-Royce’s Enrico Daenicke and Schunk Sintermetalltechnik GmbH’s Ingolf Langer report on the development of a new generation of high-performance MIM components that are now flying in Rolls-Royce aero engines: IN713LC superalloy stator vanes.

Schunk Sintermetalltechnik GmbH, based in Thale, was one of the first companies in Germany to make the move to commercial MIM part production. Today, with more than twenty-five years’ experience in the technology, the company remains at the forefront of MIM industry development with its first deliveries of components to the aerospace industry.

Schunk produces both conventional ‘press & sinter’ Powder Metallurgy parts and parts produced by Metal Injection Moulding, and employs a workforce of approximately 520 people at its Thale facility. The production of MIM parts accounts for about 10% of its annual sales. The company’s MIM business strategy has changed over the years, moving away from low-alloy steel parts and towards high-alloy steels, nickel and cobalt-base alloys, copper and titanium. The automotive industry is still the biggest consumer of Schunk’s MIM parts but, in recent years, the company has begun to diversify towards aerospace applications.

This move has led it to develop R&D relationships with leading aerospace technology providers, including Rolls-Royce plc, the UK-based global industrial giant that manufactures and distributes products and solutions for the aviation and other industries. As one of the world’s largest makers of aircraft engines, and with major businesses in the marine propulsion and energy sectors, Rolls-Royce has customers in the aerospace sector.

Fig. 1 Rolls-Royce tests its Advanced Low Pressure System (ALPS) in Derby, UK, as part of its next generation UltraFan® engine development. This engine offers the potential for MIM component design that is not limited by the constraints imposed by part substitution. (Courtesy Rolls-Royce plc)
in more than 150 countries. These comprise more than 400 airlines and leasing customers, 160 armed forces customers, 4,000 marine customers, including 70 navies, and more than 5,000 power and nuclear customers.

Rolls-Royce Deutschland is the company’s German subsidiary, with facilities at Dahlewitz, near Berlin, and Oberursel, near Frankfurt am Main, and has approximately 4,000 employees. Formerly BMW Rolls-Royce (BRR), a joint venture between BMW and Rolls-Royce established in 1990, Rolls-Royce took full control of the company in 2000, renaming it Rolls-Royce Deutschland.

Dahlewitz is the Centre of Excellence for two-shaft turbofan engines for business jets, such as the market-leading BR700 family, and its success is mirrored in the more than twenty-two million flight hours amassed by these engines. Dahlewitz is also responsible for the Tay, Spey and Dart aircraft engines.

The company’s newest engine, launched in 2018, is called the Pearl® 15 and powers the new Bombardier G5500 and G6500 (Fig. 2). Overall, Dahlewitz currently maintains approximately 8,500 aircraft engines that are in service globally.

MIM for aerospace components: A world of opportunity

The aerospace market is currently largely untapped by the Metal Injection Moulding industry, in part due to a number of challenges which must be addressed when considering MIM for such applications. MIM technology, however, offers some significant opportunities which are an enabler for flying parts. This was previously addressed in a Special Interest Seminar at the Euro PM2017 conference in Milan, Italy, and reported on in PIM International Vol. 11, No. 4 (December 2017). Some key opportunities for MIM from an end-user’s point of view include:

- **Cost reduction**
  MIM has the potential to enable component cost reduction, based on its near-net shape capability, which presents the opportunity to reduce process steps

- **Resource efficiency**
  MIM offers improved resource efficiency, particularly with regard to high material utilisation levels and lower energy consumption relative to competing, conventional manufacturing processes

- **Improved design freedom**
  Increased design freedom compared with conventional manufacturing processes

- **Material choice**
  MIM offers an improved choice of material compared with conventional processing, as nearly every alloy can be made available in powder form to be consolidated by sintering

The challenges which the MIM and aerospace industries must overcome in order to take advantage of these opportunities include:

- **Lack of fundamental process understanding and in-service experience**
  There is a lack of fundamental MIM process understanding as well as limited in-service experience on the part of OEMs. Consequently, there is a low level of confidence in the capabilities of the process, coupled with a lack of understanding among MIM suppliers of the specific requirements for aerospace components.

- **Strict validation requirements**
  The aerospace sector’s strict validation requirements, with respect to material performance and degradation, product tolerances and quality, present a challenge to the MIM industry. A high level of validation effort is required to qualify each new material, new manufacturing process, new geometry, new equipment and new supplier. Validation efforts for aero engine parts are more exacting than those for parts in other industry sectors

- **Low production volumes**
  The relatively low production volumes compared to other
industries, but high numbers of different part geometries associated with aero engine applications, are at odds with the traditional concept of a ‘good’ MIM application. The issue of the high number of part geometries might be turned into an opportunity for MIM using the technology’s capability for combining numerous different part geometries into a single integrated part.

- **Limited design flexibility for retrofit applications**
  Design considerations also feature in the list of challenges. For current engines, a retrofit using an established design is often the only option for the introduction of a MIM part, meaning that there is little or no opportunity for ‘Design for MIM’. For future engines, however, the full design freedom capabilities of MIM could be used and the technology’s full potential realised.

- **Size and weight limitations**
  The current size and weight limitations (approximately < 10-30 mm in size and < 30 g in weight) of MIM parts are seen as being an impediment to penetration of this market. An attack on these limitations would broaden the range of potential applications.

- **Distortion management**
  Distortions can be introduced in green parts or during the sintering process. In green parts, potential causes of distortion might lie in the cooling regime after moulding, resulting in residual stresses or different local particle loading, leading to segregation. Green part distortion needs to be taken into account in tooling design.

The main causes of distortion in sintering are gravity, dependent on part orientation and sinter support, friction between material and the setter plate, and shrinkage variation due to differences in material distribution.

**Schunk’s first flying MIM part in a Rolls-Royce engine**

Schunk’s entry into the market for aero engine components has been a multi-step process and is still ongoing. The first MIM part produced by Schunk for the aviation industry was a lever for the Rolls-Royce BR700 business jet engine family, which was launched in 2006. The lever is mounted on the cooler outside of the front end of a jet engine compressor and serves to adjust the angle of inflow of variable stator vanes in relation to the gas flow (Fig. 3).

Fig. 3 MIM levers are used to adjust the angle of inflow of variable stator vanes in the compressor (Courtesy Rolls-Royce/Steffen Weigelt)
The design of the lever was modified by Rolls-Royce in order to combine the original multiple part geometries into a single integrated MIM part. By using MIM, the manufacturing costs could be significantly reduced. The MIM lever, made from 17-4PH stainless steel, successfully entered production in 2008 and was the first flying MIM part on a Rolls-Royce engine.

Since then, approximately 400,000 of these parts have been manufactured by Schunk and built into Rolls-Royce business jet engines. This MIM lever is also used in the Pearl 15 engine.

Development of Inconel 713LC single-ended stator vanes

Based on the successful introduction of the MIM lever, Rolls-Royce and Schunk wished to exploit their technology for higher temperature applications with increased part complexity. Cooperation between Schunk and Rolls-Royce on the development of the MIM of Inconel 713 Low Carbon (IN713LC), a nickel-based alloy, started in 2011. This work was unique in that it was beyond the scope of what had previously been achieved by the MIM industry.

IN713LC was originally designed as a casting alloy and has a content of strengthening phases of up to 60%, which offers excellent high-temperature properties and corrosion resistance. MIM IN713LC offers equivalent or even better properties compared to other nickel-based alloys which are currently used in jet engines, which was proven through intensive material testing and the generation of a set of design data which is used to design components.

Fundamental to this development was gaining a deep understanding of all the process steps and associated key process variables, from powder production through to the sintering process itself. The material is particularly challenging...
as, during the sintering process, the powder must be exposed to very high temperatures which are close to the melting point of the metal, at which point it has almost no inherent strength. Some of the key challenges were the definition and control of material quality, including raw material (e.g. chemistry, particle size, microstructure etc, shown in Fig. 4), and the definition of process parameters, in particular for sintering (e.g. atmosphere, pressure, sintering temperature).

Tight control of furnace cleanliness was vital in order to meet the necessary low impurity levels in the as-sintered material. Tight control of the sinter furnace with regards to temperature was also crucial in order to ensure optimum sinter conditions, which result in a high level of densification (> 99% theoretical density) of the material without encountering local melting, as the sintering temperature is close to the melting temperature of the material. Exceptional temperature control across the furnace also guaranteed that the final component properties were the same across the whole furnace volume.

As the most promising application for IN713LC, a single-ended stator vane for the high-pressure compressor was selected for development (Fig. 5). The compressor of a jet engine has multiple stages of vanes and blades and each is equipped with approximately a hundred vanes (Fig. 6). The temperature to which these stages are exposed rises from the ‘cool’ front end to the ‘hot’ rear end of the compressor before the compressed air enters the combustion chamber. Nickel-based alloys are typically used for the rear stages of the compressor where temperatures can reach around 700°C. To meet aerospace requirements, a quality control system for MIM including process specification, material specification and quality acceptance standards was established at Rolls-Royce.

"Some of the key challenges were the definition and control of material quality, including raw material, and the definition of process parameters, in particular for sintering.”
In 2017, the first stage of MIM compressor vanes for Rolls-Royce BR725 business jet engines successfully entered production and further stages for Pearl 15 are currently in the product introduction phase.

Single-ended stator vanes are a new family of components for MIM and, because of their geometry, presented a number of significant challenges. The Rolls-Royce team worked closely with Schunk in order to understand the fundamental issues and key process variables and therefore to design a robust and capable process for MIM vanes.

An innovative approach was taken with regards to the design of the injection moulding tooling, which was supported by intensive process modelling. This enabled a single tool to be used for all the part derivatives [e.g. nominal vanes, undersize vanes and stop vanes] and therefore minimise the non-recurring cost for each new stage.

The free-form aerodynamic surfaces are created directly by the sintering process and, in particular, the elliptical leading edge (ELE) does not require a separate finishing process compared to the conventional manufacturing process of forging and machining. This is beneficial in that a performance benefit is realised through much improved control of the aerofoil profile.

The adoption of MIM has enabled the base of the part to be produced very close to final size, resulting in much reduced machining time and maximised cost reductions. The ultimate aim is to remove the need to machine a number of the base’s surfaces, and the learning gained from the lead products is being used to gain the necessary understanding of process control.

The technology that has been developed introduces a radical change in the way Rolls-Royce manufactures compressor aerofoils. It offers freedom in choice of material compared with conventional processing such as forging or casting. Additionally, it is highly cost efficient but also enables the variation in key aerodynamic features to be reduced, thus providing a performance benefit.

**Summary and outlook**

The MIM technology developed for aerospace levers and stator vanes forms the foundation for the further exploitation of MIM technology at Rolls-Royce. There are a number of components in several areas of an engine that have been identified as highly suitable for MIM and that could exploit the material, methods and experience gained from the vane programme.

In many cases, effective ‘Design for MIM’ will allow new design concepts to be adopted, providing increased component functionality and weight savings. This is particularly applicable to clean sheet engines, such as the forthcoming Rolls-Royce UltraFan® engine, expected to launch in 2025, where component design is not limited by the constraints imposed by part substitution.

The material development programme that has been undertaken provides a template for the development of other materials, particularly those for high-temperature applications.

In summary, the development and introduction of MIM technology is providing resource efficiency, increased design freedom and an improved choice of material compared with conventional manufacturing processes. Additionally, it offers performance benefits due to high repeatability, and a significant cost reduction, in particular for single-ended compressor stator vanes. Ultimately, it opens the door to wider exploitation by Rolls-Royce of a technology which has seen little application but has much potential in aerospace.

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"An innovative approach was taken with regards to the design of the injection moulding tooling, which was supported by intensive process modelling. This enabled a single tool to be used for all the part derivatives and therefore minimise the non-recurring cost for each new stage.”
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Where ideas take shape.
Successful high-volume part production with HP Metal Jet 3D Printing: A guide for MIM professionals

While commercial plastic Additive Manufacturing has been a reality for nearly thirty years, metal Additive Manufacturing is largely still in its infancy despite the technology existing for nearly two decades. This is due to the difficulty of using metal Additive Manufacturing to produce cost-effective parts to the high quality and high volumes necessary to make it attractive for broader applications. With its Metal Jet system, HP Inc. hopes to change this, making the technology accessible to industry. In this article, HP’s Uday Yadati explains how the Metal Jet system can bring further success for MIM producers.

Process and design innovation

HP’s Multi Jet Fusion systems for plastics and the HP Metal Jet system for metals were conceived to overcome the trade-offs and constraints limiting current AM technologies. Offering speed, quality and strength in additively manufactured products, HP is accelerating the adoption of AM across a wide range of industries and applications that use both plastic and metal parts.

With its long history of technical and commercial leadership in home and office 2D printing using inkjet technology, HP has in recent years made considerable breakthroughs in the speed, quality, reliability and cost of plastic Additive Manufacturing with its popular HP Multi Jet Fusion technology. Now, building on that technology, the company is continuing to drive further breakthroughs in the design, production and distribution of additively manufactured parts with its first metal AM system, designed specifically for mass production: HP Metal Jet.

HP Metal Jet enables the cost-effective Additive Manufacturing of metal parts with technology that can be easily incorporated into existing MIM production lines. HP Metal Jet systems can rapidly produce both industrial-scale runs of complex parts and small-scale runs of one-of-a-kind parts at a competitive cost and quality.

Fig. 1 HP Metal Jet systems
Fig. 2 HP Metal Jet builds on key assets and capabilities of HP Inc.

HP’s systems are based on a number of key assets that have enabled the company’s businesses to thrive for several decades. HP Metal Jet represents a combination of innovation and time-tested technologies (Fig. 2). The technology simplifies design and manufacturing processes and reduces costs and time-to-market by eliminating two steps: mould creation and first-stage debinding. Because an additively manufactured part is created digitally, there is no need to spend time and money to design and create a mould.

HP Metal Jet is also designed to fit seamlessly into existing production workflows and uses similar metal powders and sintering furnaces to those used in MIM. This enables MIM manufacturers to transition to HP Metal Jet, or incorporate Additive Manufacturing into their wider workflow, without the need to more broadly overhaul their production process (Fig. 3).

There are some design limitations associated with MIM that do not necessarily apply to HP Metal Jet, allowing HP Metal Jet users to unlock a new range of applications for production. HP Metal Jet can create larger parts than those commonly found in MIM, as well as parts that have much larger wall thicknesses (more than 35 mm) and varying or non-uniform wall thicknesses. The process does not require tapering for ejection, leaves neither parting line nor ejection marks and eliminates several other MIM-related artefacts.

In addition, as with most Additive Manufacturing processes, HP Metal Jet allows for greater complexity in structures and geometries, producing parts that cannot be made with other methods. For example, HP Metal Jet enables new designs involving lattices, topology-optimised structures, complex internal channels, and other complicated geometries for mass production.

Parts can also be built without support structures and with smaller holes, allowing for high-quality parts to be produced that would otherwise be challenging for other AM technologies. In addition, the technology allows for parts to be sintered to densities comparable to those achieved in MIM, with similar grain structure and isotropic properties.

Fig. 3 MIM vs HP Metal Jet
To meet the needs of a broad range of applications, HP Metal Jet offers high productivity, lower hardware costs, competitive cost-per-part, high build quality, and a wide variety of choices in materials for strength, ductility and other properties. Combined with the elimination of costs and lead time needed for tooling, lower-volume parts become more cost-effective to produce. This creates many new possibilities for innovations in design, form and function at a much lower cost than is offered by existing metal Additive Manufacturing solutions.

**What are the business benefits of HP Metal Jet?**

The primary business benefits for customers adopting HP Metal Jet include reduced time to market, the elimination of non-recurring engineering costs, the potential to expand businesses by taking on jobs with lower volume production runs or with higher complexity parts, and the ability to leverage the reach and experience of a Fortune 100 company.

The MIM workflow can take up to six months to move from a customer order to a final part, largely due to lengthy design, tooling fabrication and validation processes. Eliminating these lengthy stages, manufacturers using HP Metal Jet can remove a fixed cost and a non-recurring engineering expense (NRE) from their workflow, which could result in savings between $30,000–100,000 per design.

HP Metal Jet systems enable high-quality builds up to fifty times faster and at a lower cost relative to competitive Additive Manufacturing solutions in the marketplace today. For example, HP Metal Jet yields a lower cost-per-part than MIM for mid-volume runs; AM of parts without the high cost allows manufacturers to produce specialised, low-volume and one-of-a-kind parts for which the tooling would be cost prohibitive. This moves the crossover point – the production volume below which Additive Manufacturing is more economical than MIM – to nearly 80,000–100,000 units based on complexity and other factors (Fig. 5).

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<tr>
<th>Roller Finger Follower</th>
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<tr>
<td>Automotive valve train for cylinder shutoff</td>
<td>Surgical tool for removing tissue</td>
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<td>High tooling cost, low material weight</td>
<td>High tooling cost, low material weight</td>
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<td><strong>MIM at estimated volume of 50K parts</strong></td>
<td>$2.1</td>
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<td><strong>Laser Powder Bed Fusion 3D Printing</strong></td>
<td>$40.0–$50.0</td>
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<tr>
<td><strong>HP Metal Jet 3D Printing</strong></td>
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<td><strong>Cross Over Point</strong></td>
<td>~60–80K parts</td>
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*Fig. 4 A prototype gear shift part made for Volkswagen using the Metal Jet system*

*Fig. 5 With HP Metal Jet, the crossover point at which AM is more economical than MIM is higher than with other types of Additive Manufacturing (Note: Cross Over Point refers to the production volume below which AM is more economical than MIM)*
MIM manufacturers find it less attractive to carry out lower-volume production runs (e.g. 5,000–10,000), because the cost of taking on such jobs is high, and customers tend to use investment casting to produce higher mass parts (e.g. 100–200 g or more) with the same complexity as MIM. HP Metal Jet allows manufacturers to address both challenges. Simply put, this means manufacturers can take on more work and find more revenue in less time.

The HP Metal Jet system benefits from HP’s deep experience of fluid deposition solutions, gained through years of development of its 2D printing and plastic AM technology, to deliver accuracy and reliability, as well as remote monitoring, alerts and troubleshooting. This results in > 85% system uptime for a system that is substantially less expensive than most other Additive Manufacturing solutions. As with other HP products, the solution offers key features such as ease of use, versatility and an end-to-end digital workflow. Additionally, HP also offers a long-term upgradeability path designed to protect the customer’s investment.

How does HP Metal Jet work?

In developing HP Metal Jet’s Binder Jet technology, the company drew on three decades of investment in home, office and industrial inkjet printing, jet-able inks and fluids, precision low-cost mechanics, material science and imaging. HP Metal Jet systems are built with HP’s proprietary Multi Jet Fusion technology, originally used in inkjet printing. The process of building a metal part with HP Metal Jet is as follows (see also Fig. 6):

Spread powder: The build begins with a scanning recoater laying down a uniform, thin layer of powdered metal across the working area.

Print agent: HP printheads jet HP Binding Agent at precise locations onto the powder bed to define the geometry of single or multiple parts.

Evaporation: The liquid components of HP Binding Agent evaporate.

Retract the bed, print next layer: The powder bed drops according to the thickness of the printed layer, and the process repeats until the build is completed.

Cure the bed: The powder bed with the parts is heated to complete the evaporation of liquid components from HP Binding Agent and to achieve high strength in the green part(s).

Post-processing steps Once the build process is complete inside the HP Metal Jet build chamber, the final steps of decaking, sintering, cooling and finishing (if needed) are conducted.

A significant advantage of HP Metal Jet systems lies in their ability to precisely place up to 630 million nanogram-sized drops per second of a liquid binding agent onto a powder bed to define a part’s cross-section layer by layer. HP Binding Agent is a water-based liquid agent delivered by HP Thermal Inkjet Printheads.
It is formulated to bind the metal particles together wherever the agent is deposited. Capillary forces pull HP Binding Agent into the smallest interstices between the metal particles to produce a strong green part with a very small amount of binder (< 1% by weight). Curing the bed evaporates liquid components and cures the binding agent to produce a high-strength green part.

The red arrows in Fig. 7 show how the binder holds the metal particles together in preparation for sintering, during which the binding agent decomposes and the additively manufactured part becomes a solid metal part through high-temperature sintering where final properties and dimensions are achieved.

In MIM, a feedstock consisting of metal particles, wax and polymers is injected under high pressure into a mould. MIM feedstocks are typically less than 93% metal powder by weight versus up to 99% for HP Metal Jet. While MIM requires a two-stage debinding process to remove the wax and backbone binder, the HP Metal Jet process does not require a separate debinding stage at all, saving up to twenty hours compared to MIM.

In both processes, the backbone binding agent decomposes under sintering. The binding agent in HP Metal Jet is used at a lower weight fraction compared with MIM, facilitating the decomposition and evacuation of backbone binder residue during sintering. The absence of wax and low binder level is important in achieving high productivity of thick-walled and large-mass parts.

What makes HP Metal Jet different from the Additive Manufacturing competition?

The most widely used metal AM technology today is Laser Powder Bed Fusion (L-PBF), a point-by-point process in which a laser scans across the metal powder layer to melt and fuse one point at a time. Typically, it is slow and expensive. An HP Metal Jet system, like a traditional paper printer, uses wide-area processing to build the entire layer at one time. This is faster, less expensive and more reliable (Fig. 8).

HP Metal Jet’s advantages relative to L-PBF and some other Binder Jet systems include its higher productivity, proprietary technology (i.e. Thermal Inkjet technology and PageWide print bars), highly-innovative HP-developed binding agent and use of raw materials common to MIM.

HP Metal Jet is designed for mass production, as a cost-effective solution for high-volume metal AM, with competitive acquisition and operational costs. It produces high-quality final metal parts with mechanical properties meeting industry standards, starting with stainless steel alloys.

With respect to other Binder Jetting systems, HP Metal Jet’s major advantage is that it leverages thirty years of HP Thermal Inkjet leadership. During this period, HP’s printer performance — in terms of the number of drops ejected from Thermal Inkjet printheads per second — has doubled every eighteen months (Fig. 9).
Thermal Inkjet technology is superior to competitive Piezo printheads in aspects which are critical to high-quality and robust Binder Jetting systems (Fig. 10). HP printheads use an overlapping and digitally-stitched array of nozzles, which results in a low sensitivity to alignment errors. With 4 x nozzle redundancy, they can tolerate nozzle failure without impacting part quality or interrupting a build (Fig. 11).

HP Thermal Inkjet printheads are also far less expensive than Piezo printheads and can be replaced quickly and easily by a user, without the delays associated with waiting for technicians. The reduced replacement cost of the printheads, combined with the ability to install them without technician support, greatly reduces operating cost, downtime, and complexity over the life of the system.

The proprietary HP Binding Agent used by Metal Jet systems leverages chemistry that was developed for agents used in industrial 2D systems for signage, banners and packaging. It offers greater binder strength with lower binder by weight than binding agents used by other Binder Jet systems, resulting in higher green part strength and a simple and fast debinding process. High green part strength is essential to enable application breadth, yield and process automation.

The raw material for the HP Metal Jet solution is industry-standard stainless-steel MIM powder. HP is currently working to extend Metal Jet technology to process additional commonly used MIM metal powders.

**HP Metal Jet in the MIM industry**

GKN, the world’s largest provider of Powder Metallurgy parts for automotive and heavy industry, and Parmatech, a leading US-based provider of MIM parts for healthcare, are already producing parts with HP Metal Jet. The solution will be available to select additional partners that have interest in this technology in the second half of 2019 and 2020 and will be widely available in 2021.
Working through GKN, Volkswagen will begin integrating HP Metal Jet into its long-term design and production roadmap (Fig. 12) starting with the manufacturing of mass-customisable parts such as individualised key rings and exterior-mounted name plates.

These partnerships have been built on HP’s history of innovation, which dates back to the 1930s and extends into the present day. This legacy, combined with the scale of HP’s business, is set to provide HP Metal Jet customers with world-class capabilities.

A new AM campus in Barcelona

HP recently unveiled its new 14,000 m² Additive Manufacturing and Digital Manufacturing Center of Excellence in Barcelona, Spain. The site brings together HP’s substantial resources and industrial Additive Manufacturing expertise with our customers, partners and community to drive the technologies and skills that will help to realise the benefits of digital manufacturing (Fig. 13). The new facility in Barcelona, combined with the existing AM facilities in Corvallis, Oregon and Vancouver, Washington, allow HP to stand apart from the competition with a substantial presence in both the US and Europe.

What’s still to come

Manufacturing is the $12 trillion engine of the global economy. Today, Additive Manufacturing makes up only a small segment of that sector, but that is sure to change soon. Breakthroughs in quality and speed will accelerate the widespread adoption of Additive Manufacturing and create a digital transformation of manufacturing as widespread and profound as the way HP Thermal Inkjet technology changed the landscape of conventional 2D printing markets and applications.

HP has the technology, the heritage of leadership in printing and the IP that comes along with that, as well as the synergies and global support services to revolutionise the metal AM market. At HP, we are changing how the world designs and manufactures, and with HP Metal Jet, we are opening a new range of opportunities for our customers.

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The effect of sintering conditions on magnetic and phase characteristics of X15 CrMnMoN 17-11-3 MIM nickel-free stainless steel

There is a growing market demand for non-magnetic stainless steel components, in particular from the consumer electronics industry, that can be processed by Metal Injection Moulding. The stainless steel alloy X15 CrMnMoN 17-11-3 (also known as P.A.N.A.C.E.A. by users of BASF SE’s Catamold®) is one widely known option; however, when using this material, abnormal ferromagnetism can occur as a result of improper sintering profile design. Here, Dr Shin Lee and Shu-Hsu Hsieh, Chenming Mold Ind. Corp. (UNEEC), Taiwan, consider the root cause for this correlation between sintering parameters and final abnormal magnetic property.

Recent technology trends are putting increased demands on components for the communications and electronics industries. In particular, the need for high-strength, high-corrosion resistance, non-magnetism and good surface quality are key factors which must be considered. In this study, the high-nitrogen and nickel-free X15 CrMnMoN 17-11-3 austenitic stainless steel, one of the promising candidates to suit this combination of requirements, was manufactured by Metal Injection Moulding using commercial, ready-to-mould feedstocks. A systematic study of different sintering conditions was then carried out to obtain optimised material characteristics. The effects of the microstructural phases of δ-ferrite/austenite and of elemental compositional variations was investigated in order to discover the reasons behind an abnormal ferromagnetism phenomenon in this austenitic steel. By developing optimum sintering conditions, higher nitrogen concentration and non-magnetic MIM samples were obtained.

Background

One of the leading emerging developments in modern materials technology are electromagnetic systems based on stainless steels, thanks to their relatively high corrosion resistance combined with excellent mechanical strength and specific magnetic properties. Stainless steels were invented at the beginning of the 20th century in Germany (Eduard Maurer and Benno Strauss in 1912) and England (Harry Brearley in 1913). In some specific areas, it has been found that the magnetic properties of stainless steel adversely affect the operation and functioning of electronic devices, such as 3C industry parts and medical electronics. Therefore, the development of non-magnetic (paramagnetic) stainless
Sintering MIM nickel-free stainless steel

Steel would make it suitable for electronic and medical applications operating in environments of strong magnets, magnetic resonance imaging, alternating electrical fields, or other applications which do not allow magnetic interaction between the electromagnetic device and the material used, such as roller bearings in magnetic resonance tomography, magnetic resonance imaging, retaining rings on generator shafts or drill collars for oil and gas exploration. Other systems, such as electromagnetic valves, on the other hand, can operate only if their working part is ferromagnetic.

The magnetic properties of materials are influenced by their composition, metallic crystal structure, processing method and physical condition. With the exception of austenitic grades, all types of stainless steel respond strongly to a magnetic field. Magnetic permeability is a property of a material that responds to a magnetic field and is usually a measure of the extent to which a magnet attracts the material. Austenitic stainless steels normally have a Face Centred Cubic (FCC) crystallographic structure at room temperature and this structure is non-magnetic because the magnetic moments associated with each iron atom are arranged in an alternating pattern, therefore cancelling out any net magnetic moment.

Non-magnetic austenitic stainless steel parts for numerous industrial and consumer applications can be manufactured by powder metallurgical routes. When compounded with a polymeric material, these inorganic powders can be processed in a way that is comparable to a thermoplastic material. The most common example of this is the Metal Injection Moulding of small and complex parts at high volume, although parts with a simple shape can also be produced by extrusion or by simple compression moulding. Metal Injection Moulding uses the shaping advantage of plastic injection moulding, but expands applications to numerous high performance metals and alloys [1–13].

This advanced technology has grown in popularity in the past three decades as an effective approach to producing complex near-net shape parts, with accurate dimensions and excellent surface finish, and can make thin-walled parts to tight tolerances for a variety of industries, such as 3C, medical, automotive and aerospace [14–19].

High-nitrogen and Ni-free austenitic stainless steels

One of the most widely used austenitic stainless steels is 316L, with its main advantages being low cost, stiffness, a good combination of mechanical properties, reasonable corrosion resistance, ease of fabrication and non-magnetic properties. It has been used for numerous applications, particularly in the 3C electronic and biomedical industries, competing with advanced materials, such as Co-Cr alloys, commercially pure titanium (CP-Ti) and Ti-6Al-4V alloys, etc. However, some clinical issues have been found with stainless steels for medical applications in recent decades.

Firstly, medical stainless steels are denser, stronger and have higher elastic modulus than bones; this incompatibility of strength or modulus can cause the shielding effect of stress [20] and worsen the bone healing processes. Secondly, there is inevitable corrosion and wear of the medical stainless steels in body fluid environments, through mechanisms such as crevice corrosion, intergranular corrosion, pitting corrosion and fretting corrosion [21–24], leading to early fracture or failure of implants. Also, the corrosion of implanted devices may result in the release of harmful products into the body [23–25].

The final and most important problem is the negative effect of metal ions or fretting debris [25–30], which can be released from the implant devices because of corrosion, wear or other reasons. Nickel is known to be a potentially harmful element in medical stainless steels [26, 29] due to its ions acting as allergens, which may cause cutaneous inflammations such as swelling, reddening, eczema and itching on the skin, and may also lead to extreme allergic reactions, teratogenicity and carcinogenicity in the human body [29–39].

In addition, nickel is relatively scarce worldwide, and its high cost or price fluctuations can be an issue in mass production. Based on these reasons, high-nitrogen nickel-free austenitic stainless steels have been considered a promising alternative in recent years [40, 41].

Nitrogen is a strong austenite forming element and has been successfully used to replace nickel and to significantly improve the mechanical properties and corrosion resistance of steels [42, 43]. The term ‘high-nitrogen steel’ should be used if a steel contains greater than 0.08 wt.% nitrogen in a martensitic matrix, or greater than 0.4 wt. %

“The magnetic properties of materials are influenced by their composition, metallic crystal structure, processing method and physical condition. With the exception of austenitic grades, all types of stainless steel respond strongly to a magnetic field.”
nitrogen in an austenitic matrix [41]. Within this family, the high-nitrogen and Ni-free Fe–Cr–Mn–Mo–N grade of stainless steel has emerged as a rather new, promising class of advanced material during the last decade. The nitrogen content of stainless steel prepared by conventional melting processes is relatively low, as the solubility of nitrogen in liquid Fe is very low at atmospheric pressure. Higher nitrogen content, strength and toughness can be obtained by several means, such as high pressurised induction furnace melting, plasma arc remelting under pressure (PARP), pressurised electro-slag remelting (PESR) and Powder Metallurgy.

Compared with melting processes, high-nitrogen steel produced by Powder Metallurgy-based technologies are more likely to be promising and beneficial, as the nitrogen solubility is relatively higher in the solid phase than in the liquid state without affecting the good ductility and toughness properties, as long as the solubility limit of nitrogen is not exceeded (normally, less than 0.9 wt.%). As the solubility limit is exceeded, Cr$_2$N precipitates are formed and the ductility, corrosion resistance and toughness are reduced.

Additionally, nitrogen strongly stabilises the austenitic phase. Nitrogen-alloyed austenitic stainless steels can be work-hardened to very high strength levels without the issue of strain-induced martensite phase formation. Therefore, instead of adding nitrogen in the liquid state, it may be introduced into a steel powder thermally by diffusion or mechanically milling and, subsequently, powder is compacted to give pre-shapes or near-net shape products with a wide range of nitrogen content. Moreover, flexible processing and low capital expenditure have made this kind of process one of the most favourable options for high-nitrogen stainless steels.

In addition to nitrogen as elements for nickel replacement and austenite stabilisation, other potential candidates are cobalt, carbon, manganese, molybdenum and copper. Cobalt should not be considered as a replacement for nickel because it is very similar to nickel in its allergologic behaviour. Carbon is not regarded as a primary replacing element for nickel due to its negative influences on toughness, nitrogen solubility and corrosion resistance, even if it is very effective in increasing the nickel equivalent. Manganese is an essential trace element for the human body and thus may be biocompatible. Molybdenum could enhance nitrogen solubility, and also increases localised corrosion resistance. However, like chromium, higher molybdenum contents lead to formation of δ-ferrite and σ-phase, which decrease toughness and corrosion resistance.

From a chemical composition perspective, nitrogen is the most promising nickel-substituting element. Since nitrogen is an austenite stabilising element, it increases the resistance against undesired δ-ferrite and suppresses the formation of martensite during deformation. Also, nitrogen, which has a strong effect on the properties of steels, in particular inducing solid solution strengthening, stabilises austenite and increases pitting corrosion resistance, and is therefore the most beneficial alloying element in promoting high strength in austenitic stainless steels. As the nitrogen level increases, however, the ductile-to-brittle transition temperature (DBTT), or brittleness, also increases. In view of this, it is suggested that the level of nitrogen should be kept below 0.9 mass. % to avoid the ductile to brittle transition of implants at body temperature. Therefore, nitrogen content must be limited in order to attain a precipitate-free and homogeneous microstructure.

The development of high-nitrogen and Ni-free Fe–Cr–Mn–Mo–N austenitic stainless steels is based on a superior combination of properties, such as improved mechanical properties, non-magnetism and enhanced chemical properties at the

Fig. 2 A MIM specimen in the form of a round disk
surface for applications in corrosion-resistant materials and biomaterials. A new grade of Fe–Cr–Mn–Mo–N MIM austenitic stainless steel, X15 CrMnMoN 17-11-3, could be obtained from its original pre-alloyed ferritic steel powder state via solid state nitriding, either simultaneously during sintering (one-step process) or during a solution nitriding after sintering (two-step process). Atomic nitrogen is absorbed on the surface of the steel and then diffuses inwards to increase the nickel equivalent, resulting in a fully austenitic phase. During conventional furnace cooling after sintering, CrN precipitates tend to be formed. Therefore, a post sintering solution annealing in the austenite regime, followed by rapid cooling (> 150°C/min), is necessary. Changes in chemical composition during nitrogen absorption cause changes in densification ability, shrinkage behaviour, microstructure and mechanical properties. In addition, the final nitrogen amount of X15 CrMnMoN 17-11-3 MIM parts should be limited to less than about 1 wt.% to prevent brittle cleavage fracture along the (111) crystal lattice plane. X15 CrMnMoN 17-11-3 has a high Mn and nitrogen content and a negligible Ni level (<0.2 wt.%) in accordance with ASTM E 112: 4-5. Such a low Ni content does not induce Ni ion release and, consequently, prevents allergic reactions to Ni.

There are several attributes which make the use of X15 CrMnMoN 17-11-3 advantageous compared to more conventional alloys, such as high yield strength, tensile strength and ductility; high strength-fracture toughness combination; high strain hardening potential; resistance to deformation-induced martensite formation; absence of ferromagnetism with low magnetic permeability; high pitting, crevice and intergranular corrosion resistance; and the use of nitrogen as a potential low-cost alloying element. Therefore, this study was aimed at the introduction and development of MIM X15 CrMnMoN 17-11-3 through sintering condition optimisation, which influences magnetic intensity from the viewpoints of element composition variation, microstructure and phase differentiation.

**Experimental procedure**

Pre-alloyed X15 CrMnMoN 17-11-3 ferritic stainless steel-based commercial feedstocks were applied in this investigation. Specimens in the form of round disks, shown in Fig. 2, were moulded, catalytically debound by fuming nitric acid and then sintered in a nitrogen atmosphere in a batch-type vacuum furnace. Sintering profiles...
with different sintering pressures, secondary sintering holding temperatures and sintering holding periods, as shown in Figs. 3–5, were designed to study the effect of sintering conditions on the magnetic and phase behaviour of Ni-free X15 CrMnMoN 17-11-3 stainless steel. For all MIM-sintered specimens, the post-solution annealing step was conducted to totally dissolve chromium nitride \((\text{Cr}_2\text{N})\) precipitates into the austenite matrix and overpressure inert gas quenching was then applied with a cooling rate higher than 150°C/min to form the \(\text{Cr}_2\text{N}\)-free final parts for the assessment of corrosion resistance and toughness issues.

The relative magnetic permeabilities \((\mu_{\text{rel}})\) of MIM specimens sintered with the different profiles were firstly measured by permeability meter (Stefan Mayer Instruments, FERROMASTER). The specimens were then cut into pieces for metallographic, X-Ray Diffractometer (XRD), Electron Back-Scattered Diffraction (EBSD), Electron Probe Micro-Analyzer (EPMA) and nitrogen content analysis. Metallurgical samples were polished and etched using 10 ml \(\text{HNO}_3\) (98%) + 80 ml \(\text{HCl}\) (37%) at room temperature for 2 min. The metallurgical images of the specimens were observed by optical microscope (OLYMPUS, BX53M). Phase identification was performed by XRD (PANalytical, X'Pert PRO MPD), Field Emission Scanning Electron Microscopy (FESEM, JEOL, JSM-7800F Primel with EBSD detector (Oxford Instruments, NordlysNano) was applied for phase mapping analysis. Chemical compositions of specimens were characterised by EPMA (JEOL, JXA-8200SX) for elemental mapping. Nitrogen elemental analysis was carried out by the combustion method (LECO, ON836).

### Results and discussions

Table 1 lists the corresponding density, relative magnetic permeability and nitrogen/carbon contents of sintered specimens processed using profile 1. The density and carbon content complied with the material standard, whereas the nitrogen content was relatively lower. Based on the definition of SEW 390 (Stahl Eisen Werkstoffblatt), the stainless steel could be classified as non-magnetic or paramagnetic, once its relative magnetic permeability \((\mu_{\text{rel}})\) is lower than 1.01.

Meanwhile, it was found that the relative magnetic permeability is higher in the MIM-sintered specimen upside (ferromagnetism) than the bottom side (paramagnetism). The surfaces of the sintered specimens directly contacted with the nitrogen atmosphere during the sintering stage, thus it is rational to assume that lower relative magnetic permeability would be obtained in the upside region compared with the bottom side. However, the results in Table 1 were in contrast with this assumption. Therefore, analysis of the MIM specimen upside and bottom side microstructures was necessary.

Fig. 6 shows the metallurgical images and XRD patterns of specimens sintered by profile 1. An obvious dense layer, with very few pores, was seen near the outermost surfaces of the specimen shown in Fig. 6(a) and (b). Meanwhile, a significant amount of \(\delta\)-ferrite (Body Centred Cubic, BCC crystal structure) was found in the dense layer, as shown in Fig. 6(c).

<table>
<thead>
<tr>
<th>Profile 1</th>
<th>Density (g/cm³)</th>
<th>Relative magnetic permeability ((\mu_{\text{rel}}))</th>
<th>Nitrogen content (wt.%)</th>
<th>Carbon content (wt.%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upside</td>
<td>7.547</td>
<td>1.056</td>
<td>1.007</td>
<td>0.56</td>
</tr>
<tr>
<td>Bottom</td>
<td>1.007</td>
<td>0.56</td>
<td></td>
<td>0.145</td>
</tr>
</tbody>
</table>

Table 1 The density, relative magnetic permeability \((\mu_{\text{rel}})\) and nitrogen/carbon contents of MIM specimens sintered by profile 1

Fig. 6 The metallurgical images and XRD patterns for X15 CrMnMoN 17-11-3 MIM specimen via sintering profile 1. (a) Metallographic image of upside before etching, (b) metallographic image of bottom side before etching, (c) metallographic image of upside after etching, (d) the XRD patterns of the specimen.
The BCC crystal structure is exactly the root cause of the ferromagnetism phenomenon, resulting in higher relative magnetic permeability. Moreover, since iron atoms have higher diffusivity in a BCC crystal structure than in the FCC austenite, this could explain the formation of the dense layer in this BCC δ-ferrite layer after high-temperature sintering. Based on the absence of a dense layer and δ-ferrite, found in the bottom surface in Fig. 6(b), the relative magnetic permeability on the bottom surface is lower than the upside. Fig. 6(d) shows the XRD patterns; this only reveals the fully austenitic structure (with FCC phase) of the whole specimen, due to total fraction of δ-ferrite in the specimen being too low to be detected.

Next, EBSD was used to precisely analyse the phase inside the dense layer, since it is rational to suspect this ferromagnetism phenomenon is highly correlated to the presence of non-FCC crystal structures inside the specimen. EBSD results, shown in Fig. 7, identified the phase and its volume fraction. The results also indicated that the BCC phase (12.63%) occurs in the dense layer, which is in line with the observation from the metallographic image in Fig. 6(c). Based on these results, the ferromagnetism phenomenon of the specimen is related mainly to the δ-ferrite, existing in the dense layer, and the formation mechanism of this δ-ferrite will be investigated next.

Fig. 7 EBSD results for X15 CrMnMoN 17-11-3 MIM specimen upside region via sintering profile 1. (a) SEM image, (b) BCC phase mapping, (c) FCC phase mapping, (d) BCC/FCC phase fraction comparison

<table>
<thead>
<tr>
<th>Phase</th>
<th>Fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BCC</td>
<td>12.63</td>
</tr>
<tr>
<td>FCC</td>
<td>87.37</td>
</tr>
</tbody>
</table>

Fig. 8 shows the results of EPMA elemental mapping, which verified the homogeneous distribution of Ni and Cr elements, whereas a significant amount of the Mn composition reduction phenomenon happens near the outermost surface of the MIM specimen upside region, as in Fig. 8(c). Due to the sublimation of Mn at relatively low temperatures and its partial pressure reaching about $10^{-3}$ Pa at 700°C, further temperature increases lead to higher manganese partial pressure [44-46]. In addition to nitrogen, Mn is also the stabilisation element for the austenite structure. Thus, the reduction of Mn will break the equilibrium state of austenite and a partial amount of the FCC austenite structure will transform into BCC δ-ferrite to reestablish the equilibrium state. From EPMA mapping, it is found that the depth
of the Mn-reduction area is similar to the thickness of the dense layer near the specimen’s outermost surface. This could provide the correlation between the formation of dense layer and Mn sublimation and evaporation phenomena.

From the results discussed above, it can be concluded that the ferromagnetism behaviour of a MIM part could arise from the reduction of the Mn composition in the surface region, inducing the formation of δ-ferrite. Next, the sintering conditions will be optimised to obtain the paramagnetic MIM part via the following approaches: increasing sintering operational pressure; adding a secondary holding step to absorb nitrogen sufficiently during sintering; and adjusting the sintered density.

**Increasing sintering operational pressure**

Sintering of X15 CrMnMoN 17-11-3 under high-vacuum conditions (60 kPa N₂ atmosphere) is adverse to the reaching of high nitrogen content in the final MIM parts and, of course, this high-vacuum condition will also generate severe Mn evaporation or sublimation phenomena. Therefore, the sintering profiles were optimised as shown in Fig. 3, through the variation of N₂ atmosphere pressures during the sintering stage. The intention of increasing the sintering operational pressure is to reduce the intensity of Mn evaporation, to increase the nitrogen content and to suppress δ-ferrite formation. Table 2 lists the corresponding sintering pressures and densities, relative magnetic permeabilities and nitrogen contents of specimens processed.

![Figure 8 EPMA mapping results for a X15 CrMnMoN 17-11-3 MIM specimen processed via sintering profile 1. (a) SEM image of upside region, (b) (c) (d) Cr, Mn, N elemental mapping of upside region respectively, (e) SEM image of bottom region, (f) (g) (h) Cr, Mn, N elemental mapping of bottom region respectively](image)

<table>
<thead>
<tr>
<th>Sintering pressure (kPa)</th>
<th>Density (g/cm³)</th>
<th>Relative magnetic permeability (μᵣ₀)</th>
<th>Nitrogen content (wt.%)</th>
</tr>
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<tbody>
<tr>
<td>Profile 1</td>
<td>60</td>
<td>7.547</td>
<td>1.056</td>
</tr>
<tr>
<td>Profile 2</td>
<td>70</td>
<td>7.516</td>
<td>1.039</td>
</tr>
<tr>
<td>Profile 3</td>
<td>80</td>
<td>7.502</td>
<td>1.012</td>
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</table>

*Table 2 The densities, relative magnetic permeabilities (μᵣ₀) and nitrogen contents of MIM specimens based on operational pressures from 60 kPa to 80 kPa*
by profiles 1 to 3. It is clearly shown that the increment of operational pressure will improve the nitrogen absorption and reduce the sintered density, which is in line with reported literature [47-48]. After increasing the nitrogen content, relative magnetic permeability will be reduced, since nitrogen is a major austenite FCC phase-stabilising element and suppresses the δ-ferrite BCC phase formation.

Fig. 9 EBSD results for BCC phase mapping of MIM specimen upside region: (a) profile 1, (b) profile 2, (c) profile 3; EBSD results for BCC and FCC phase fraction comparison of MIM specimen upside region: (d) profile 1, (e) profile 2, (f) profile 3

<table>
<thead>
<tr>
<th>Phase</th>
<th>Fraction (%)</th>
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<tbody>
<tr>
<td>BCC</td>
<td>12.63</td>
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<tr>
<td>FCC</td>
<td>87.37</td>
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<table>
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<tr>
<th>Phase</th>
<th>Fraction (%)</th>
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<tbody>
<tr>
<td>BCC</td>
<td>10.71</td>
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<tr>
<td>FCC</td>
<td>89.29</td>
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<table>
<thead>
<tr>
<th>Phase</th>
<th>Fraction (%)</th>
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<tbody>
<tr>
<td>BCC</td>
<td>2.97</td>
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<tr>
<td>FCC</td>
<td>97.03</td>
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</table>

Fig. 9 shows the EBSD results based on various sintering pressures. The results show that the δ-ferrite BCC phase fraction is inversely proportional to the pressure. The BCC phase fraction is around 12.63% at...
60 kPa, and 2.97% at 80 kPa, and this will certainly stabilise the austenite FCC phase. As a consequence, lower relative magnetic permeability could be obtained by using higher sintering operational pressures.

Fig. 10 shows the corresponding SEM images and EPMA Mn elemental mapping from profiles 1 to 3. Based on the results for the 60 kPa to 80 kPa sintering conditions, even though it is inevitable that Mn sublimation and evaporation occurred in the vacuum furnace environment, the extent could be gradually diminished when increasing the sintering operational pressure. However, with increasing pressure, the nitrogen content also increased, suppressing the formation of δ-ferrite and further stabilising the austenite FCC phase.

Adding a secondary sintering holding step

To suppress the formation of δ-ferrite and to increase the absorption of nitrogen, the second approach of adding a secondary holding step in the sintering profiles, as shown in Fig. 4, was investigated. Table 3 lists the corresponding sintered densities, relative magnetic permeabilities and nitrogen contents of MIM specimens processed by various profiles for improving nitrogen absorption. Upon reducing the secondary holding step temperature, it can be seen that the nitrogen content is increased, as the nitrogen’s absorption efficiency (solubility in austenite) is inversely proportional to temperature [49-50]. This increment in nitrogen will thus, in turn, reduce the relative magnetic permeability.

Fig. 11 shows the complementary EBSD analysis to Table 3, which revealed that the amount of δ-ferrite in the dense layer decreased on lowering the secondary holding step temperature. The δ-ferrite BCC phase fraction is 12.63% from profile 1 without adding a secondary holding step, and this is reduced to 0.39% when the secondary holding step temperature is set as 1050°C (profile 6) of MIM specimen upside.

<table>
<thead>
<tr>
<th>Secondary holding step temperature (°C)</th>
<th>Density (g/cm³)</th>
<th>Relative magnetic permeability (μ_rel)</th>
<th>Nitrogen content (wt.%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Profile 1</td>
<td>7.547</td>
<td>1.056</td>
<td>0.56</td>
</tr>
<tr>
<td>Profile 4</td>
<td>1150</td>
<td>7.549</td>
<td>1.012</td>
</tr>
<tr>
<td>Profile 5</td>
<td>1100</td>
<td>7.546</td>
<td>1.003</td>
</tr>
<tr>
<td>Profile 6</td>
<td>1050</td>
<td>7.540</td>
<td>1.002</td>
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Table 3 The densities, relative magnetic permeabilities (μ_rel) and nitrogen contents of MIM specimens based on different secondary holding temperatures during sintering.
Fig. 11 EBSD results for BCC phase mapping of MIM specimen upside region: (a) profile 1, (b) profile 4, (c) profile 5, (d) profile 6; EBSD results for BCC and FCC phase fraction comparison of MIM specimen upside region: (e) profile 1, (f) profile 4, (g) profile 5, (h) profile 6

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Adjusting the sintered density

The nitrogen content of a MIM part is also inversely proportional to the sintered density [49-50]. Therefore, the correlation between sintered density and relative magnetic permeability, via controlling the holding period during the sintering stage (Fig. 5), was investigated. Table 4 lists the corresponding sintered densities, relative magnetic permeabilities and nitrogen contents of MIM specimens derived from various holding periods. It can be observed that nitrogen content increased and relative magnetic permeability reduced when the sintered density was lowered. From the EBSD analysis results shown in Fig. 13, δ-ferrite BCC phase fraction is reduced upon decreasing the sintered density.

From the EPMA Mn elemental mapping shown in Fig. 14, the extent of Mn sublimation and evaporation is diminished upon shortening the

<table>
<thead>
<tr>
<th>Holding period (hours)</th>
<th>Density (g/cm³)</th>
<th>Relative magnetic permeability (µ_rel)</th>
<th>Nitrogen content (wt.%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Profile 1</td>
<td>6</td>
<td>7.547</td>
<td>1.056</td>
</tr>
<tr>
<td>Profile 4</td>
<td>6</td>
<td>7.549</td>
<td>1.012</td>
</tr>
<tr>
<td>Profile 7</td>
<td>3</td>
<td>7.513</td>
<td>1.008</td>
</tr>
</tbody>
</table>

Table 4 The densities, relative magnetic permeabilities (µ_rel) and nitrogen contents of MIM specimens based on the variation of holding periods during sintering.
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Fig. 13 EBSD results for BCC phase mapping of MIM specimen upside region: (a) profile 1, (b) profile 4, (c) profile 7; EBSD results for BCC and FCC phase fraction comparison of MIM specimen upside region: (d) profile 1, (e) profile 4, (f) profile 7

Conclusions

In this paper, a systematic study of the influence of designed sintering profiles to obtain high-nitrogen and nickel-free MIM X15 CrMnMoN 17-11-3 austenite stainless steels was pursued. The correlation of relative magnetic permeability to nitrogen content and BCC/FCC phase fraction was also explored. Moreover, those effects related to the variation of MIM...
parts in microstructure, δ-ferrite/austenite phase formation and Mn/N contents were also examined, to determine the root cause of the abnormal ferromagnetism phenomenon. Mn sublimation and evaporation phenomena seems inevitable in vacuum furnace system from 60 kPa to 80 kPa operational pressure. However, the reduction of FCC phase stability (due to Mn sublimation and evaporation) can be compensated by the sufficient absorption of another FCC phase stabilising element, nitrogen, to recover the FCC phase stability and thus, in turn, obtain a uniform and fully austenitic MIM part. In addition, the correlation between the thickness of the pore-free dense layer and BCC phase fraction was examined and discussed, since this BCC phase is favourable to the acceleration of the densification efficiency during the sintering stage.

To summarise, after verification from: increasing sintering operational pressure, adding a secondary holding step to absorb nitrogen sufficiently during the sintering stage and adjusting the sintered density, optimised sintering conditions could be obtained for MIM parts via profile 6 with very low relative magnetic permeability ($\mu_{rel} = 1.002$). This study provides the optimisation approach, via lowering operational pressure, keeping a lower secondary holding temperature and lowering the sintered density, for obtaining non-magnetic X15 CrMnMoN 17-11-3 MIM parts. The optimised parameters in this study are not fully applicable to all MIM samples, due to sample geometry and dimension differences, but provide the appropriate directions to pursue.

Acknowledgements

The authors wish to thank Chenming Mold Ind. Corp. (UNEEC) and R&D centre colleagues for sharing their pearls of wisdom during this research, assisting us at every point and, without whom, this task would not have been possible to accomplish.

References

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November 5-6, Munich, Germany
www.aviationforummunich.com

formnext 2019
November 19-22, Frankfurt, Germany
www.formnext.com

Hagen Symposium 2019
November 28-29, Hagen, Germany
www.pulvermetallurgie.com/symposium-termine/symposium-aktuell/

Rapid + TCT 2020
April 20-23, Anaheim, United States
www.rapid3devent.com

Ceramics Expo 2020
May 5-6, Cleveland, United States
www.ceramicsexpousa.com

WorldPM2020
June 27 - July 1, Montréal, Canada
www.worldpm2020.org

Formnext + PM South China
September 9-11, Shenzhen Shi, China
www.formnext-pm.hk.messefrankfurt.com/shenzhen/en.html

2020

MIM2020
March 2-4, Irvine, United States
www.mim2020.org

4th Additive Manufacturing Forum Berlin 2020
March 11-12, Berlin, Germany
www.additivemanufacturingforum.com

PM China 2020
March 24-26, Shanghai, China
en.pmexchina.com

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If you would like to see your PIM/MIM/CIM-related event listed in this magazine and on our websites, please contact Nick Williams, email: nick@inovar-communications.com.

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