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INTERNATIONAL



in this issue

Company profile: Matrix MIM
Mitigating sintering distortion
MIM High-Cycle Fatigue study



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Subscriptions

Powder Injection Moulding International is published on a quarterly basis as either a free digital publication or via a paid print subscription. The annual print subscription charge for four issues is £145.00 including shipping.

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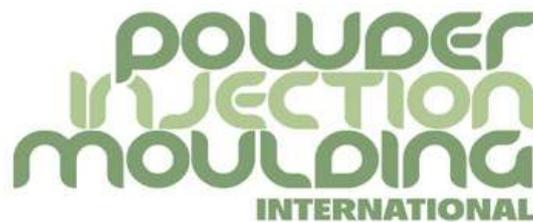
Printed by

Cambrian Printers, Aberystwyth, United Kingdom

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

Vol. 14 No. 3 September 2020

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For the MIM, CIM and sinter-based AM industries

Understanding the fatigue performance of MIM and sinter-based AM parts

When it comes to using sintered steel parts in heavily loaded applications, be it parts produced by MIM, sinter-based AM or conventional Powder Metallurgy, understanding the unique fatigue properties of the materials used, and the impact of processing variations, is crucial.

Whilst static mechanical property data for PM and MIM parts is readily available through international standards and resources such as the Global Powder Metallurgy Database (GPMD), fatigue data, and in particular High-Cycle Fatigue (HCF) test data, is less readily available.

With MIM, some unique factors come into play when looking at the fatigue performance of a component. In this issue of *PIM International*, a team from GKN Sinter Metals explains how weld lines, where two flows of molten feedstock come together in the mould, need to be considered when looking at HCF performance, particularly if they are located in highly-loaded regions of a MIM part (page 75). As this paper also highlights, the performance of two supposedly comparable steel materials can differ significantly when it comes to HCF testing.

In light of the above, it will be interesting to develop an understanding of the HCF performance of parts made by sinter-based metal AM processes such as Binder Jetting and Material Extrusion. The MIM industry has had decades to achieve today's component performance levels, and still, there is much to learn. Sinter-based AM technologies will benefit from this knowledge base, but factors such as surface roughness and the impact of the layer-by-layer build process mean that some interesting data may be generated by these new technologies in the coming years.

Nick Williams,
Managing Director & Editor



Cover image

Industrial-scale sintering furnaces for metal injection moulded part production (Courtesy Matrix s.r.l.)



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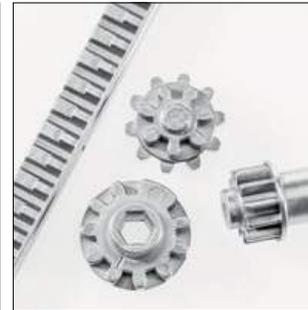
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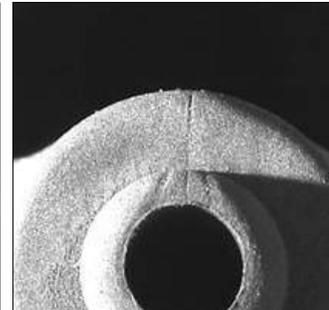
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In this issue

59 The evolution of MIM at Matrix: From transforming the production of eyewear components to luxury goods and beyond

There are a number of applications where Metal Injection Moulding turned out to be the 'perfect fit'. Whilst some well-known successes are the high-volume, high-precision parts needed for smartphones, dental braces and surgical instruments, a less well-known area of success for MIM is in the eyewear sector. Here, the combination of small, complex components, high-volume production and high strength requirements has seen the technology flourish. As the following article reveals, Italy's Matrix s.r.l. has been a driving force behind this success and is now applying its expertise to an ever-growing range of industries. >>>

67 Desktop Metal's Live Sinter™: How simulation software is mitigating sintering distortion

Sintering distortion is a fact of life in the Metal Injection Moulding industry. However, through the combination of an experienced eye, the 'trial and error' iteration of a part's design, and the use of sintering supports when needed, stable high-volume production is achieved. With the growth of processes such as metal Binder Jetting, however, the need to manufacture a much wider range of parts at lower production volumes and in a shorter time frame means that a more efficient and streamlined approach is required. Andy Roberts, VP Software at Desktop Metal and the inventor of Live Parts, presents the simulation software along with a number of case studies illustrating its capabilities. >>>

77 High-Cycle Fatigue response of MIM 8620 and 100Cr6 steels and their sensitivity to mean stress, notch sharpness and weld line position

Case-hardened MIM 8620 and hardened MIM 100Cr6 are two typical high-strength steel grades used widely for automotive applications produced by Metal Injection Moulding (MIM). In a comprehensive study by GKN Sinter Metals, the notch sensitivity of both these grades is investigated under both static and cyclic loading conditions. Of particular interest was the impact of weld lines – an often unavoidable feature of complex injection moulded components. What is the effect on a component's HCF response when weld lines are located in highly-loaded regions? Here, Dr.-Ing. Markus Schneider and colleagues present conclusions that will be of value to MIM producers and users alike. >>>



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95 **Perspectives on extrusion-based metal Additive Manufacturing: From bionic design to hollow structures and foams**

Not so many years ago, the idea of taking a Powder Injection Moulding feedstock and adapting it to create filaments for use in an extrusion-based Additive Manufacturing machine would have sounded far-fetched. Today, however, a variety of sophisticated systems are available, along with metal and ceramic filaments from a range of manufacturers. Here, Dr Uwe Lohse, from XERION BERLIN LABORATORIES GmbH, considers how the unique combination of feedstock extrusion and sintering presents a range of component design concepts that enable previously impossible forms and functions. >>>



103 **How on-site gas generation supports the integration of sintering facilities into MIM and sinter-based AM operations**

Metal Injection Moulding and industrial-scale sinter-based Additive Manufacturing facilities require a secure supply of industrial gases for use as sintering atmospheres. In addition to cost considerations, a strategic view needs to be taken of how these gases are supplied or generated, what infrastructure is required to store them, and what the risks are in terms of health & safety and supply stability. In this article, David Wolff, Stefan Joens, Bryan Sherman, Mike Montesi and John Boyle outline the challenges and the solutions. >>>

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Discover the leading suppliers of materials and equipment for MIM, CIM and metal Additive Manufacturing, as well as part manufacturing partners and more. >>>

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View a list of upcoming events for the MIM, CIM & sinter-based AM industries. >>>

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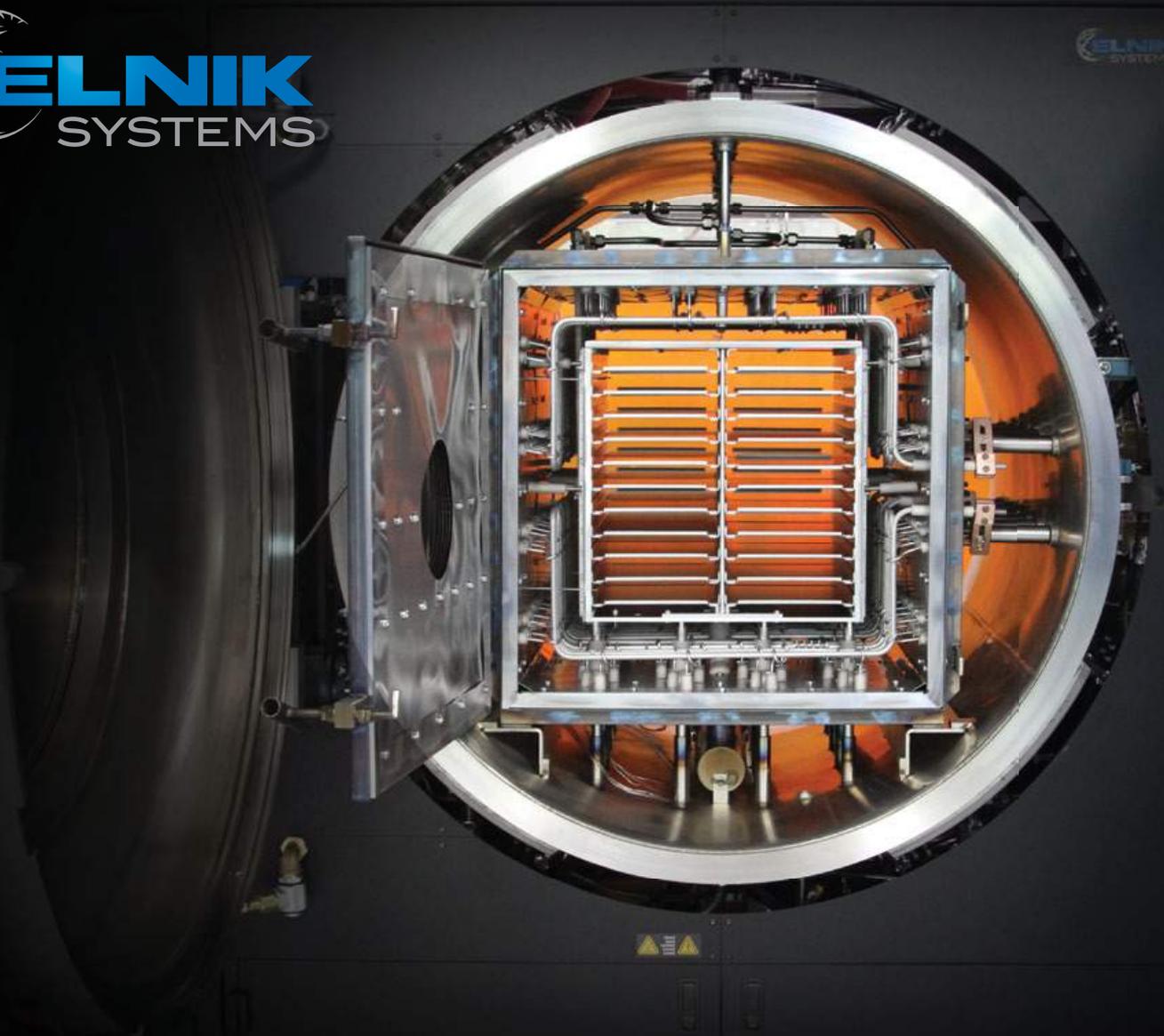
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Industry News

Sinter-based AM specialist Desktop Metal to be publicly listed

Sinter-based metal Additive Manufacturing technology developer Desktop Metal, Burlington, Massachusetts, USA, has announced that it will become a publicly listed company during the fourth quarter of 2020. The company has signed a definitive business combination agreement with Trine Acquisition Corp. (TRNE), a special purpose acquisition company led by Leo Hindery, Jr., and HPS Investment Partners, a global credit investment firm.

Desktop Metal's existing shareholders will hold approximately 74% of the issued and outstanding shares of common stock immediately following the closing of the business combination. The resulting operating company will be named Desktop Metal, Inc. and will continue to be listed on the New York Stock Exchange and trade under the ticker symbol 'DM.'

"We are at a major inflexion point in the adoption of Additive Manufacturing, and Desktop Metal is leading the way in this transformation," stated Ric Fulop, co-founder, chairman & CEO of Desktop Metal. "Our solutions are designed for both massive throughput and ease of use, enabling organisations of all sizes to make parts faster, more cost-effectively, and with higher levels of complexity and sustainability than ever before."

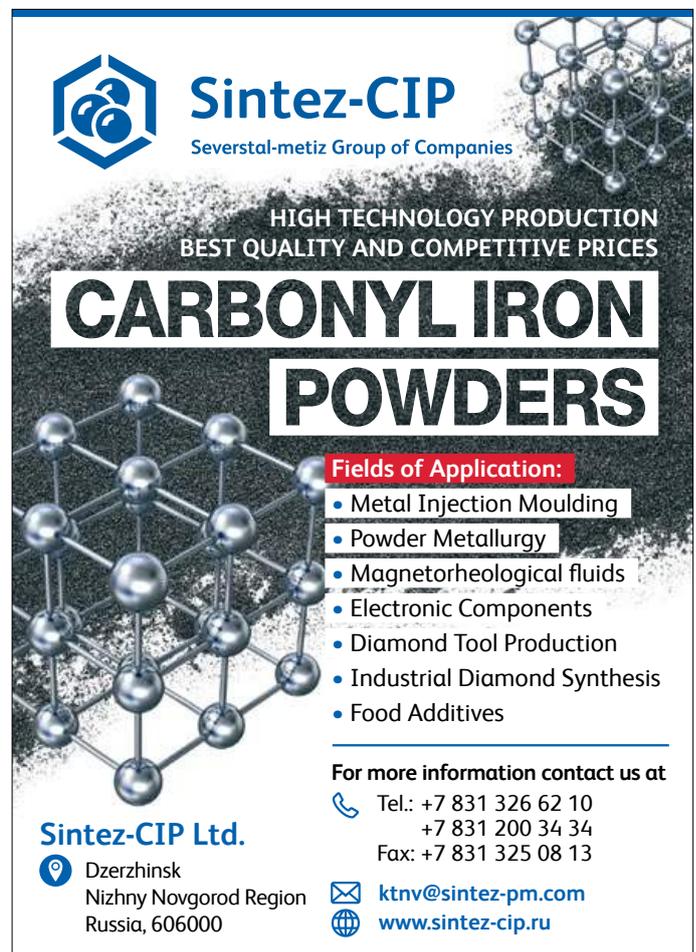
"We are energised to make our debut as a publicly-traded company and begin our partnership with Trine, which will provide the resources to accelerate our go-to-market efforts and enhance our relentless efforts in R&D," Fulop continued.

Desktop Metal stated that the AM industry grew at a 20% annual compound rate between 2006 and 2016 before accelerating to 25% compound annual growth over the last three years, a rate that is expected to continue over the next decade as the market surges from \$12 billion in 2019 to an estimated \$146 billion in 2030.

This market inflexion is said to be driven by a shift in applications, from design prototyping and tooling to the mass production of end-use parts. Desktop Metal explained that the transaction will enable the company to

capitalise on its position by accelerating its rapid growth and product development efforts. The company states that it will also use the proceeds to support constructive consolidation in the AM industry. Trine, which currently holds \$300 million in cash in trust, will combine with Desktop Metal at an estimated \$2.5 billion pro forma equity value.

Leo Hindery, Jr., chairman & CEO of Trine, commented, "After evaluating more than 100 companies, we identified Desktop Metal as the most unique and compelling opportunity, a company that we believe is primed to be the leader in a rapidly growing industry



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thanks to their substantial technology moat, deep customer relationships across diverse end markets, and impressive, recurring unit economics.”

“Ric has put together an exceptional team and board of directors with whom we are excited to partner to create the only publicly traded pure-play Additive Manufacturing 2.0 company,” he concluded.

The boards of directors of both Desktop Metal and Trine have unanimously approved the proposed transaction. Completion is subject to the approval of Trine and Desktop Metal stockholders and other closing conditions, including a registration statement being declared effective by the Securities and Exchange Commission.

Tom Wasserman, director of Trine and Managing Director of HPS Investment Partners, concluded, “We are thrilled to partner with



Desktop Metal's Shop System, with machine and sintering furnace. This is one of several sinter-based metal Additive Manufacturing systems offered by the company (Courtesy Desktop Metal)

Ric and Desktop Metal to help the company achieve its goals and capture the massive Additive Manufacturing 2.0 opportunity. Thanks to its tremendous team, we believe Desktop Metal has incredible

potential for future growth, which will only be accelerated by the extensive financial resources provided by this transaction.”

www.desktopmetal.com
www.sec.gov ■

MIM2021 to take place as virtual conference

The Metal Powder Industries Federation (MPIF) reports that MIM2021: International Conference on Injection Molding of Metals, Ceramics and Carbides, scheduled to take place in West Palm Beach, Florida, USA, February 22–24, will now be held as a virtual conference.

In an official statement, the MPIF wrote, “Due to continued concerns regarding the global coronavirus (COVID-19) pandemic, the MIM2021 International Conference on Injection Molding of Metals, Ceramics and Carbides that was to be held February 22–24, 2021 in West Palm Beach, Florida, will now be held virtually. West Palm Beach will host the MIM2022 conference.”

James P Adams, MPIF Executive Director/CEO, commented, “It is disappointing that the Powder Metallurgy industry will miss another opportunity to meet in person due to COVID-19. Our industry desires to meet, network, and discuss ongoing

R&D to advance the technology. However, the health and safety of our industry is paramount, so MIM2021 will be held as a virtual conference.”

The virtual edition of the MIM2021 conference will include presentations on the latest advancements in MIM, including e-handouts of the presentations; a virtual exhibit; the latest technological process & product innovations; commercial presentations; several publications; and an optional PIM Tutorial instructed by Matt Bulger, the former president of the Metal Injection Molding Association (MIMA).

The conference’s target audience is product designers, engineers, consumers, manufacturers, researchers, educators, and students, although all individuals with an interest in this technology and application of its parts are encouraged to attend. The abstract submission deadline is September 30, 2020.

www.mim2021.org ■

GC Advanced Material Solutions qualifies new steel powders from Mitsubishi Steel

Hong Kong-based GC Advanced Material Solutions Ltd (GCAMS) has announced the recent evaluation, and subsequent qualification, of gas-atomised steel powders from Mitsubishi Steel Mfg. Co., Ltd., Japan, for the preparation of MIM and AM feedstocks.

Mitsubishi Steel’s 316L, 17-4PH and D11 powders are said to offer exceptionally high and reproducible tap density values, and have been qualified for the GCAMS Medpimould® and AmbientPrint™ feedstocks.

The steel powders are considered to be especially suitable as raw material for manufacturers using Material Extrusion (MEX)-based AM machines, or what GCAMS refers to as a Bound Material Powder Deposition process.

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Japan's MIM industry output drops in 2019

After a strong performance in 2017 and 2018, the Japanese MIM industry reported a significant drop in output for 2019, with sales of JPY 10.94 billion recorded (\$103.7 million at current exchange rates) – a reduction of 7% compared with the previous year (Fig. 1). According to the Japan Powder Metallurgy Association (JPMA), which collected statistical data from nineteen companies involved in MIM production in the country, the drop in sales can be attributed to tax increases, natural disasters and trade friction between major economies. It was stated that a bigger decrease is forecast for 2020 because of the coronavirus (COVID-19) pandemic.

Fig. 2 shows that the main markets for MIM in Japan were relatively stable in comparison with recent years. Industrial machine parts accounted for 26.5% of production (previous year: 29%), medical device parts accounted for 19.2% of production (previous year: 20.2%) and automotive parts accounted for 16.2% of production (previous year: 16.1%). The total percentage of these core MIM markets is 61.9%. In other sectors, bicycle parts saw a year on year increase of 23.2%. MIM production for industrial robots also saw a growth increase as manufacturers moved to increase automation in industrial manufacturing.

Fig. 3 shows the breakdown of MIM materials in Japan in 2019. Stainless steels accounted for 74.8% of production (previous year: 73.8%). Together, stainless steels, Fe-Ni materials, low-alloy steels and magnetic materials accounted for over 90% of production. Magnetic material saw a decrease in use for the second year in a row, whilst titanium continued to fluctuate, with most demand coming from the medical device sector. Looking ahead, growth in the production of heat resistant MIM materials is anticipated.

www.jpma.gr.jp/en/ ■

Sales of MIM parts in Japan

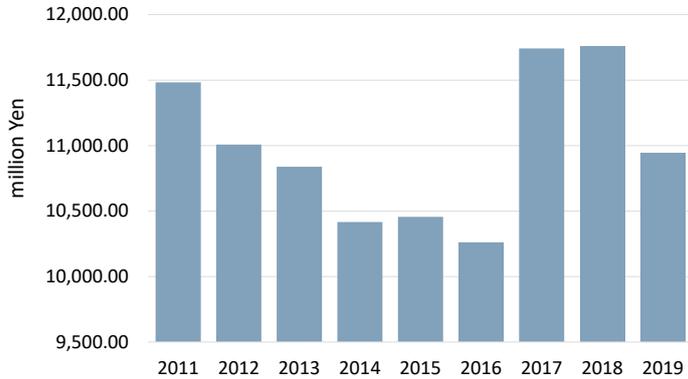


Fig. 1 Sales of MIM products in Japan (FY 2011–2019) (Courtesy JPMA)

MIM markets in Japan FY2019

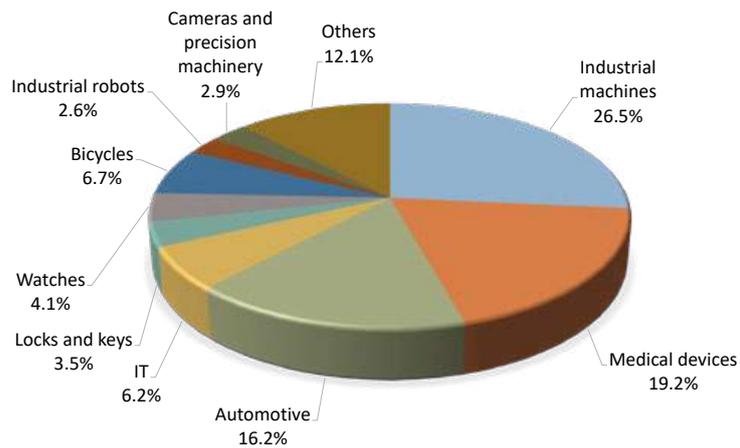


Fig. 2 Breakdown of MIM markets in Japan (FY2019) (Courtesy JPMA)

MIM materials in Japan FY2019

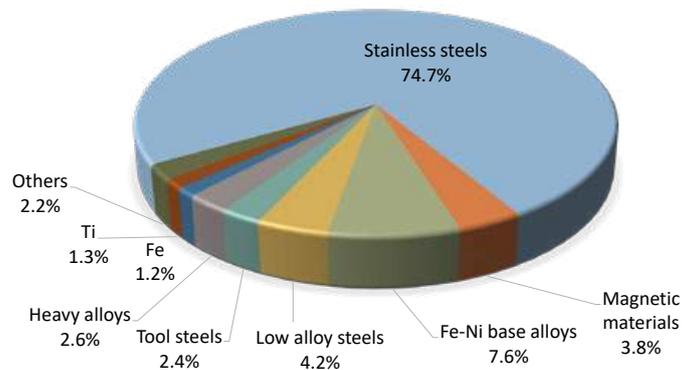


Fig. 3 Distribution of materials used for MIM production in Japan (FY 2019) (Courtesy JPMA)

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State of the Industry: MPIF reports on Metal Injection Moulding and Additive Manufacturing in North America

In its annual 'State of the PM Industry in North America' presentation, the Metal Powder Industries Federation (MPIF) reported on the activities of its members, the state of the market and the outlook for the coming year. At the start of the year, prior to the coronavirus (COVID-19) outbreak, MPIF President Dean Howard reported that the business outlook was tempered by cautious optimism; based on the MPIF's annual PM Industry Pulse Survey from September 2019, the majority of responding companies expected sales to increase in 2020 compared to 2019, but showed concern that the economy may be due 'correction'. Since then, of course, the global COVID-19 pandemic has altered all forecasts and pushed the wider PM industry into uncharted territory.

Looking back to 2019, Howard stated that, in contrast to the press & sinter community, Metal Injection Moulding and metal Additive Manufacturing gained over the previous year. Sales of MIM parts in the US increased by an estimated 5% to a range of \$460-480 million in 2019. It is estimated that MIM-grade powders,

generally considered as powders of less than 20 µm, consumed in the US (both domestically produced and imported) increased by 5% in 2019 to 3,637,627 kg (8,020,968 lb). This amount includes MIM-grade fine powders for metal AM applications.

"Interest in metal AM as a complement to MIM parts manufacturing is growing," Howard observed. "More than ten Metal Injection Molding Association (MIMA) member companies reported that they anticipate purchasing metal AM production machines within the next two years, with the binder jet process leading the way. Initially, MIM parts makers expect to use metal AM to print prototype designs to avoid the need for costly tooling. Additionally, others will use metal AM to build tooling to reduce the time from part design to part production."

MIM end-markets remained stable in 2019, dominated by firearms and medical applications (Fig. 1).

MIM and metal AM's outlook for 2020

MIM and metal AM markets have a brighter outlook for 2020, stated Howard, compared to conventional



MPIF President Dean Howard reported on the state of the North American PM industry (Courtesy MPIF)

Powder Metallurgy. "The firearms and medical markets will dominate MIM production again. Firearms sales, for both handguns and long guns, are expected to be robust in response to recent social injustices and this fall's presidential election."

"Medical and dental shipments could suffer a slight downturn as elective medical/dental procedures were prohibited due to state lockdowns. At best, MIM parts sales may increase by single digits or stay even with last year."

It was noted that there continues to be tremendous activity in the metal AM sector. From one manufacturer reportedly concentrating on making large parts, up to 450 kg (992 lb), for the aerospace and defence industries, to another developing binder jet AM of tungsten heavy alloys and the Directed Energy Deposition (DED) of molybdenum, there are many opportunities for this sector.

"Metal AM continues to be on a roll, especially for aerospace and medical applications such as custom implants that replace forgings," he added. Some common metal AM materials include nickel-cobalt alloys, aluminum-silicon-magnesium alloys, low-alloy steel, stainless steel and Inconel.

In addition, advances continue for metal AM processes such as Binder Jetting and Material Extrusion (MEX), all of which are debound and sintered, leveraging the existing successes of MIM technology

www.mpif.org ■

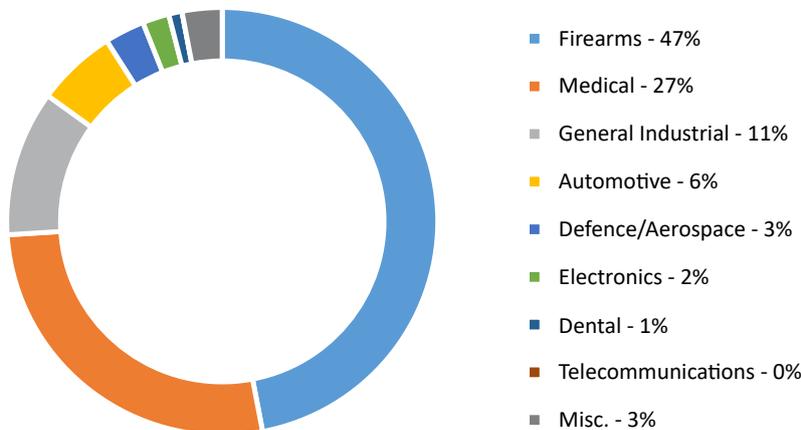


Fig. 1 MIM market mix according to weight of parts shipped

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Cobra Golf expands its metal injection moulded range with King MIM Black wedges

Golf club manufacturer Cobra Golf, headquartered in Carlsbad, California, USA, reports that it is expanding its family of 'King MIM' wedges, manufactured using Metal Injection Moulding (MIM), with the addition of its King MIM Black wedges to the well-received line.

The company explains that the MIM process offers a more exact way of building a wedge than casting. The wedge is produced from 304 stainless steel and, after sintering, robotically polished to exact specifications, eliminating the variability that can come from hand-polishing on a wheel. The end-to-end process is fully automated to deliver consistency from club to club, including on grind shapes and bounce. The King MIM black wedges have a glare-reducing Quench Polish

Quench (QPQ) black finish.

The club faces and grooves are CNC milled for maximum surface roughness to deliver the right spin profile, with milling performed in a circular pattern in order to maximise spin on softer shots where the ball won't go as deep into the grooves. The grooves are shaped uniquely to each wedge, with weaker lofts featuring wider, shallower grooves, Grooves become narrower and deeper as loft decreases.

"When we introduced MIM Wedges last year, it marked a steep change in the way wedges were manufactured," stated Tom Olsavsky, vice president of R&D for Cobra Golf. "Since then, we have received requests from better players asking for the type of black finish that is preferred on Tour."



The King MIM Black wedges have been added to Cobra Golf's King MIM family range (Courtesy Cobra Golf)

Olsavsky added, "The new QPQ finishing process allows us to deliver this option while maintaining soft, consistent performance for a wide variety of shots, now with a wider variety of grind options."

www.cobragolf.com ■






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Lithoz partners with ESCI president to advance ceramic AM for dental implants

Lithoz GmbH, Vienna, Austria, has entered into a collaboration with Dr Jens Tartsch, founder and president of the European Society for Ceramic Implantology (ESCI), to identify new applications and partnerships to further develop additively manufactured ceramic implants in the dental market.

The demand for metal-free dental implants is reportedly increasing due to possible negative health effects and an increased tendency to inflammation. Ceramic is said to be the material of choice in these cases as it provides an exceptional combination of biocompatibility, long-term stability and high mechanical performance.

Lithoz's ceramics have been optimised for medical use and the company states that it will soon be certified according to EN ISO 13485. Additively manufactured dental devices overcome the limitations of milled ceramics in terms of design freedom, with the process being particularly efficient due to its low levels of material consumption and high productivity.

In addition, since Additive Manufacturing does not require any tools, hard machining of hot isostatically pressed (HIP) ceramic blanks is no longer necessary, saving costs related to tools and maintenance. AM is already an established technology for numerous dental applications, and now ceramic AM is also being recognised as a viable process for the manufacture of ceramic dental implants.

According to Lithoz, a further application of its VAT photopolymerisation (VPP) based ceramic AM technology, which the company

calls LCM (Lithography-based Ceramic Manufacturing), is bone augmentation using resorbable materials such as hydroxyl apatite or tricalcium phosphate. Interconnected pore network-based implants can be manufactured according to the patient's bone status, therefore supporting dental implant in-growth in a situation where there is insufficient bone availability in the jaw.

Dr Tartsch is a renowned expert in ceramic implantology in Switzerland, where he works at his private dental clinic in Zurich. His main areas of focus are ceramic implant dentistry, the biomaterial and immunological aspects of dentistry, and material incompatibilities. He is an international educator, speaker and author on the topic of ceramic implantology and immunology in dentistry.

www.lithoz.com

www.esci-online.com ■

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Formnext 2020 to be run digitally amid ongoing COVID-19 crisis

Mesago Messe Frankfurt GmbH, the organiser of Formnext, the leading international event for Additive Manufacturing and other 'next generation' manufacturing technologies such as Powder Injection Moulding, has confirmed that it will now be held solely as a virtual event. Named 'Formnext Connect', the dates of the event have been shortened to November 10–12, 2020.

In an official statement, the organiser explained, "Due to the recent rise of the coronavirus (COVID-19) infection figures worldwide, and the associated increase in travel restrictions, Mesago Messe Frankfurt GmbH has decided to hold Formnext 2020 purely virtually."

"Formnext 2020 was previously planned as a hybrid trade fair, that is, with the on-site event at the Frankfurt exhibition grounds plus a

digital add-on component. This plan was based on the Corona Contact and Operating Restrictions Ordinance valid in the State of Hesse and a health and hygiene concept agreed upon with the City of Frankfurt am Main, the State of Hesse and Messe Frankfurt."

Formnext Connect will offer a wide range of digital services which will include exhibitor presentations in showrooms (products, information, videos, chat function, lead generation/lead tracking), intelligent matchmaking with all participants supported by AI, live streaming and on-demand content of the supporting programme and webinars as well as the scheduling/assignment of appointments for online meetings with exhibitors.

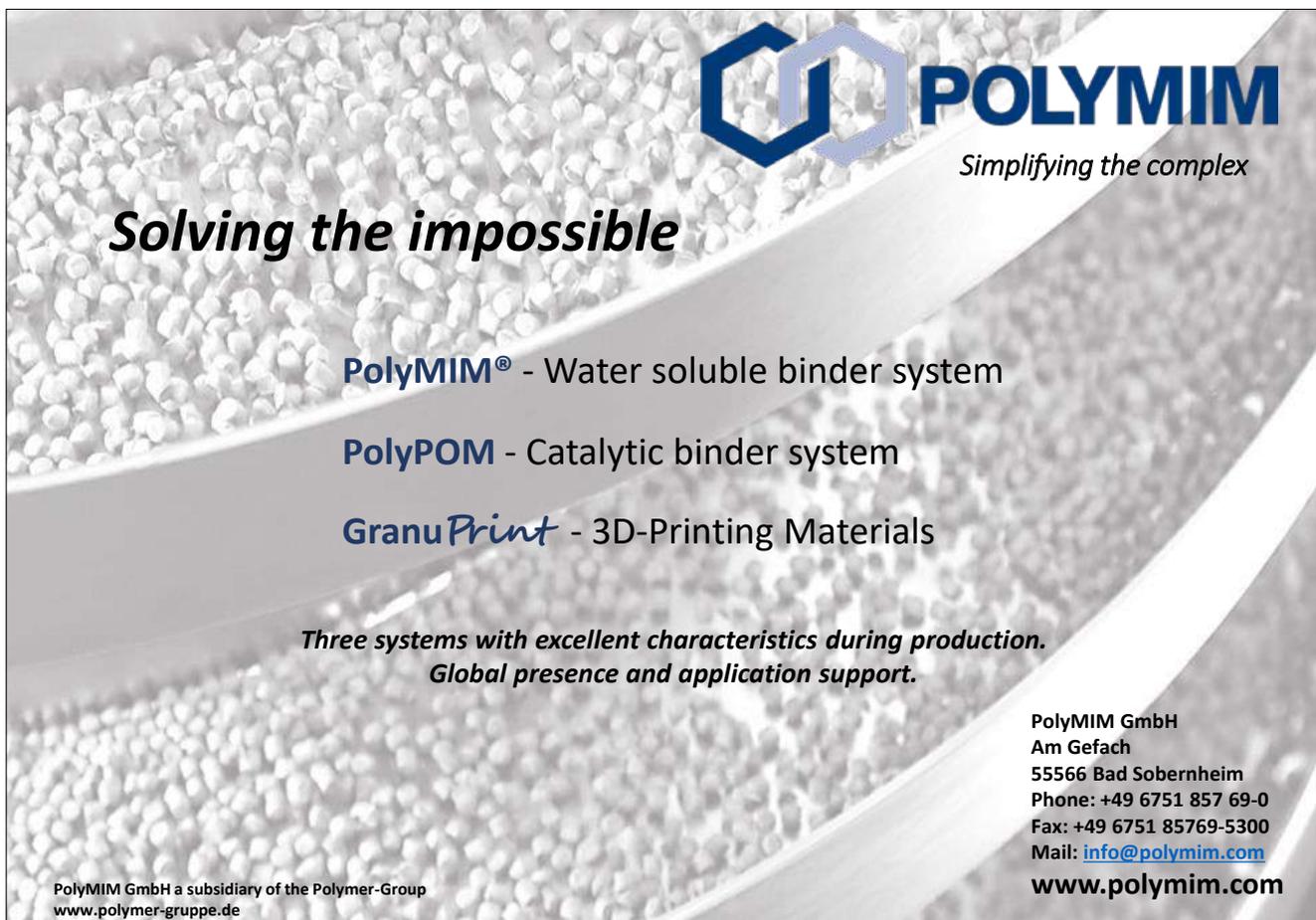
Petra Haarburger, president of Mesago Messe Frankfurt,



PIM International's MIM & CIM technology showcase at Formnext 2019

stated, "The current rise of the COVID-19 infection figures in Germany, Europe and around the world have led to increasing uncertainty among exhibitors and visitors. Together with the renewed tightening of official and in-house travel restrictions, this will no longer allow the otherwise highly international Formnext to be carried out in the accustomed quality."

www.formnext.com ■





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Classic car specialist turns to ExOne binder jet AM for vintage Ferrari part



The carburettor body for a vintage Ferrari produced using ExOne binder jet Additive Manufacturing (Courtesy The ExOne Company)

HV3DWorks LLC, Sewickley, Pennsylvania, USA, recently used Binder Jetting (BJT) Additive Manufacturing technology from The ExOne Company, North Huntingdon, Pennsylvania, USA, to enable the production of a carburettor body for a vintage Ferrari. HV3DWorks specialises in the restoration of collector cars using AM parts.

HV3DWorks' client approached the company for assistance in producing replacement parts for the top section of a Weber 40 DFI-6 carburettor for a 1969 Ferrari 365 GT 2+2 V-12 engine. The original carburettor had stripped threads and was leaking fuel, and attempts to source an original replacement part had proved unsuccessful.

The original carburettor top served as the design guide for the part, which was modelled and initially produced in plastic to confirm fit and finalise the design. Once the design was approved, the part was produced in 316 stainless steel infiltrated with bronze on an ExOne M-Flex metal Binder Jetting machine.

The overall production time for the part was twelve weeks, including CAD design, Additive Manufacturing, post-production impregnation and thread clean-up. While sourcing the original part would have cost HV3DWorks' client \$2,500, the cost of the AM part was significantly lower at \$1,200, a saving of \$1,300.

www.exone.com | www.hv3dworks.com ■



A 1969 Ferrari 365 GT 2+2 V-12 (Courtesy Thesupermat / Wikimedia)

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XJet helps Straumann Group to advance production on Carmel 1400 ceramic AM machine

XJet Ltd., Rehovot, Israel, reports that it will be collaborating with the dental equipment and supplies specialist Straumann Group, headquartered in Basel, Switzerland, to advance production on the Carmel 1400 ceramic AM machine.

Straumann develops, manufactures, and supplies dental implants, instruments, biomaterials, CAD/CAM prosthetics, digital equipment, software, and clear aligners for applications dentistry. Despite the coronavirus (COVID-19) pandemic, Straumann reports that it has been able to keep its XJet Carmel 1400 AM machine running throughout.

"We've been working with XJet NanoParticle Jetting technology for some time, up to now it has been used for developing product iterations and providing proof of concept," stated Stephan Oehler, Straumann Group VP. "Now we're scoring the first product development project to reach the next level of bringing this technology to production of ceramic end-use parts. We believe this technology can scale-up for production effectively, there's a large print bed and with the soluble support material we find post-processing simple and efficient."

Straumann was an early adopter of ceramic Additive Manufacturing and reportedly one of the first companies to invest in XJet's NPJ technology. According to Oehler, Straumann was won over by the technology because of the accuracy of parts, shorter overall production cycles and soluble support material.

Philippe Chavanne, Head of New Technology Competence Center, Straumann Group, commented, "We work with ceramic in a lot of our products, so when we learned there was a new technology in the field, we looked into it. XJet convinced us with the quality of parts, the fine details and accuracy. In addition to that, the density of the material is extremely high, close to 100%, so it's not like working with an 'AM material'."

"We're well-versed with the benefits of AM, so we knew that the freedom of design and complex geometries delivered by the technology, now for ceramic materials, could open up new product and application possibilities for the business," he continued.

"We were very impressed with the outstanding dedication and support provided by the XJet team, particularly Avi Cohen, vice president, Healthcare



XJet has partnered with Straumann Group to develop production on its Carmel 1400 ceramic AM machine (Courtesy XJet Ltd)

and Education, who supported us in this collaboration from the very first moment."

Oehler added, "There's already a demand for the ceramic parts produced on the Carmel 1400, and social distancing is viable because operation of the system is very simple, so we've been able to keep the system running even through the global pandemic."

Dror Danai, XJet CBO, noted, "It's incredible working with global leaders such as Straumann who are passionate and innovative about the products and services they provide. Working with them to move into production parts is hugely motivating and we're delighted to see our partnership go from strength to strength."

www.xjet3d.com

www.straumann.com ■

Call for papers issued for MPIF's PowderMet2021 conference

The programme committee for the International Conference on Powder Metallurgy & Particulate Materials (PowderMet2021), scheduled to take place in Orlando, Florida, USA, from June 20-23, 2021, has issued a call for papers and posters. The four-day event is co-located with Additive Manufacturing with Powder Metallurgy (AMPM2021) and the 10th International Conference on Tungsten, Refractory & Hardmaterials (Tungsten2021).

The technical programme co-chairmen for 2021 are Gregory (Jerry) Falleur and Roland T Warzel III. Abstracts are invited covering PM and particulate materials technology. All topics related to metal Additive Manufacturing should be submitted to AMPM2021, for which a call for papers has also been issued.

"The annual PowderMet conference reunites the robust Powder Metallurgy industry," stated James P Adams, Executive Director

& CEO, Metal Powder Industries Federation. "It includes the largest North American exhibit to showcase leading suppliers of PM, particulate materials, and metal Additive Manufacturing. Additionally, strategic networking opportunities bring delegates face-to-face, to finally catch up on the latest research and development, celebrate industry achievements, and more."

The abstract submissions deadline is November 13, 2020. Further information and registration details are available via the event website.

www.powdermet2021.org ■

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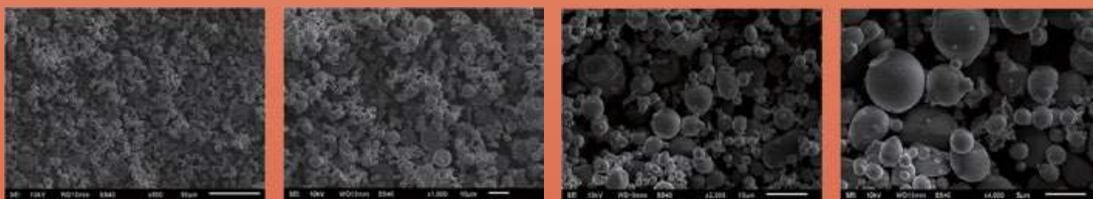
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17-4PH	4.7	0.34	7.7
304L	4.8	0.34	7.8
HK30	4.7	0.34	7.7
4J29	4.9	0.34	7.95
F75	5.0	0.34	8.1



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Rado introduces olive green colour to its latest True Thinline ceramic watches

High tech ceramics have played a central role in Rado's approach to watchmaking for nearly three decades. Their unique surfaces can be metallic or matte and the ceramic can be processed in an ever expanding array of colours for the company's watch cases and bracelet parts produced in Lengnau, Switzerland. High-tech ceramic watches produced by Rado start with ultrafine, high-purity zirconium oxide powder to which pigments are added to set its colour. These are then mixed with a polymer binder to produce the necessary ceramic feedstock for injection moulding under high pressure into a precision mould. After debinding and sintering, the high hardness of the lightweight ceramic material used (1250 Vickers) gives it its scratch resistance.

In 2011 Rado started producing its True Thinline ceramic watches with the cases of the quartz models measuring as little as 4.9 mm in thickness and powered by an ultra-thin movement of just 1 mm. The ground breaking ceramic cases required no stainless steel core, which not only gave True Thinline its extreme lightness and



Rado's limited edition True Thinline Anima ceramic watch (Courtesy Rado)



Rear view of Rado's True Thinline Anima ceramic watch (Courtesy Rado)

super slim silhouette, but it also paved the way for new design possibilities in the Rado collection. Examples of colours include charcoal black, snow white or metallic-look 'plasma high-tech', with extras available such as diamonds, mother of pearl, or rose gold coloured accents.

In May 2018 Rado, in partnership with the Grandi Giardini Italiani, introduced the True Thinline Leaf, which uses a polished green high-tech ceramic case and bracelet with a green mother-of-pearl dial and leaf structure printed on the back.

In July 2020, Rado produced a limited edition True Thinline Anima timepiece which features a matte olive green watch case. The name Anima refers to the openness of the watch's skeleton mechanical movement. The olive green case is a mere 10.8 mm thick with a 40 mm x 44.8 mm diameter, and includes a sapphire exhibition caseback framed by a titanium ring with an engraving indicating the watch as a 'Limited Edition One out of 2,020'. The watch's bracelet is also made from the olive green high-tech ceramic with a titanium triple folding clasp.

www.rado.com ■



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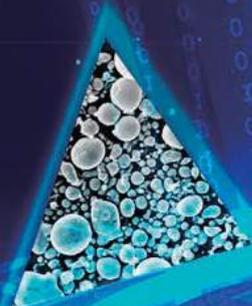
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MIM powder: 304L 316L 17-4PH and F75

主要产品：304L 316L 17-4PH 和 F75等

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3D printing etc

主要应用领域： MIM 3D打印等



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SimpaTec announces release of Moldex3D 2020

SimpaTec GmbH, Aachen, Germany, a leading engineering and software company for the development and optimisation of processes, components and tools, reports that the latest version of Moldex3D injection moulding simulation software, named Moldex3D 2020, has been released.

The company, a Moldex3D accredited distributor, states that with this release, CoreTech System Co., Ltd., Taiwan, the developers of Moldex3D, maintains its position as a leading software solutions provider for the simulation and optimisation of the injection moulding process.

The incorporated innovations are said to be based on customers' needs in order to help conduct moulding analyses in a faster and more convenient manner. Thus, more comprehensive, in-depth

and detailed simulation options have been developed in this latest release. Moldex3D 2020 reportedly also makes it easier to identify and evaluate potential sources of error in the process, tool or component, and to implement a design that is optimal in terms of cost and quality.

According to SimpaTec, one of the goals with Moldex3D 2020 was to keep pushing the boundaries to further develop committed simulation capabilities and to improve and optimise Moldex3D's solver to reach faster calculation times. This has reportedly been achieved by refining the solver architecture of the software, which has resulted in an improved computational performance resulting in a time saving of 20%.

In addition, many new geometry and mesh repairing tools have been added to allow users to process related problems in a more conven-

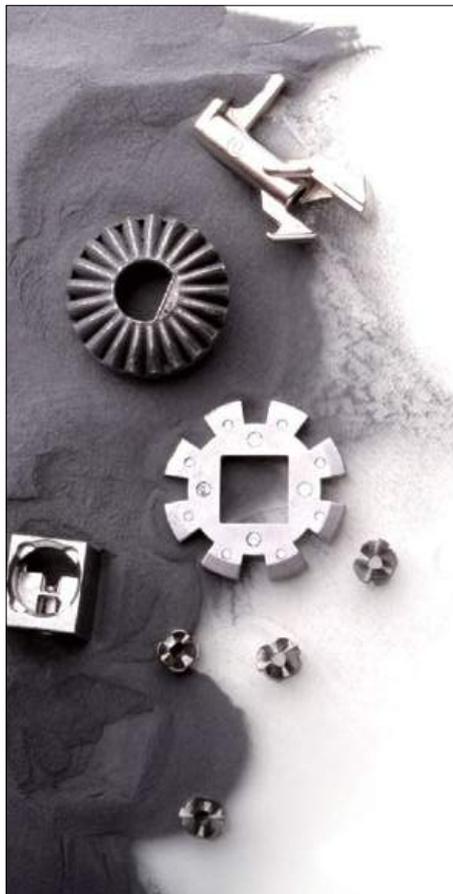
ient and faster manner, improving the speed of design changes.

Industries are facing more severe challenges due to the rapidly changing market demands and the impact of the current global trade situation, explains SimpaTec. Moldex3D provides comprehensive advanced processes to enable users to be more competitive in product innovation and development.

"With Moldex3D 2020, the development and production of components is considerably simplified," commented Steffen Paul, Managing Director and Product Manager at SimpaTec. "The new version sets a milestone which literally goes 'beyond simulation'. The dispatch to our users is primarily completed. We are extremely pleased about the first initial reactions, which show us that not only the name giving conveys something fundamentally new, but that Moldex3D 2020 delivers exactly what it promises."

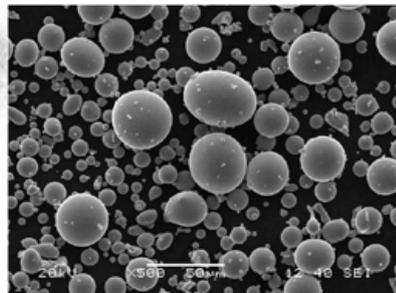
www.simpatec.com

www.moldex3d.com ■



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CREMER completes project to develop industry-first 2500°C industrial furnace

CREMER Thermoprozessanlagen GmbH, Düren, Germany, has completed its EU-funded CARBIDE2500 project. The project launched in May 2018 and is reported to have met its objectives, developing the first 2500°C industrial furnace, enabling higher efficiency and the production of tungsten carbide with up to five times higher material strength than otherwise possible.

CREMER specialises in pusher furnace systems with graphite coatings which operate at extremely high temperatures, above 2000°C. These systems are used in the carburising process for carbide powders such as tungsten carbide (WC). According to the company, at the time of the project's launch in 2018, the economic downturn and subsequent recovery in Europe had resulted in increasing demand for higher-strength materials.

Tungsten carbide is used in many different applications across multiple large industrial sectors, including automotive and aerospace manufacturing, construction, surface and underground mining, oil & gas exploration, as well as in many manufacturing industries (including paper, textiles, electronics, etc).

As a result of increasing demand, the company in 2018 expected the global tungsten carbide powder market to grow from €13.6 billion in 2016 to €22.91 billion in 2026, at a compound annual growth rate of 5.4%. Demand for other carbides, such as tantalum carbide or niobium carbide, was also said to be increasing.

Over the course of the project, material tests were conducted by CREMER to compare the properties of tungsten carbide powder produced using the same input material at 1600°C, 2200°C and 2500°C in the CARBIDE2500 furnace. The analysis results clearly show

the change in particle morphology obtained at 2500°C in comparison to the lower carburisation temperatures. The company states that the results show the potential of the plant to produce WC powder with a whole range of characteristics, tuned by selecting the optimum

input material and process parameters needed for a specific application. High-quality tungsten carbide powder is not only used to produce hardmetal tools, but is also relevant for AM products as well as coatings, cladding or hardfacing.

The total project cost was reported at €1,331,000, of which the EU contributed €931,700 through its Horizon 2020 research and innovation programme.

www.cremer-polyfour.de ■

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Headmade Materials completes €1.9 million funding round

Headmade Materials GmbH, Würzburg, Germany, has completed a €1.9 million funding round thanks to Industrial Technologies Fund of btov Partners, a European venture capital firm.

Headmade Materials was founded in 2019 as a spin-off from the Würzburg-based polymer research institute SKZ and its sinter-based Additive Manufacturing process, which it calls Cold Fusion AM, was developed for the serial production of metal parts using an existing ecosystem of machines and processes in Additive Manufacturing and Powder Metallurgy.

Headmade Materials explains that the AM process is carried out with standard polymer Laser Beam Powder Bed Fusion (PBF-LB) systems, which are widely available

on the market from established manufacturers. This reportedly allows customers to scale from a very capital-efficient entry point all the way to very high production output.

The company states that its technology is aimed at the Additive Manufacturing of series with up to 100,000 parts per year, thus having the potential to provide access to a new market segment for metal AM. Its Cold Fusion technology is said to offer users full flexibility and scalability at low investment cost. At the



Left to right: Christian Staudigel and Christian Fischer, co-founders and Managing Directors of Headmade Materials (Courtesy Headmade Materials GmbH)

www.mut-jena.de

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core of the process lies its Headmade feedstock, a combination of metal powder and a special polymer binder system.

This feedstock can reportedly be processed on almost any PBF-LB machine, giving users complete freedom to define the process chain depending on their own applications and needs. Parts are produced in the green state, and require a debinding and sintering process compatible with existing powder metallurgical processes (e.g. the MIM process), significantly simplifying process integration.

In addition to the sale of feedstock based on standard alloys (stainless steel 316L, titanium 6Al-4V), Headmade Materials also adapts individual alloys on request, e.g. hard or refractory metals. Customers are also supported in the design, part manufacturing and process integration of AM in their facilities.

The company explains that it will use the funds raised in this round for

scaling up its technology, as well as for marketing and customer development.

"We have been working on the technology for five years and the partnership with btov now gives us the opportunity to accelerate the company's development and realise our vision of 3D series production," stated Christian Staudigel, Managing Director of Headmade Materials.

Robert Gallenberger, partner of the btov Industrial Technologies Fund, commented, "We see the Cold Metal Fusion technology as a very viable approach for serial production due to the high cost-efficiency of the process. The combination of mechanical part properties known from the metal Powder Injection Moulding process and considerable process advantages, such as reduced safety requirements due to easier powder handling and higher green part stability, is also significant here."

www.headmade-materials.de
www.btov.vc ■

Euro PM2020 Virtual Congress programme published

The European Powder Metallurgy Association (EPMA) has published the programme for its Euro PM2020 Virtual Congress. The Virtual Congress, the first online edition of the EPMA's annual Powder Metallurgy Congress, will take place from October 5-7, 2020.

The online event will cover the latest developments in Powder Metallurgy, with over 150 technical papers to be presented over three full days. The programme of plenary, keynote, oral and poster presentations will focus on the following aspects of PM:

- Additive Manufacturing
- Environment and sustainability
- Functional materials
- Hard materials and diamond tools
- Hot Isostatic Pressing
- Metal Injection Moulding
- Materials



- Press & sinter

The EPMA states that live Q&As will also follow all oral presentations to provide the opportunity to further enhance participant knowledge.

The full Virtual Congress programme and registration details are available via the EPMA.

www.europm2020.com ■

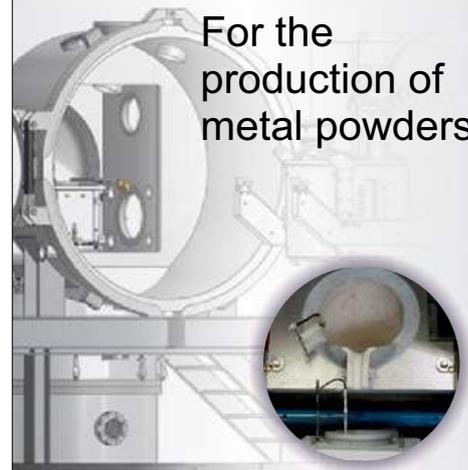


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Tekna's powder manufacturing operations achieve AS9100 and ISO 9001 compliance

Tekna, a subsidiary of Arendals Fossekompani ASA, with its headquarters in Sherbrooke, Canada, has announced that all of its powder manufacturing facilities are now in compliance with AS9100 and ISO 9001 quality management system requirements.

The announcement includes the company's recently-certified plant in France, where its nickel-base superalloy powders are produced, as well as its Canadian plant, which produces titanium and aluminium powders and was certified in 2017.

"This certification reinforces our position as a major player offering personalised client approach in the market. We are delivering on our commitment: Powder on time, every time, everywhere," stated Rémy Pontone, VP Sales & Marketing at Tekna.

"This milestone is a major achievement for Tekna on its mission to consistently deliver high-quality plasma powders among the most regulated business segments in the world: aviation, space and defence," added Luc Dionne, CEO at Tekna.

www.tekna.com ■

JSJW brings its metal powders to the US market

JiangSu JinWu New Material Co., Ltd., (JSJW), headquartered in Taizhou City, Jiangsu Province, China, is introducing its range of metal powders to the US market under its Superflow brand. Suitable for Metal Injection Moulding, Additive Manufacturing and thermal spray coating, the powders will be distributed by Kuzma Industrial Corp, located in Brooklyn, New York, USA.

Having over ten years experience in metal powder manufacturing, JSJW specialises in titanium powder production and has two facilities and 100 tons annual production capacity. With its advanced R&D and manufacturing facility, the company states that it provides high-quality metal powders at highly competitive prices.

"Our customers rely on our powder products because of high trust in JSJW's superior technology, reliable equipment and process management. JSJW's unique IPCA technology produces the powder with very good sphericity, very few satellites, and very low porosity," the company stated.

www.jsjinwu.com

www.kuzmaindustrial.com ■



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Xerion's Fusion Factory installed at Fraunhofer IFAM's facility in Dresden

The Fraunhofer Institute for Manufacturing Technology and Advanced Materials (IFAM), Dresden, Germany, reports that it has installed a new Fusion Factory Additive Manufacturing system from XERION BERLIN LABORATORIES GMBH, Berlin, Germany, at its Innovation Centre Additive Manufacturing (ICAM).

The Fusion Factory is a compact production line for the Additive Manufacturing of metal and ceramic components. It has three modules that combine the process steps of Additive Manufacturing, debinding and densification (the final heat treatment to produce a purely metal and dense component) into one plant. With additional AM modules, the system can be expanded for industrial series production.

The Fusion Factory was developed by Xerion with scientific support from Fraunhofer IFAM Dresden and



Xerion's Fusion Factory has been installed at Fraunhofer IFAM's facility in Dresden (Courtesy XERION BERLIN LABORATORIES GmbH)

brought to market maturity. Parts can be produced with a particularly high degree of design freedom, as both open and closed porosity can be achieved in the build stage. IFAM explains that it plans to implement new filament materials and further develop the technology and the process chain for optimised industrial production.

www.ifam.fraunhofer.de ■

Sandvik achieves ISO medical certification for its titanium powders

Sandvik Additive Manufacturing, a division of Sandvik AB, headquartered in Stockholm, Sweden, reports that its new titanium powder plant in Sandviken, Sweden, has received ISO 13485:2016 medical certification for its Osprey titanium powders.

The plant was inaugurated at the end of 2019, and since then, Sandvik states that extensive work has been ongoing to ramp-up the highly automated facility. The process uses advanced EIGA atomisation technology to produce highly consistent titanium powder with low oxygen and nitrogen levels. The production facility also includes dedicated downstream sieving, blending and packing facilities – integrated through the use of industrial robotics.

www.additive.sandvik ■

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Inaugural Formnext + PM South China exhibition postponed until 2021

Formnext + PM South China, a new trade show for the Powder Metallurgy, Metal Injection Moulding and Additive Manufacturing, scheduled to take place in Shenzhen, China, September 9–11, 2020, has been postponed until 2021 due to coronavirus (COVID-19). The event is organised by Mesago Messe Frankfurt GmbH, Germany, Guangzhou Guangya Messe Frankfurt Co Ltd, China, and Uniris Exhibition Shanghai Co Ltd, China.

Hubert Duh, Chairman of Guangzhou Guangya Messe Frankfurt Co Ltd, explained, "The concept of the fair we had presented to our stakeholders emphasised it as a platform for the latest products and technologies for the entire Additive Manufacturing and Powder Metallurgy industries, and for multiple end uses. In our debut edition, we wanted to have this full picture presented;

however after consulting with our exhibitors, supporting associations and other partners, due to various complications arising from the coronavirus pandemic we came to the conclusion that this concept couldn't be realised adequately in 2020."

Duh added, "In particular, there is ongoing uncertainty over entry into China for foreign participants which is making it difficult for our overseas stakeholders to plan ahead. What's more, many companies in the industry will likely only just have resumed normal operations around September, which makes decision making about participating in trade fairs for that time challenging. We felt, therefore, it was in everyone's best interests to focus on ensuring the full participation of the industry in 2021 instead."

Zhu Xiao Feng, General Manager of co-organiser Uniris Exhibition Shanghai Co Ltd, commented, "It is unfortunate that we cannot hold the debut edition of Formnext + PM South China this year, but in the end the decision was unavoidable. China, as the centre of the global supply chain and boasting one of the most diverse manufacturing sectors, has seen steady growth in manufacturing demand which will further deepen the importance of Additive Manufacturing and Powder Metallurgy technology in the Chinese market."

He continued, "As the fair focuses on both the AM and PM industries, its location in Shenzhen, given the rapid development of the city's high-tech industries, and the participation of the leading Chinese and international brands due to the cooperation between Uniris and Messe Frankfurt, we are highly confident the fair will be a great success in 2021."

www.formnext-pm.com ■

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Ipsen reports strong start to its third quarter, announces new global Technology Excellence Centres

Ipsen USA, Cherry Valley, Illinois, USA, reports that despite uncertain market conditions presented by the coronavirus (COVID-19) pandemic, it has seen an increase in orders placed during July, building positive momentum for its third quarter.

According to Ipsen, it was awarded five vacuum furnace orders between four customers, each with unique process requirements in the aerospace, defence and commercial heat-treating industries. In addition to the five new orders, Ipsen states that it shipped nine furnaces in July to customers across six states in the USA, as well as Canada and the UK. Orders this year have reportedly included a mix of new equipment, aftermarket parts, service and retrofits. Ipsen is hopeful that this trend will continue into the fourth quarter. "Ipsen has worked with international operations teams for decades, shipping equipment from the US to countries all over the world," stated Patrick McKenna, Ipsen USA president and CEO. "With the identification of Ipsen USA as the Vacuum Center of Excellence, we can continue servicing those companies with the level of quality they expect and deserve."

The company also reports that it is establishing Technology Excellence Centres, while further strengthening the company's offerings, in order to ensure it is addressing market needs of its current and future customers. These will enable faster response times, supported by advanced new service products, in all the regions that Ipsen serves. The company's equipment manufacturing business will be driven by an Atmosphere Technology Excellence Center in Kleve, Germany, and a Vacuum Technology Excellence Center near Rockford, Illinois, USA. Ipsen explains that this focus on one field of technology will enable faster-paced innovation and a focus on performance and quality.

As a result of this change, new furnace equipment will reportedly be manufactured at fewer locations globally with a focus on specialisation. The Ipsen Germany location will exclusively build atmosphere batch and continuous systems, while the US location will exclusively build vacuum furnaces. In addition,

Ipsen India will continue to build atmosphere furnaces for the Indian and Southeast Asian markets. Its Chinese and Japanese locations will no longer manufacture furnaces and will focus on customer service and sales from its Excellence Centres. According to Ipsen, this consolidation of manufacturing sites, together with the uncertainty of COVID-19, has resulted in a reduction of staff, which the company described as a regrettable but necessary outcome from its careful strategic planning.
www.ipsenusa.com ■

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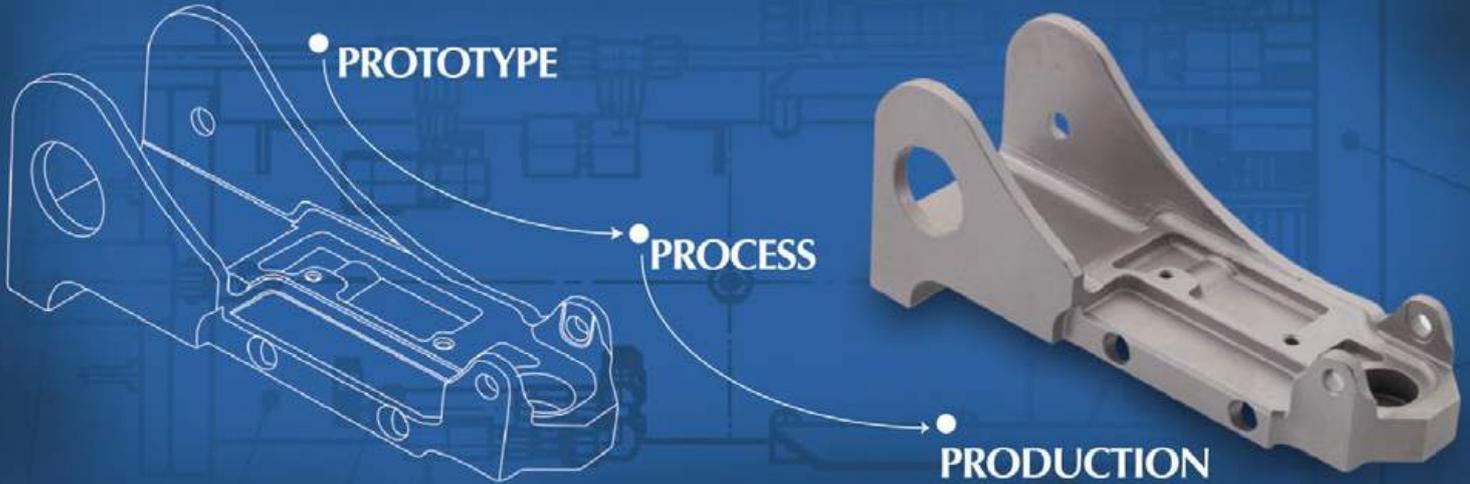
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Quality Certifications:
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and ISO 14001:2004

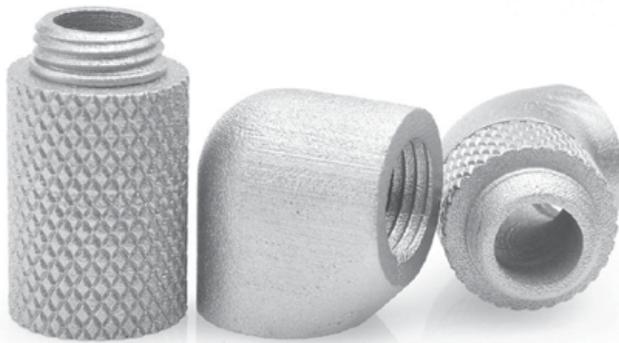
ExOne qualifies Inconel 718 for binder jet AM applications

The ExOne Company, North Huntingdon, Pennsylvania, USA, reports that the nickel-base alloy Inconel 718 has been certified as Third-Party Qualified, the company's highest designation of material readiness for its binder jet metal Additive Manufacturing machines.

Frequently used in the aerospace, energy and automotive industries, Inconel 718 is known for its high strength and hardness, with strong resistance to corrosion, chemicals and extreme temperatures ranging from sub-zero to 704°C. It also has outstanding welding characteristics and is often used for high-temperature applications such as jet engines and tooling, or corrosive environments such as those featuring seawater or acids.

"Today's qualification of Inconel 718, following on the heels of M2 Tool Steel earlier this year, shows the ExOne R&D team is aggressively delivering new materials for binder jet 3D printing," stated Rick Lucas, ExOne CTO and VP, New Markets. "Our increasing pace of material qualifications is a testament to the strength of our new metal 3D printer systems equipped with Triple ACT, an advanced compaction technology that is essential for Binder Jetting metals and other materials at high speeds and densities."

The company explains that as is the case with Inconel 718, ExOne's patented Triple ACT enables the Additive Manufacturing of standard MIM powders, followed by the use of



Inconel 718 has been certified as Third-Party Qualified for use in ExOne's metal AM machines (Courtesy The ExOne Company)

standard sintering profiles and heat treatments, that deliver high-density results consistent with wrought material. Independent testing verifies that Inconel 718 additively manufactured and sintered by ExOne meets ASTM standard B637-18.

Lucas added, "ExOne can now transition R&D materials to full qualification as demand increases." ExOne has three tiers of material qualification, used to signify the varying levels of readiness of materials for binder jet AM applications: R&D, Customer-Qualified and Third-Party Qualified.

Previously, the company had recognised Inconel 718 as an R&D material, which meant it had been deemed buildable for researchers, supported by ongoing development. The new Third-Party Qualified status means that the material has passed rigorous ExOne tests over multiple builds and has verified material property data from an independent third party.

Customer-Qualified materials are those that have been qualified

by ExOne customers with their own standards and are currently being successfully additively manufactured for their own applications. However, they have not yet earned ExOne's highest level of qualification for general market readiness.

Currently, twenty-two metal, ceramic and composite materials are Third-Party or Customer-Qualified. In addition, more than two-dozen materials are recognised as R&D ready, including aluminium, which has been fast-tracked for qualification. ExOne believes the ability to additively manufacture aluminium at high speeds will have a transformative, sustainable effect on the automobile and aerospace industry.

The company explains that its proprietary CleanFuse binder was a critical component in the new qualification of Inconel 718. CleanFuse is a clean-burning binder for additively manufactured metals that are sensitive to carbon left behind by other binding agents during sintering.

www.exone.com ■



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Novamet acquires Rhode Island metal powder atomisation facility

Ultra Fine Specialty Products, LLC, a division of Novamet Specialty Products Corporation, Inc, Lebanon, Tennessee, USA, has acquired a high-purity, fine metal powder atomising facility, located in Woonsocket, Rhode Island, USA. The facility was formerly owned by Carpenter Powder Products, Inc., a subsidiary of Carpenter Technology Corporation.

The company explains that Ultra Fine will now focus on refining and expanding the capabilities of the Ultra Fine atomising facility to produce high-quality metal powders in the finest range of sizes available through gas atomisation. The process used by Ultra Fine to produce powders is said to be unique, enabling the highest possible quality powders in the size range of under 30 µm.

Ultra Fine was recently formed by Jeffrey Peterson, Novamet CEO;

John Torbic, Novamet president; and Novamet General Counsel Michael Hinchion, to locate and acquire technically-oriented production assets to support the advancement of metal powder technologies and their use in aerospace, electronics, batteries, industrial parts and other markets in the US and around the world.

Novamet was formed in 1976 to apply its technology for the development of nickel-base powders and technologies into different morphologies, shapes and sizes for various industrial uses, focusing on nickel powders produced by its then-parent company, Inco.

The company was acquired by investors in 2010 and after nearly forty years in Bergen County, New Jersey, USA, moved its headquarters and manufacturing facilities to Lebanon.

Novamet currently processes and distributes various metal powders and coated products for the Metal Injection Moulding, aerospace, automotive, coatings and electronic materials markets.

"We are very excited about the beginning of Ultra Fine as a separate organisation, and its acquisition of this facility," stated Peterson. "Ultra Fine will not only supply its own customers high-quality products as it did before, but it will be a source for Novamet of a broader selection of competitively priced, high-quality feed materials from a US-based provider that is focused on supporting our markets."

Torbic commented, "Novamet has a strong record of working with the types of powders this facility can produce, and we see even more potential for growth as Novamet and Ultra Fine combine their technical strengths and manufacturing skill sets."

www.novametcorp.com ■

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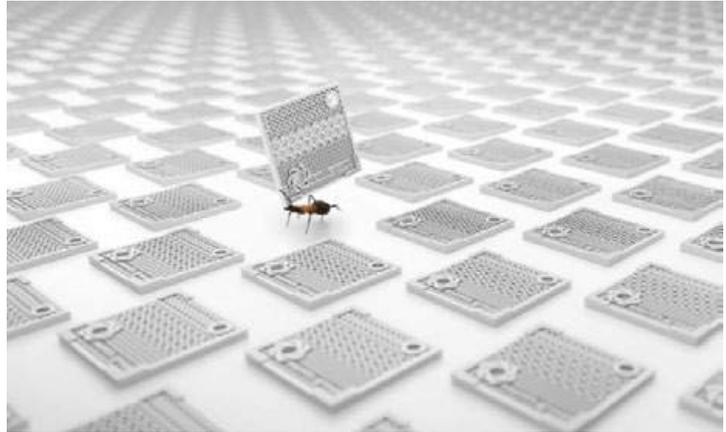
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Exentis Group is the inventor and pioneer of an innovative manufacturing technology, industrial 3D screen printing “**Exentis 3D Mass Customization®**” which represents and enables industrialized additive manufacturing with **free choice of materials**. Its strength lies in the process of applying pastes layer by layer with the aid of a screen printing system and a squeegee, especially for flat components with filigree geometry. Due to the low tooling costs, components can be economically produced in small and medium batch sizes as well as in **mass production**. The short delivery time for screen printing screens enables fast design changes and optimization of components in production.



Conventional screen printing finally achieves the third dimension. Widely used are applications that include graphic screen printing or printing in the LTCC or electronics industry with only few layers. Due to remarkable development steps over the last decade, driven by Exentis Group, this technology has achieved a high technical level, allowing new applications across segments like sensor-, cutting, medical-, energy, semiconductor-, filter-, casting-, safety-, vacuum technology, electrical engineering, e-Mobility and the watch industry.

High resolutions are possible, even with wall thicknesses of **less than 70 µm** in the case of fine-line printing. Screen printing equipment fulfills highest demands with regard to quality and component throughput. Screen printing screens, alongside with the processing equipment itself, are the key component of screen printing. A fully developed technology, also in view of their production-quality and durability.

3D Mass Customization® combines all advantages of conventional screen printing, but it also allows not only to print just a single material layer, but also to apply numerous printing, etc. While one complete component is built in seconds, at the very same time several components are produced simultaneously. Changing screens with different designs allows the **geometrical complexity** of the components to be increased.

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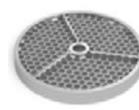
- ✓ Use of composite materials
- ✓ Cost advantages through avoidance of milling

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New president and board members at JPMA



Nobuhiro Hashimoto, Sumitomo Electric Industries, Ltd. has been announced as the new president of the Japan Powder Metallurgy Association (Courtesy JPMA)

The Japan Powder Metallurgy Association (JPMA), based in Tokyo, Japan, has announced the election of a new president and the appointment of a number of new board members at its General Assembly, May 18, 2020. Yoichi Inoue, Fine Sinter Co., Ltd., retired as president of the association and was succeeded by Nobuhiro Hashimoto, Sumitomo Electric Industries, Ltd.

Following his retirement from the presidency, Inoue remains a permanent member of the JPMA board.

www.jpma.gr.jp ■

PM China 2020 reports 14% visitor growth

The 13th International Exhibition for Powder Metallurgy, Cemented Carbides and Advanced Ceramics (PM China 2020) which was held August 12–14, 2020, welcomed over 25,793 visitors on-site, an increase of 14% on last year's show, reports the organiser, Uniris Exhibition Shanghai Co., Ltd. The 30,000 m² exhibition represented an increase of 20% on the previous year, with a total of 494 exhibitors from China and the rest of the world. According to the organiser, the exhibition made headway in bringing more cutting-edge technologies and products to its visitors.

In addition to the exhibition, the event comprised five summits featuring sixty-two academics, professors and business executives in the fields of Powder Metallurgy, cemented carbide and advanced ceramics to share new trends and development with more than 1,200 participants.

The 14th International Exhibition for Powder Metallurgy, Cemented Carbides and Advanced Ceramics (PM China 2021) is scheduled to take place from May 23–25, 2021.

www.pmexchina.com ■

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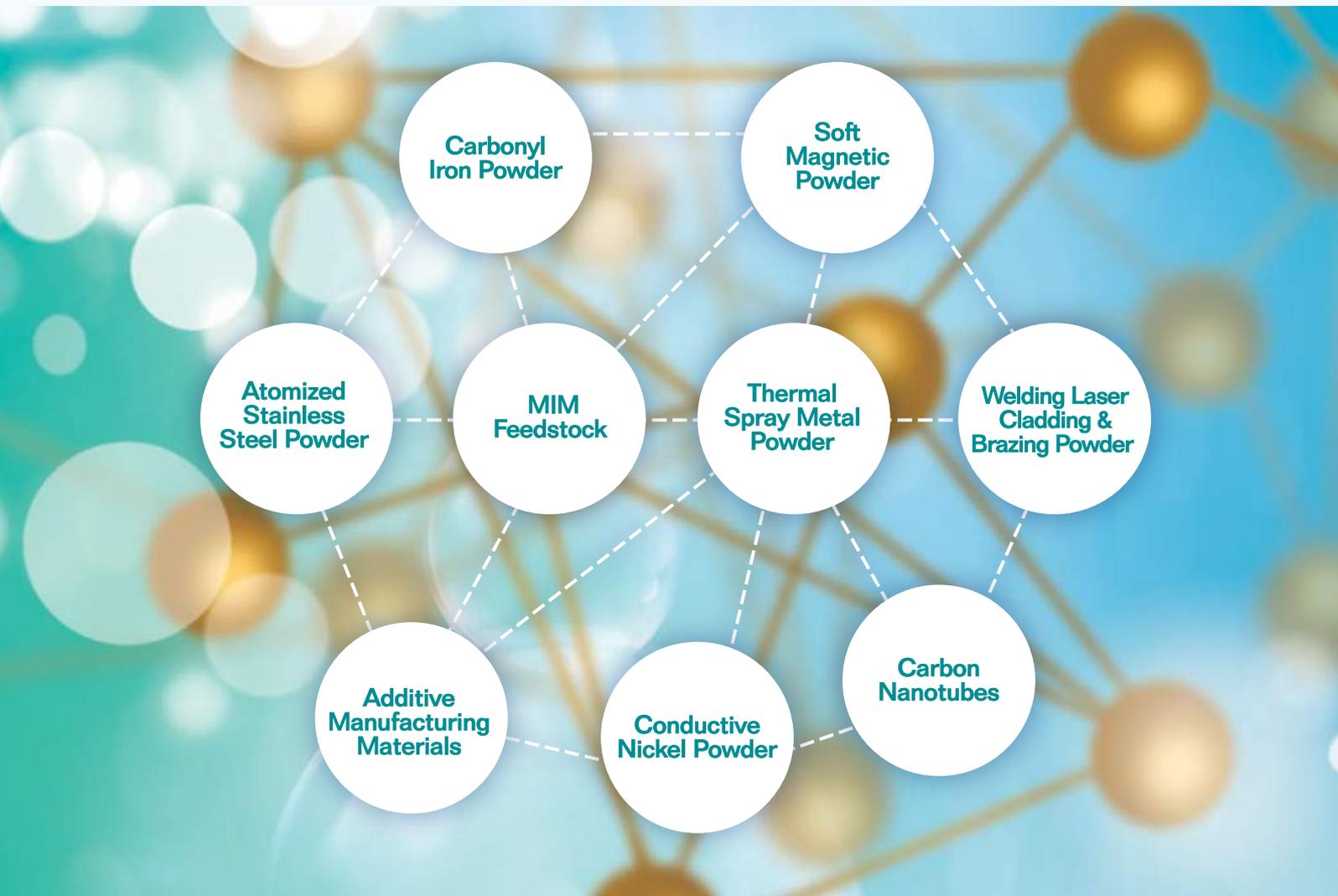


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Metal Injection Moulding shines once again in MPIF's 2020 PM Design Excellence Awards

The Metal Powder Industries Federation (MPIF) announced the winners of its annual Powder Metallurgy Design Excellence Awards over the summer through a series of online announcements, in lieu of the usual presentation ceremony at the organisation's main annual industry conference and exhibition.

Metal Injection Moulding featured heavily in a 'Special Technologies' category, as well as in the 'Consumer Goods' and 'Automotive' categories. All of the MIM and sinter-based AM related winners are outlined below, whilst conventional 'press and sinter' PM award winning parts can be found in the current issue of *PM Review* magazine.

Further in-depth information on all of the award winning parts is available in special MPIF award videos, viewable via www.mpif.org or the MPIF's YouTube Channel.

Grand Prizes

Special Technologies–Aerospace/Military/Firearms Category

The Grand Prize in this category was awarded to Advanced Powder Products Inc., Philipsburg, Philadelphia, USA, for a trigger mechanism housing for a new 9 mm sub-compact pistol produced for O.F. Mossberg & Sons Inc. (Fig. 1). The component originally comprised two pieces (metal and plastic), and was redesigned as a single MIM part. Over 5,000 rounds were fired to test the part and no failures were observed.

Special Technologies–Medical/Dental Category

Advanced Powder Products Inc. also received a Grand Prize for a guide tube used in dental surgery (Fig. 2). This extremely small part has very thin wall sections and a built-in impingement plate on the inner diameter of the tip. This impingement plate has a gaussian curvature that can only be formed economically by Metal Injection Moulding.

Consumer Goods–Hand Tools/Recreation Category

In this category, the Grand Prize was awarded to Smith Metal Products, Center City, Minnesota, USA, for a jaw frame used in an archery string release device. This device retains the 'fingers' that hold the bowstring securely and accurately while the shooter aims at the target. It also houses the trigger for when the archer is ready to shoot (Fig. 3).



Fig. 1 A trigger mechanism housing for a new 9 mm sub-compact pistol (Courtesy MPIF)



Fig. 2 A guide tube used in dental surgery featuring a gaussian curvature that can only be formed economically by Metal Injection Moulding (Courtesy MPIF)



Fig. 3 A jaw frame used in an archery string release device (Courtesy MPIF)

**Consumer Goods–Hardware/
Appliances Category**

A Grand Prize was awarded to ARC Group Worldwide, Denver, Colorado, USA, for a gearbox used in a drive system for motorised blinds. The component holds nine gears that rotate when actuated, to allow blinds to function with a remote-control device (Fig. 4).



Fig. 4 A MIM gearbox used in a drive system for motorised blinds (Courtesy MPIF)

Automotive—Transmission Category

Phillips-Medisize – Metal Injection Molding, Menomonie, Wisconsin, USA, won in this category for an actuator arm supplied to Means Industries and used in a 9-speed forward transmission assembly for General Motors and Ford Motor Company. The actuator arm is part of a Means-patented selectable one-way clutch that replaces the reverse clutch (Fig. 5).



Fig. 5 Actuator arm parts supplied used in a 9-speed forward transmission assembly (Courtesy MPIF)

Awards of Distinction

**Special Technologies–Aerospace/
Military/Firearms Category**

An Award of Distinction was given in this category to Alpha Precision Group – Metal Injection Moulding, Ridgway, Pennsylvania, USA, for a shroud that houses the firing pin and firing pin collar in a bolt-action rifle (Fig. 6).



Fig. 6 A shroud that houses the firing pin and firing pin collar in a bolt-action rifle (Courtesy MPIF)

A further Award of Distinction was given in this category to ARC Group Worldwide for lever actuators for vanes in a turbo-prop engine. The actuators control the angle of the variable inlet guide vanes and the variable stator vanes (Fig. 7).



Fig. 7 Lever actuators for vanes in a turbo-prop engine (Courtesy MPIF)

**Special Technologies–Aerospace/
Military/Firearms Category**

An Award of Distinction was given to 3DEO, Gardena, California, USA, in this category for an anchor link used in a firearms application (Fig. 8) 3DEO uses a proprietary hybrid sinter-based metal AM process to make the parts.

**Special Technologies–Medical/
Dental Category**

In this category, an Award of Distinction was given to MPP, Noblesville, Indiana, USA, and its customer Coracoid for a buckle used in an

implanted shoulder repair device (Fig. 9). Several technologies were considered for making the part but MIM processing was the only one that produced a part that could withstand the stresses induced during the cinching of the device during surgery and the placement of the cleat.

A second award was given in this category to OptiMIM, Portland, Oregon, USA, and its customer Atricle for one of two jaws of a surgical device for deploying a clip around a heart's left-atrial-appendage (Fig. 10). The mould produces two parts that are mirror images of one another.



Fig. 8 An additively manufactured anchor link used in a firearms application (CourtesyMPIF)



Fig. 9 A buckle used in an implanted shoulder repair device (Courtesy MPIF)



Fig. 10 A part from a surgical device for deploying a clip around a heart's left-atrial-appendage (Courtesy MPIF)



Fig. 11 MIM part for an EZ change removable brush holder (Courtesy MPIF)



Fig. 12 Minimum-flow setting devices used in the turbochargers of four-wheeler vehicles (Courtesy MPIF)

Special Technologies—Electronic/ Electrical Components Category

An Award of Distinction was given to ARC Group Worldwide and its customer Cutsforth Inc. in this category for a lower beam EZ change holder for removable brush holders (Fig. 11). These parts are used in brush excitation maintenance on turbine generators in the nuclear, gas, coal, wind and hydro industries.

Automotive—Engine Category

Indo-MIM Pvt. Ltd., Bangalore, India, and San Antonio, Texas, was recognised with an Award of Distinction in this category for three minimum-flow setting devices used in the turbo-charger of a four-wheeler vehicle (Fig. 12). The parts are made using MIM-316L and replaced components that were machined in multiple steps.

Automotive—Transmission Category

Indo-MIM Pvt. Ltd. received a second Award of Distinction for a park lock lever manual override used in a vehicle handbrake (Fig. 13).

Automotive—Chassis Category

Indo-MIM Pvt. Ltd. also received an Award of Distinction in this category, for left- and right-hand-side cable guides used in a four-wheeler roof assembly (Fig. 14). The MIM parts are made in a two-cavity mould and replaced expensive machined components.

www.mpif.org ■



Fig. 13 A park lock lever manual override component (Courtesy MPIF)



Fig. 14 Left- and right-hand-side cable guides used in a four-wheeler roof assembly (Courtesy MPIF)

John Zink reports positive results with Desktop Metal Studio System

John Zink Hamworthy Combustion, a developer of emissions control and clean-air solutions based in Tulsa, Oklahoma, USA, and part of Koch Industries, Inc, headquartered in Wichita, Kansas, USA, recently adopted the Desktop Metal Studio System to additively manufacture parts that are engineered-to-order and optimised for each customer's application.

After several months of working with the Studio System, a Material Extrusion (MEX)-based metal Additive Manufacturing machine said to be the world's first office-friendly metal AM machine for rapid prototyping and low-volume production, the company reports that since adopting Desktop Metal's AM technology, it has reported the following positive results:

- Quick turnaround of aftermarket replacement parts
- The ability to test different iterations of prototype designs faster
- Eliminated need for casting tooling, saving both time and money because parts can now be additively manufactured in-house

- Freedom to create part designs that cannot be manufactured by traditional methods, only by AM

"Our primary goal at John Zink is to custom-engineer new systems that eliminate waste so our customers can operate safely and efficiently," stated Jason Harjo, Design Manager, John Zink.

"Additive Manufacturing rewrites the book on what is possible from a design standpoint, and working with Desktop Metal allows us a very low-cost entry point into the technology," he added. "The versatility of the Studio System has enabled our engineers and designers to find both applications for the technology as well as design and performance benefits we hadn't even considered."

John Zink offered several examples of parts where the adoption of metal Additive Manufacturing has proven beneficial:

Fuel atomiser – cost savings 75%, time savings 37%

Using atomisers to improve the fuel-air mix inside burners onboard ships is a simple way John Zink helps customers minimise their environmental footprint.

By using the Studio System, the company's designers and engineers were able to prototype and test a variety of options before creating a new design featuring airfoil-like fins. The geometric freedom of Additive Manufacturing allowed them to reconsider the shape of the holes – instead of drilling round holes, the part is built with flat openings to improve atomisation and increase burner efficiency.

Where the previous design was able to reduce fuel use to 120 kg per hour, the new design cut fuel use to just 38 kg per hour. With three burners per ship, the environmental impact across an entire fleet is significant.

Cost-savings can be equally significant, as per ship, the new atomiser could save companies between \$90,000 and \$160,000 in fuel costs annually. The additively manufactured atomiser can be produced in a few days for less than half the cost of a traditionally manufactured fuel atomiser.

YE-6 burner tip – cost savings 72%

A key component in the efficient operation of industrial burners, burner tips are used to control the injection of fuel into the combustion chamber, or as atomisers, mixing fuel with an atomising medium like steam to increase burner efficiency.

This burner tip – originally cast and post-processed via CNC machining – was first manufactured thirty years ago, and the tooling used to produce it is no longer available. Because the part is too complex to machine as a single component, manufacturing spare parts using traditional techniques would require large investments in both time and money.

Instead, John Zink explained that its engineers used the original engineering drawings to model the burner tip and additively manufactured it using the Studio System.

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The finished part was produced in just weeks, as opposed to months, and cost significantly less than a cast part.

Laser gas nozzle

A useful tool found in many machine shops, laser cutters can make precise cuts in a variety of materials. The challenge for John Zink engineers when producing this tool was that the cutter’s nozzle could become clogged or slag could build up on the edges of cut parts, requiring labour-intensive post-processing.

The company’s engineers designed and additively manufactured a new nozzle on the Studio System that incorporates a series of internal channels to direct high-pressure nitrogen gas across the cuts and blow away slag, preventing clogs and ensuring cleaner cuts. The complex geometry of the new nozzle could only have been made using AM, states the company, and was additively manufactured in metal after an earlier version, which was produced from PLA, melted at higher temperatures.

Machine tool handles

Additive Manufacturing has helped John Zink engineers recreate legacy parts and redesign existing parts, as well as helping them to find creative solutions that improve how they manufacture them. Designed by a machinist with three decades of experience at John Zink, these handles were created to make it easier to lift and place heavy tools in a lathe, and were additively manufactured in metal using the Studio System after the initial parts, which were additively manufactured in plastic, broke.

The handles were additively manufactured rather than machined to minimise waste as, if machined, each handle would have to be made from a relatively large piece of metal, and to leave the company’s machine shop capacity free for customer jobs.

Safety shutoff yoke and handles

Shutoff yokes and handles are a key piece of safety equipment that

is installed on the USS Blue Ridge (LCC-19). Because no tooling exists for these parts, creating them via Additive Manufacturing was the most time- and cost-effective option for manufacturing.

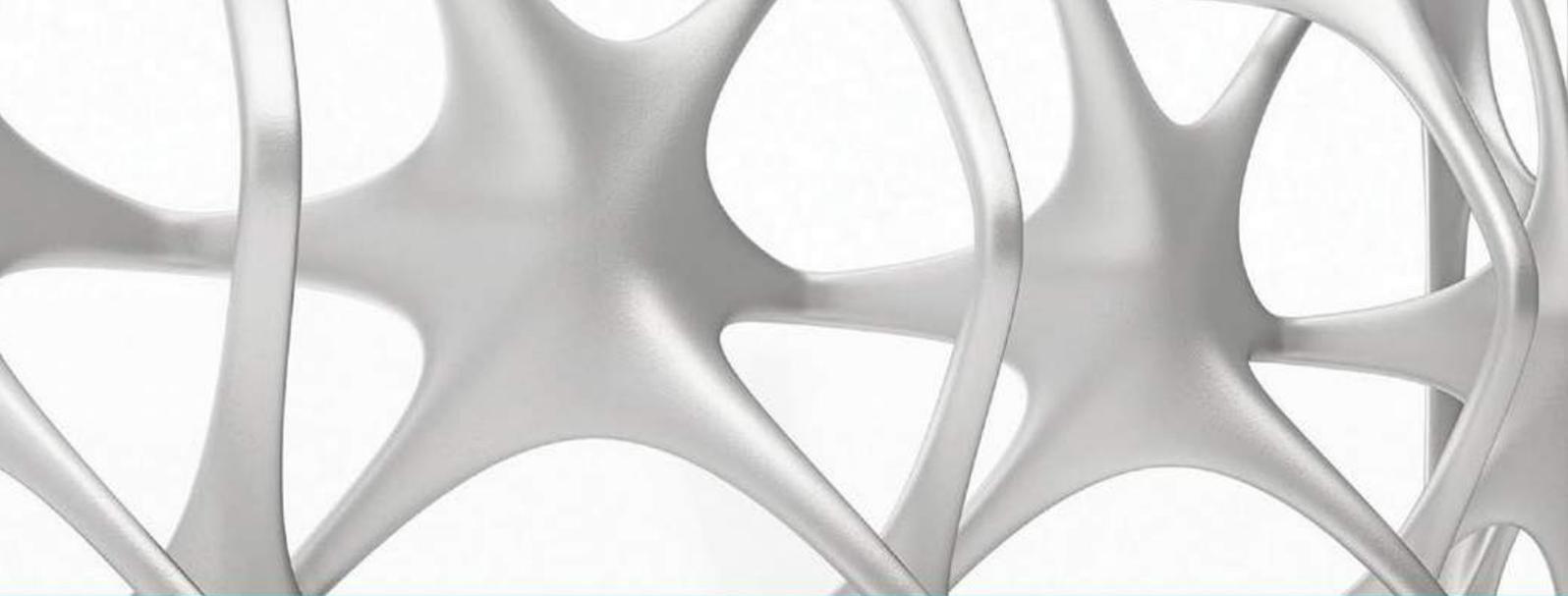
Customers are said to have benefited from less downtime, as the additively manufactured parts can be delivered and installed in days rather than weeks or months.

“By eliminating the need for hard tooling with the Studio System, John Zink engineers have been able

to produce innovative new parts, reproduce parts for which tooling no longer exists and find creative solutions to improving their workflow,” reported Jonah Myerberg, CTO of Desktop Metal. “As a result, their team has been able to significantly speed up the design, manufacture and deployment of parts, while saving money and delivering parts faster to customers.”

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The advertisement features a woman with long red hair in a denim shirt, looking upwards with a smile. The text 'enjoy INNOVATION' is overlaid in a stylized font. At the top, the 'Wittmann' and 'Battenfeld' logos are displayed. Below the woman, the 'Wittmann 4.0 plug & produce' logo is shown. The bottom half of the ad shows a collage of industrial equipment, including a lathe, a 3D printer, and various tooling components, with red lines connecting them to a central point on a machine's control panel. The website 'www.wittmann-group.com' is at the bottom.



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Use of coarser powders to lower MIM part costs

It is well known that the key differences between the metal powders used for Metal Injection Moulding and for conventional 'press and sinter' Powder Metallurgy for the mass production of highly-complex structural parts is the particle size and shape of the powder. The MIM process requires fine spherical powders (-20 µm) whereas conventional PM can use coarser (+100 µm) and irregular shaped powders. However, achieving the fine particle size and shape desired for MIM requires more expensive production processes resulting in significantly more expensive powder for the same composition, which inevitably increases the cost of the finished MIM parts.

To reduce the production costs for MIM parts, researchers at the Bauman Moscow State Technical University (BMSTU), Moscow, Russia, have been investigating the use of a new composition of BMSTU 42CrMo4 feedstock, using a coarser 42CrMo4 steel powder (-50 µm particle size). A. Yu. Korotchenko and colleagues reported on the results of their research in a paper published in *Powder Metallurgy and Metal Ceramics*, Vol. 58, Nos. 11-12,

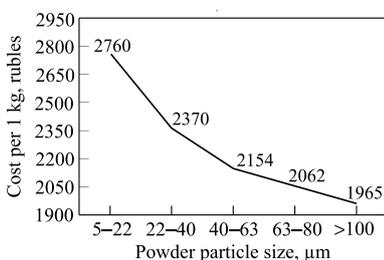


Fig. 1 Cost of metal powders as a function of particle size (From paper: 'Use of coarse powder in injection moulding process', by A Yu Korotchenko, et al, *Powder Metallurgy and Metal Ceramics* Vol. 58, No. 11-12, March 2020, 730-736. Russian original Vol. 58, No. 11-12, Nov-Dec 2019)

Temperature, °C	MFI, g/10 min	
	Catamold 42CrMo4	BMSTU 42CrMo4
180	253	243
190	400	285
200	516	408

Table 1 The temperature dependence of melt flow index (MFI) (From paper: 'Use of coarse powder in injection moulding process', by A Yu Korotchenko, et al, *Powder Metallurgy and Metal Ceramics* Vol. 58, No. 11-12, March 2020, 730-736. Russian original Vol. 58, No. 11-12, Nov-Dec 2019)

March 2020, 730-736, translated from the Russian original published in *Poroshkova Metallurgiya*, Vol. 58, No. 11-12, Nov-Dec 2019.

The researchers found that the cost of metal powders, produced by a number of Russian powder manufacturers increased exponentially with a decrease in particle size, as can be seen in Fig. 1. They therefore investigated the use of a 40 KhMA alloy powder, produced by the Polema JSC in Russia, which is said to be identical in composition to the 42CrMo4 alloy steel powder (Fe-C0.37-0.44-Cr1.00-1.30-Mo0.10-0.30-Ni0.01-Si0.01-0.13) used for a wide range of parts for the defence and automotive industries. The particle shape of the powder is close to spherical with a particle size range within 50 µm.

MIM feedstock was prepared from this powder with a binder based on 90 wt.% polyacetal (PA), 10 wt.% low density polyethylene (LDPE) and

0.5 wt.% stearic acid (SA). Powder loading in the feedstock was reported to be 90 wt.%. The BMSTU 42CrMo4 feedstock was mixed using a rotary twin-screw laboratory mixer, with mixing temperature at 180°C and mixing time of no more than 50 min. The researchers tested the rheological properties of the prepared feedstock and compared them with those of the BASF Catamold 42CrMo4 feedstock. As can be seen in Fig. 2, the melts of both the BMSTU 42CrMo4 feedstock and the Catamold equivalent have similar viscous flows. Also the melt flow indicator (MFI) was used to determine the rheological properties of both feedstocks at three temperatures (180, 190, and 200°C) with the experimental results shown in Table 1.

Analysis of the MFI values shows that MFI decreases for the BMSTU 42CrMo4 feedstock, due to an increase in the powder particle

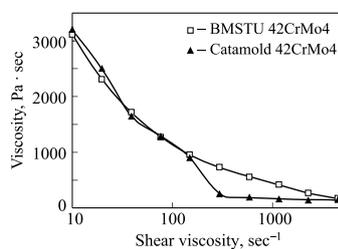


Fig. 2 Viscosity versus shear velocity (From paper: 'Use of coarse powder in injection moulding process', by A Yu Korotchenko, et al, *Powder Metallurgy and Metal Ceramics* Vol. 58, No. 11-12, March 2020, 730-736. Russian original Vol. 58, No. 11-12, Nov-Dec 2019)

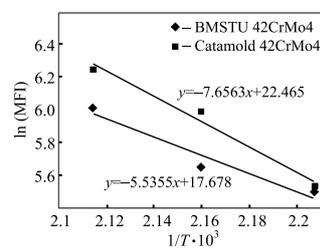


Fig. 3 Temperature dependence of MFI (From paper: 'Use of coarse powder in injection moulding process', by A Yu Korotchenko, et al, *Powder Metallurgy and Metal Ceramics* Vol. 58, No. 11-12, March 2020, 730-736. Russian original Vol. 58, No. 11-12, Nov-Dec 2019)

size. The MFI values at different temperatures were used to determine the activation energy of both the Catamold 42CrMo4 and BMSTU 42CrMo4 feedstocks. Temperature dependences of MFI were plotted for this purpose, as shown in Fig. 3.

In terms of mechanical properties, the researchers reported on their work to determine tensile strength and hardness for the new BMSTU 42CrMo4 feedstock. Tensile strength of sintered MIM samples ranged from 360 to 400 MPa, which is around 70% of the value given by BASF for the

Catamold 42CrMo4. The reduction in strength was attributed to a lower sintered density (7.25 g/cm^3) in the sintered samples made of BMSTU 42CrMo4, compared with 7.54 g/cm^3 in the Catamold samples. However, the authors stated that, if a higher tensile strength is required, this could be achieved by heat treatment of the MIM BMSTU 42CrMo4 parts. Tensile strength is said to increase by more than twice after heat treatment.

Hardness of the MIM test samples was measured using samples which had been polished to $R_a = 0.32 \mu\text{m}$.

Hardness tests indicate that values varied between 144 and 220 HV1 and corresponded closely to the values specified for the Catamold 42CrMo4 feedstock (130–230 HV10). The surface roughness of the MIM BMSTU 42CrMo4 samples found R_a to be in the range $1.85\text{--}2.22 \mu\text{m}$ and R_z varied from 10.50 to $11.50 \mu\text{m}$.

The authors concluded that the use of metal powders with coarser particles allows the cost of MIM parts to be reduced without a significant decrease in their mechanical properties. They attributed the lower strength values of the powders investigated to lower sintered density and also the different microstructures in the Catamold 42CrMo4 and BMSTU 42CrMo4 samples. The BMSTU 42CrMo4 samples were found to have a ferrite/pearlite structure resulting from the equilibrium decomposition of austenite in carbon steels with carbon content less than 0.8%, whereas the Catamold 42CrMo4 samples had a pearlite structure—a eutectoid mixture of ferrite and cementite. They further concluded that, because the coarser powder possesses thixotropic properties with the viscosity substantially decreasing with higher shear velocity, it allowed the use of lower cost automatic injection moulding machines operating at lower injection pressures. The decrease in the melt flow index also makes the BMSTU 42CrMo4 feedstock less sensitive to temperature differences in the mould, when green parts are produced, allowing lower moulding temperatures to be used.

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Optimising particle size fraction for water atomised 17-4PH stainless steel MIM feedstock

Generally speaking, any metal or alloy powder in a size range between 0.5 and 20 µm should be processable by Metal Injection Moulding. However, powder particle shape also plays a key role in injection moulding and sintering. Spherical powders produced by gas atomisation provide suitable viscosity to the MIM feedstock to achieve higher moulding density and good strength after debinding and sintering. In contrast, rounded or irregularly shaped powder particles produced by water atomisation exhibit higher resistance to feedstock flow and lower packing density, resulting in lower sintered density and, consequently, lower mechanical properties.

B N Mukund, Indo MIM Pvt. Ltd., Bangalore, India, and B Hausnerova at the Dept of Production Engineering at the Tomas Bata University in Zlin, Czech Republic, have previously reported on research on the processability by Metal Injection Moulding of a set of gas atomised (spherical) and water

Powder	Particle fraction (%)			
	<5 µm	>5 µm <10 µm	>10 µm <20 µm	>20 µm <35 µm
WA_24	29.93	39.58	23.64	6.85
WA_34	17.45	43.25	33.76	5.54
WA_44	15.19	34.26	43.60	6.95

Table 1 Tailored particle size distributions of 17-4PH stainless steel powders. (From paper: 'Variation in particle size fraction to optimise Metal Injection Molding of water atomized 17-4PH stainless steel feedstocks' by B N Mukund and B Hausnerova, Powder Technology Vol. 308, April 2020, 130-138)

atomised (irregular) powders having the same mean particle sizes. The research focused mainly on the advantages/disadvantages of finer and coarser particle size on the flow performance of MIM feedstocks and the authors' current work gives emphasis to the tailoring of particle size fractions to produce defect-free complex-shaped MIM parts from water atomised 17-4PH stainless steel powder. The results of the research have been published in Powder Technology, Vol. 308, April 2020, 130-138.

The authors used three different tailor-made particle size fractions to prepare the 17-4PH stainless steel MIM feedstocks (Table 1) with the powder abbreviations WA_24, WA_34 and WA_44 reflecting the percentage of particles with a size between 10 to 20 µm produced by

water atomisation. The differences in size fractions are reflected also in the powder shape, as can be seen in Fig. 1, with the most sensitive shape parameters - sphericity factor and aspect ratio - measured using dynamic image analysis. The aspect ratio, defined as the ratio of the width to the length of the particle, attains a value between 0 (irregular) and 1 (spherical). The authors reported that the WA_24 powder contains almost 58% of spherical particles with sphericity index of 0.91, whereas WA_34 and WA_44 contain 52 and 41% of spherical particles with sphericity indices of 0.89 and 0.87 respectively. Concerning aspect ratio, WA_24 powder reaches the value of 0.82, whereas WA_34 and WA_44 have aspect ratios of 0.8 and 0.76, respectively. Thus, the finer powder

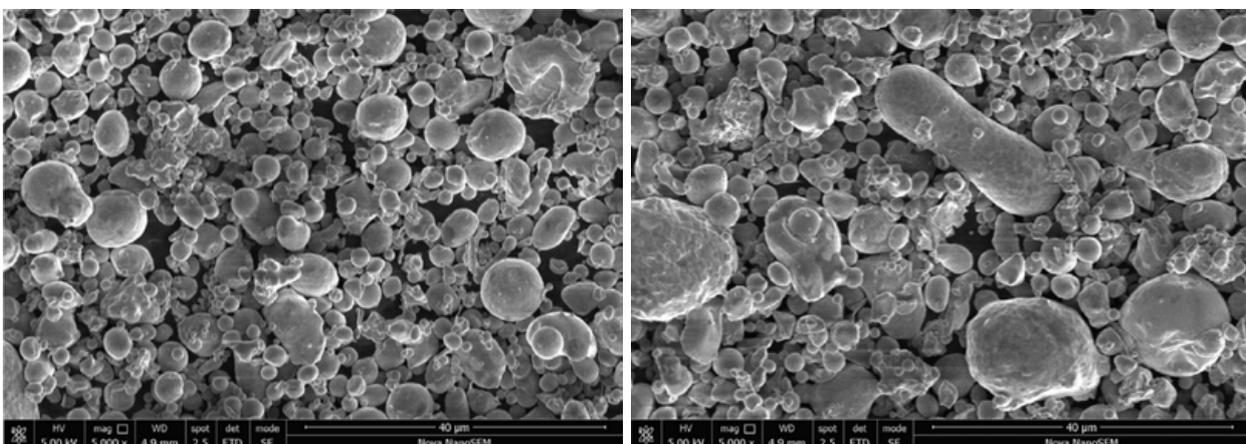


Fig. 1 SEM micrographs of 66 vol.% feedstocks containing WA_24 (a) and WA_44 (b) powder (From paper: 'Variation in particle size fraction to optimise Metal Injection Molding of water atomized 17-4PH stainless steel feedstocks' by B N Mukund and B Hausnerova, Powder Technology, Vol. 308, April 2020, 130-138)

(WA_24) contains more particles having closer-to-spherical shape than the other two (WA_34 and WA_44).

The 17-4PH stainless powders were mixed with a wax-polymer binder system composed of a 50/50 mixture of paraffin wax and high-density polyethylene with critical powder loading at 66 vol.%. Fig. 2 shows the viscosities of the WA_24, WA_34 and WA_44 feedstocks as a function of shear rate at a temperature of 180°C. All feedstocks exhibited pseudoplastic behaviour, with viscosity decreasing with shear rate. Injection moulding parameters were optimised for the water atomised 17-4PH feedstock (Table 1) to produce a test component weighing 25 g, having a length of 43.7 mm and complex design features such as multiple holes, slots and perpendicular features varying in cross-sections. The components were moulded in a 45 ton CNC controlled injection moulding machine. Any defects generated during injection moulding were screened and related to the particle size fractions tested.

Binder removal from the green parts was done through a combination of solvent (in trichloroethylene at 50°C for 300 min) and thermal debinding. The weight loss of the extracted paraffin wax binder was controlled to reach 90% minimum before moving forward to thermal debinding and sintering, which were performed in a vacuum furnace, firstly by increasing temperature to 600°C for debinding followed by ramping up to 1350°C sintering temperature under partial pressure in an argon atmosphere. The sintered components were kept at the solution treatment temperature of 1038°C for 30 min followed by heat treatment to H900 conditions (480°C, 60 min).

The authors stated that the results of the study showed that the feedstocks having higher amounts

of coarser (10–20 µm) fraction, together with higher particle shape irregularity determined from sphericity factor and aspect ratio, led to increases in viscosity, flow instability and injection pressure, lower sintered density with enhanced dimensional deformations. The MIM parts had no surface defects after sintering and heat treatment.

The properties of the final heat-treated 17-4PH stainless steel MIM

parts showed no significant differences in densities, carbon contents and hardness values (Table 2) after sintering and H900 heat treatment. The lowest sintered density of WA_44 samples might indicate feedstock inhomogeneity (as revealed from the flow stability test). The final MIM 17-4 PH materials showed a fine martensitic microstructure.

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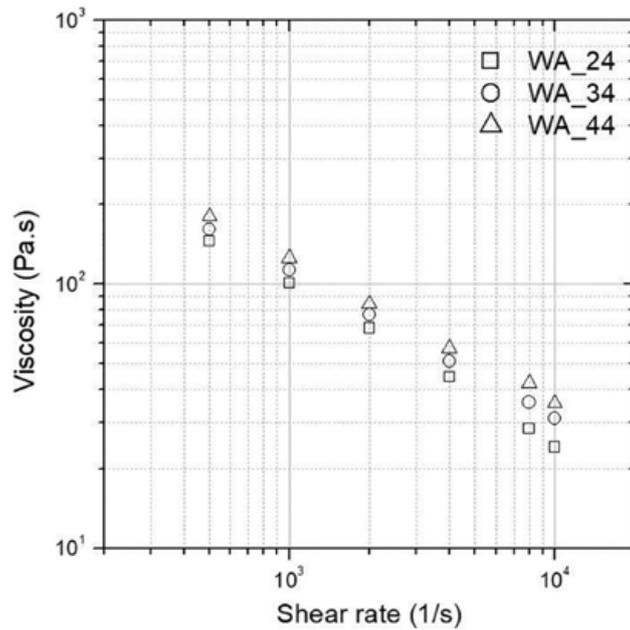


Fig. 2 Viscosity as a function of shear rate of 66 vol.% feedstocks containing WA_24, WA_34 and WA_44 powders (180°C) (From paper: 'Variation in particle size fraction to optimise Metal Injection Molding of water atomized 17-4PH stainless steel feedstocks' by B N Mukund and B Hausnerova, Powder Technology, Vol. 308, April 2020, 130-138)

Powder	Density (g/cm ³)	Carbon content (wt%)	Hardness (HRC)
WA_24	7.64–7.68	0.011–0.013	38.8–40.6
WA_34	7.60–7.65	0.019–0.023	38.9–39.7
WA_44	7.58–7.61	0.021–0.028	36.8–39.2

Table 2 Metallurgical parameters of 17-4PH sintered parts after H900 treatment (From paper: 'Variation in particle size fraction to optimise Metal Injection Molding of water atomized 17-4PH stainless steel feedstocks' by B N Mukund and B Hausnerova, Powder Technology, Vol. 308, April 2020, 130-138)

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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)

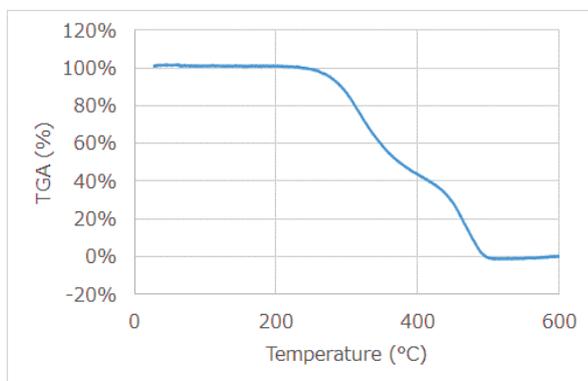


Fig.3 TGA Curve of Binder

※All components are vaporized at around 500°C.

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.

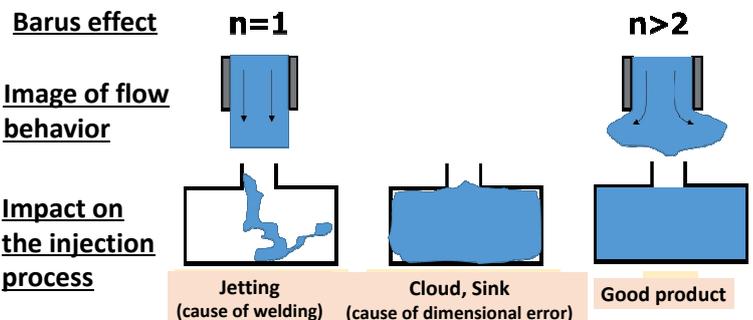


Fig.1 Schematic of the relationship between n value and flow characteristic

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

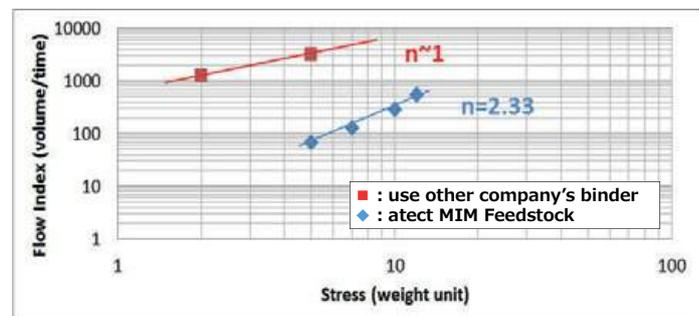


Fig.2 Flow characteristic compared with pellets using the other company's binder

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

Microstructure of tungsten composites produced by Powder Injection Moulding for the EUROfusion project

In the December 2016 issue of *PIM International* (Vol. 10 No. 4), we reported on the development of tungsten composite materials produced by Powder Injection Moulding for use in the EUROfusion project – a Europe-wide consortium established in 2014 to find the most efficient way of realising fusion electricity by 2050.

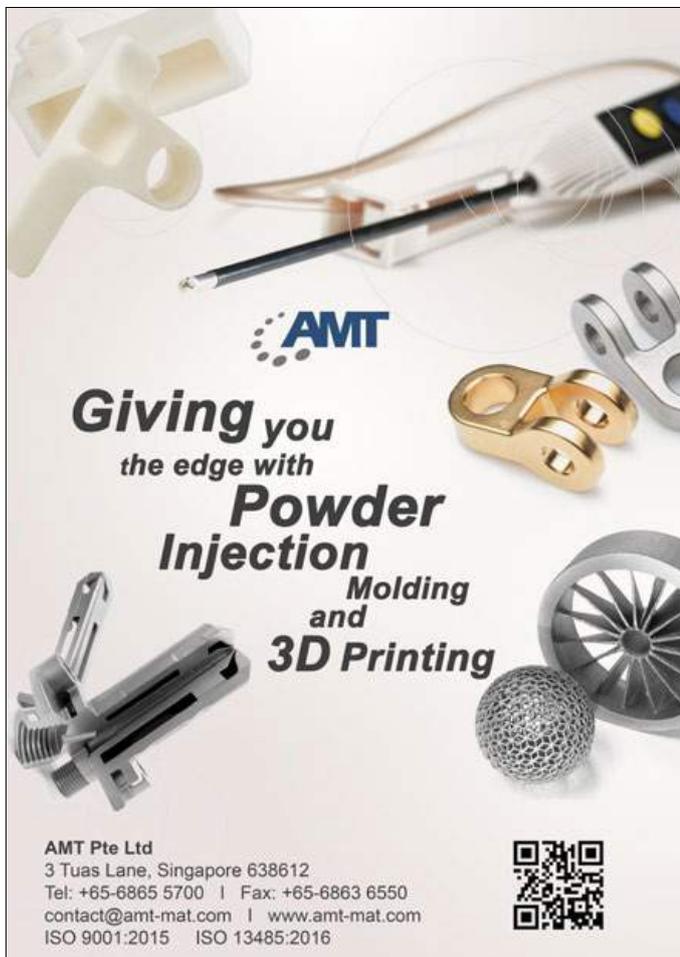
Tungsten-based materials are considered as potential plasma-facing materials in future fusion reactors beyond the International Nuclear Experimental Reactor (ITER), as these materials exhibit excellent high temperature properties such as: exceptionally high melting point, good sputter resistance, high thermal conductivity, low thermal expansion and remarkable high-temperature (creep) strength. The powder injection moulded tungsten composite materials were produced for the EUROfusion Consortium at the Institute of Applied Materials, Karlsruhe Institute of Technology (KIT), Germany.

Recent research work undertaken at KIT as part of the EUROfusion project has focused on a detailed microstructural analysis of the PIM W-composites to establish their structure-properties relationship and a paper authored by Dr Michael Duerrschnabel and colleagues on the results of this phase of the research has been published in *Nuclear Materials & Energy*, June 2020, 20pp. The research reported here covers the microstructural characterisation of unirradiated particle-reinforced W-PIM materials, with the results of the irradiated materials to be reported separately.

Five PIM W-composite samples (8 mm x 8 mm x 4 mm) from different alloys: W-1TiC, W-1HfC, W-3Re-TiC, W-3Re-2Y₂O₃, and W-1La₂O₃-1TiC, were tested for high heat flux properties at Forschungszentrum Juelich, Germany, and additional plasma exposure tests were performed on some of these materials in the Magnum-PSI facility (DIFFER, The Netherlands). The five PIM W-composite samples were analysed in detail at KIT, including texture analysis via electron backscatter diffraction (EBSD), comprising scanning (SEM) and transmission (TEM) electron microscopy analyses, and some results from four-point bending tests, which were done in the temperature range between 200°C and 800°C.

Table 1 summarises the maximum flexural strengths obtained for the five samples. At 200°C, none of the PIM W composite samples were ductile, whereas, at 400°C, only W-3Re-2Y₂O₃ and W-3Re-1TiC remained brittle. Above 400°C, W-3Re-2Y₂O₃ was the only brittle sample. It exhibited a maximum flexural strength of 721 MPa at 400°C and, for all other measured temperatures, it was below this value. The carbide-containing samples in general yielded higher flexural strengths than W-3Re-2Y₂O₃.

The authors stated that a clear benefit of the PIM process to produce the W-composites was the isotropic microstructures obtained, i.e. equiaxed grain orientations found in EBSD mapping, as shown in Fig. 1. The grain size distribution, as well as the average grain size, are plotted for all five samples in the bottom row in Fig. 1. The W grain size is an important quantity, stated the



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Sample	200°C	400°C	600°C	800°C
W-1TiC	1112	1262*	1403*	1277*
W-1La ₂ O ₃ -TiC	1030	1493*	1147	501
W-1HfC	837	1030*	-	-
W-3Re-1TiC	413	1446	911	976
W-3Re-2Y ₂ O ₃	1018	1572*	1743*	1564

Table 1 Maximum flexural strength (MPa) at different temperatures for all analysed PIM-W composite samples. Values marked by a star (*) denote measurements in which the maximum deflection of 1.5 mm was reached (From paper: 'Elucidating the microstructure of tungsten composite materials produced by Powder Injection Moulding' by M Duerrschnabel et al, *Nuclear Materials & Energy*, June 2020, 20 pp)

authors, because it influences, for example, hardness, strength, fatigue and toughness, in general, but also high heat flux test properties such as surface roughening and crack formation, which are important for the thermo-mechanical behaviour of the material. The latter plays an important role for the qualification as a divertor armour material in a future fusion reactor.

The smallest grain size was measured with an average grain size of $5 \pm 2 \mu\text{m}$ in sample W-3Re-2Y₂O₃, whereas the largest matrix grain size was measured with $14 \pm 8 \mu\text{m}$ in sample W-1HfC, i.e. Y₂O₃, precipitates are the best-performing grain stabilisers (tungsten grain growth suppression) within this study for the sintering process. For sample W-3Re-1TiC, a bimodal matrix grain size distribution was observed.

The authors' use of the combination of SEM and TEM revealed that W/TiC and W/Y₂O₃ composites are the most promising candidates for plasma facing components in future fusion reactors. They stated that future work will include improved 4-point bending tests (at least 3-5 measurement per sample and temperature) for the PIM W-composites, improved sample preparation

(minimised surface topography) by the use of an ion cross section mill, a variation of the Y₂O₃ content to find an optimum, and a comparison with the irradiated samples to assess

their potential use as a plasma facing material in DEMO under operating conditions.

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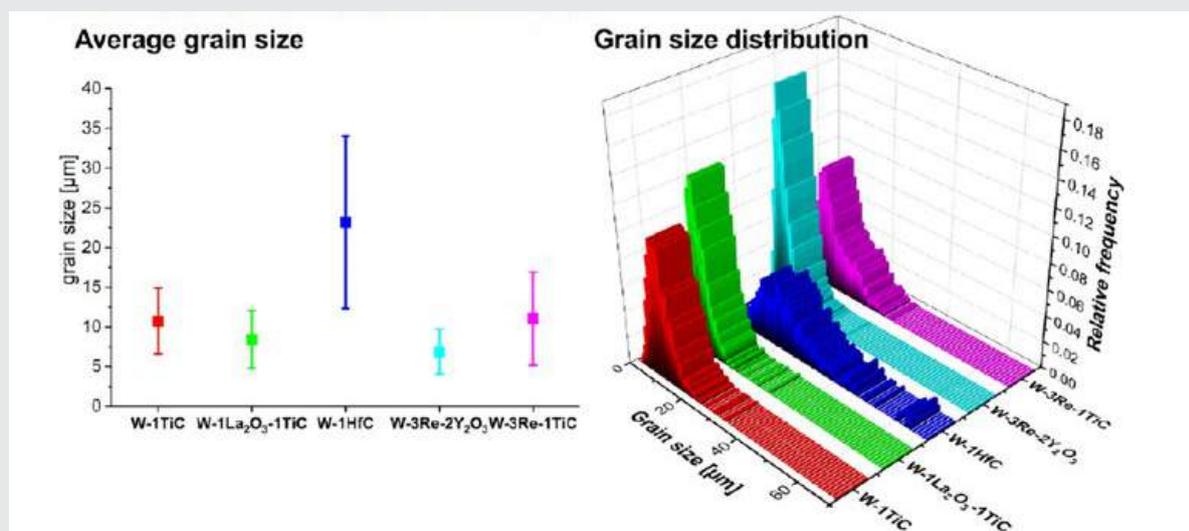
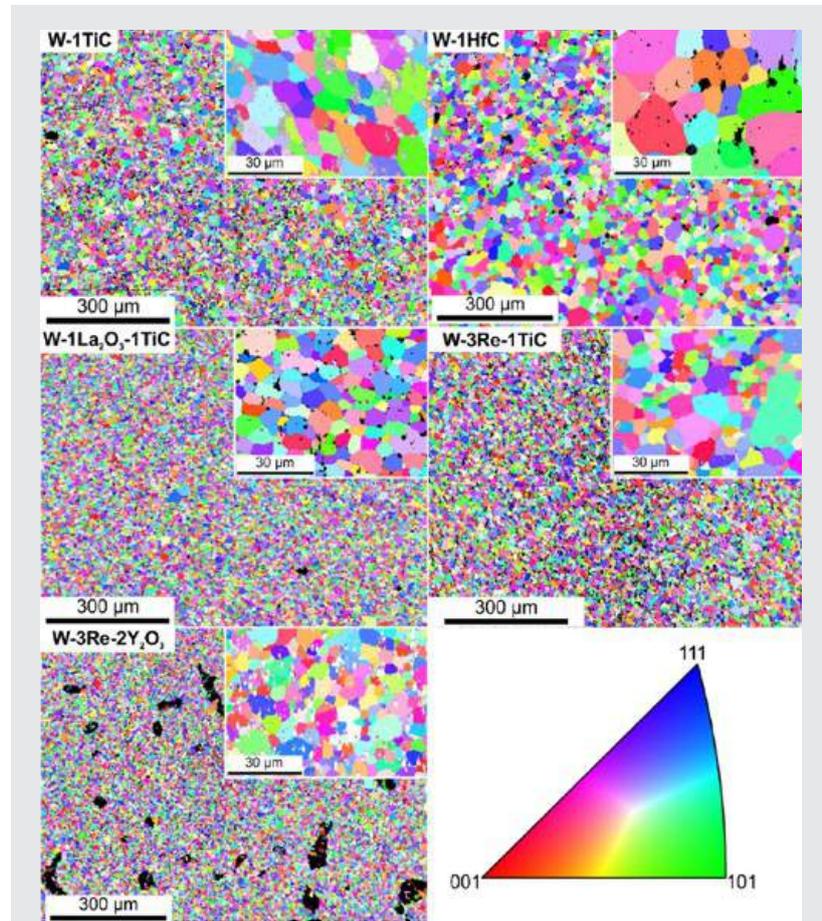


Fig. 1 EBSD mappings, revealing the texture of the W matrix, for all analysed materials. The large-scale mappings were used to determine the grain size distribution and an average grain size for the matrix. The insets show magnified regions to illustrate that the indexing fails (black or noisy regions) for secondary phase regions (From paper: 'Elucidating the microstructure of tungsten composite materials produced by Powder Injection Moulding' by M Duerrschnabel et al, Nuclear Materials & Energy, June 2020, 20 pp)

Metal matrix syntactic foams produced by low-pressure injection moulding

Syntactic foams comprise a metal matrix in which hollow particles are embedded to provide a particulate composite or foam having excellent specific strength and stiffness as well as lightness and thermal insulation. The reinforced porosity in these foams is the primary cause of this increase in strength-to-density ratio. Metal matrix syntactic foams (MMSFs) have not yet been used commercially to any great extent, but there are considered to be potential commercial applications in transportation (aerospace and automotive) and packaging, as well as in lightweight military body armour. Quality MMSFs are, however, difficult to manufacture, with the interactions between the thin-walled hollow particles and composite materials at high temperatures causing most of the issues.

Research carried out at the Missouri University of Science and Technology, Rolla, USA, has been aimed at overcoming some of the manufacturing difficulties and low pressure injection moulding is considered a promising route to produce MMSFs without extensive fracture of the hollow particles. A paper, published in the Proceedings of the 11th International Conference on Porous Metals and Metallic Foams (MetFoam 2019) by the authors M Spratt, J W Newkirk and K Chandrashekhara, outlines the work done at the Materials Science and Mechanical Engineering Departments in Rolla to produce MMSFs by the Powder Injection Moulding route.

The authors stated that the primary objectives of their research were to select and optimise a water-

based agar-glycerine binder for PIM and to test the compatibility between copper alloys and glass microsphere materials to identify potentially viable MMSF systems. The optimised binder composition was established as 7% agar, 4% glycerine and 89% water. Agar is a substance similar to gelatine, that forms a gel with water, and glycerine is used to support the polymer chains. This binder requires a drying step after moulding, which removes the majority of the water, followed by a debinding step at 400°C. Each binder composition was 45 vol.% of the final specimen with the copper alloy powder at 33 vol.% and glass microspheres filling the rest of the space. The response variables measured were the green, dried and sintered density. Each material used in the study is shown in Table 1.

To prepare binder feedstock for injection moulding, the authors reported that de-ionised water was first heated on a hot plate to boiling. The agar and glycerine were then



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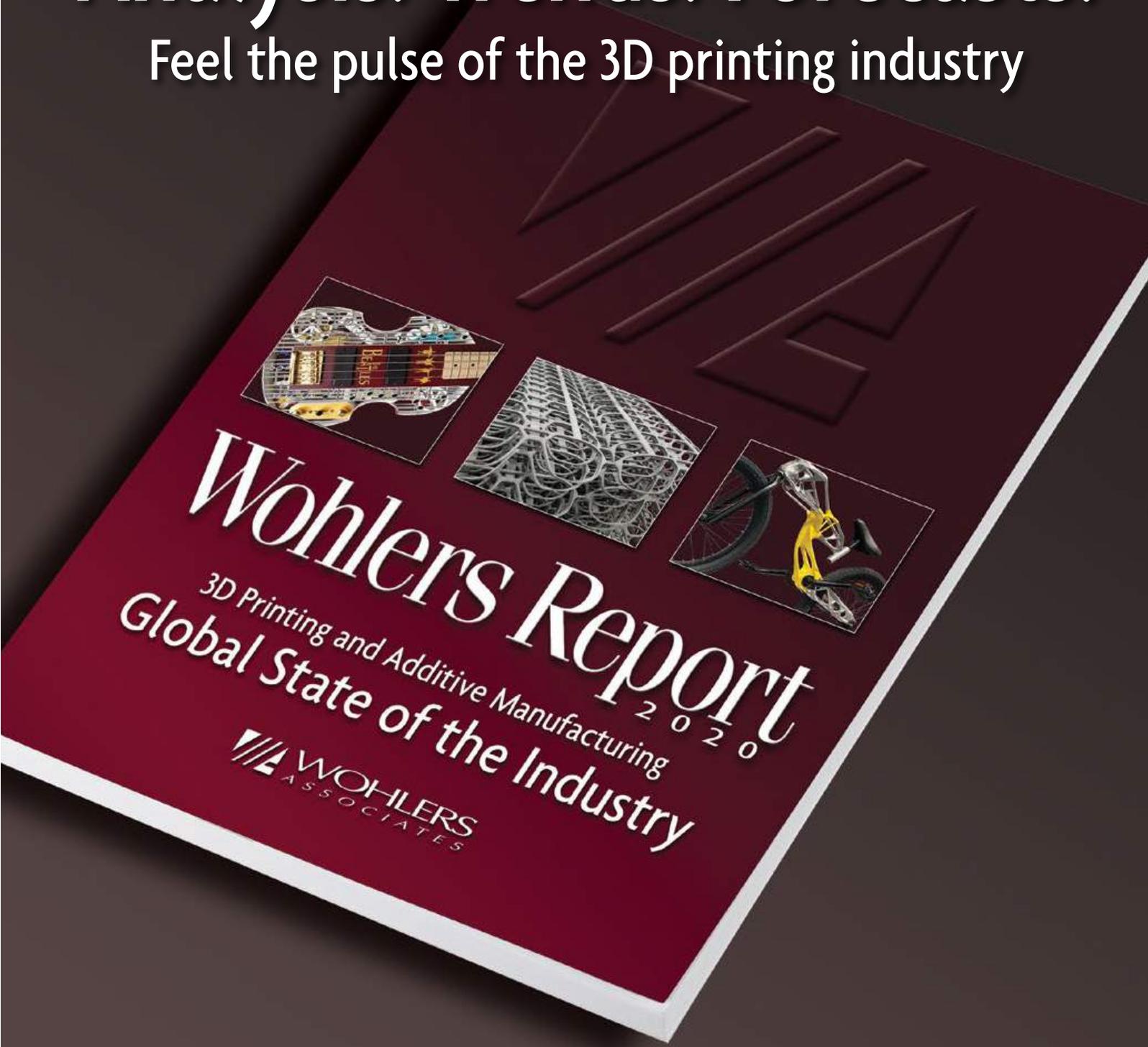
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Material	Supplier	Chemistry	Particle size data (mesh size %)	Density (g/cm ³)	Morphology
Borosilicate glass	MO-SCI Corp.	70–85% SiO ₂ 10–15% B ₂ O ₃ 5–10% Na ₂ O 2–5% Al ₂ O ₃	–140	0.15	Hollow, spherical
Silica	The ceramic shop	SiO ₂	–325	2.65	Solid, angular
Copper	Royal Metal Powders Inc.,	99.8% Copper 0.06% Hydrogen loss	+325 0.4% –325 99.6%	8.94	Solid, spherical
Bronze	Royal Metal Powders Inc.,	88.46% Copper 11.3% Tin 0.24% Phosphorous	+100 0.1% +140 20.8% +200 5.5% +325 21.6% –325 4.0%	8.73	Solid, spherical
Brass	ARTMOLDS	Cu ₃ Zn ₂	–325	8.73	Solid, spherical

Table 1 Materials used in the study to produce metal matrix syntactic foams (From paper: 'Design and Fabrication of Metal Matrix Syntactic Foams by Low-Pressure Injection Molding', by M Spratt, et al, published in the Proceedings of the 11th International Conference on Porous Metals and Metallic Foams (MetFoam 2019), pp 95–106, by Springer Verlag GmbH, 2020

added and the solution agitated for approx. 5 min to form a stable gel. The metal powder and glass microspheres were heated to between 50 and 100°C before being added to the binder. Thirty copper specimens were injection moulded using the optimised binder with a solids loading of about 60 vol.%. The low pressure injection moulding machine used in this research has a heated reservoir that holds the IM feedstock and the reservoir includes a paddle that turns at a fixed rate of 58 rpm. The working temperature of this binder is between 50 and 100°C, but typically it was kept at 80°C. To prevent seizing, the binder was added to the heated reservoir first, with the hot metal powders being added slowly while the paddles stirred the solution. After adding the powders, binder additions of about 2% were made as needed. It was stated that 10 psi of gas pressure, held for 10 s, was used to push the slurry into the mould.

Moulded samples were dried for at least 12 h at 120°C to de-water the part. They were then debound at

450°C for 1 h in flowing air, followed by 1 h at 450°C in flowing argon, and sintered directly after debinding at a temperature respective to the alloy. The density of the specimens decreased after drying. Because water expands as it heats up, swelling occurred, which caused the volume of the specimens to increase slightly during the drying step.

Of the matrix materials tested, bronze and brass both have relatively low melting temperatures (ca 950°C) and high density. The low melting temperature, and therefore low sintering temperature, was beneficial as it allows for lower temperature glass microsphere materials to be used. However, the differences between the density of the copper alloy metals and the hollow borosilicate glass were about as extreme as any metal matrix syntactic foam is likely to be. The authors stated that this was useful when creating a generalised procedure for MMSFs, as this research intended.

The authors reported that the second goal of their study was to test

the material compatibility between silicate-based glass materials and the copper alloys. It was found that the alloying elements in the copper alloys (tin in bronze and zinc in brass) reacted negatively with the silica glasses by diffusing out of the copper and into silicate glass, thereby lowering its melting temperature and causing the glass to melt in the matrix, which is not acceptable for syntactic foam processing. Pure copper powder did not react negatively with silica glass during sintering. However, even after sintering for 10 h, the highest density attained was 7.82 ± 0.04 g/cm³ and the sample still retained 10% closed porosity and 3% open porosity. The authors concluded that, to use a copper alloy that is easier to sinter to full density, a micron-sized hollow refractory ceramic material is recommended.

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The evolution of MIM at Matrix: From transforming the production of eyewear components to luxury goods and beyond

There are a number of applications where Metal Injection Moulding turned out to be the 'perfect fit'. Whilst some well-known successes are the high-volume, high-precision parts needed for smartphones, dental braces and surgical instruments, a less well-known area of success for MIM is in the eyewear sector. Here, the combination of small, complex components, high-volume production and high strength requirements has seen the technology flourish. As the following article reveals, Italy's Matrix s.r.l. has been a driving force behind this success and is now applying its expertise to an ever-growing range of industries.

The eyewear district of Belluno, in the Veneto region of northern Italy, is home to many of the leading firms in the international eyewear industry. The area accounts for 80% of Italian eyewear production, a staggering 70% of global eyewear production for the luxury sector, and 50% of licensed global production for the major fashion brands. Together, this generates revenues of €1.5 billion. It should, therefore, come as no surprise that the story of Matrix s.r.l., Italy's leading manufacturer of eyewear components by Metal Injection Moulding begins here, in the small town of Rasai in the municipality of Seren del Grappa.

The idea to establish a MIM operation at Matrix was conceived in 2002 following the merger of three small lost wax micro investment casting companies, each specialising in the production of miniature precision components for the eyewear sector. In 2003, the company's new MIM operation was established – one of the first in Italy. To many, MIM was still a relatively new technology and

for the company it looked like a leap in the dark. Nonetheless, MIM also showed great potential, as it enabled the production of more cost-efficient components, minimising waste, and opening up a wider range of markets.

"MIM represented a revolution," stated Alessandro Zatta, General Manager at Matrix, "especially for the transition from commonly used materials like copper, zinc, nickel and Monel (Cu-Zn-Ni alloys) to stainless steels." Today, 90% of



Fig. 1 Industrial-scale sintering furnaces for metal injection moulded part production at Matrix s.r.l.



Fig. 2 MIM eyewear bridge sections after debinding, sintering and finishing at Matrix s.r.l.

MIM production at Matrix is divided between the two main MIM stainless steels: 316L and 17-4 PH. The company uses feedstock manufactured externally; since 2016 it has been one of the largest buyers of MIM feedstock in Italy.

"The move into MIM wasn't an easy sell", stated Zatta. "It took a lot of convincing to venture into a market where other companies had already failed, prematurely betting on MIM in its earliest stages. Matrix seized the moment just as the technology was ripe to thrive in the precision

miniature components market, following the intuition of a few in the company's management who believed it was as a better alternative to the manufacturing technologies out there."

Meeting the needs of the eyewear sector

Apart from timing, the company's geographic location was also an important supporting factor, as its management team was already

known in the eyewear industry and could benefit from an established network of clients. However, Zatta stated, "Having the technology and a favourable position would have been meaningless without our understanding and expertise in the manufacturing processes for eyewear and an almost obsessive attention to the product and to the service provided." Once the benefits of the technology became apparent, demand came quickly from the eyewear industry, which soon recognised the superiority of MIM over conventional manufacturing processes for the types of components that the eyewear industry required.

The most noticeable advantage of MIM is undoubtedly its cost-effectiveness in relation to the complexity of the design. The process requires far less material than conventional precision metalworking processes and has fewer process steps than required by other routes where, for example, blanking, turning, milling, CNC machining and pressing may be needed at various stages. "With MIM it becomes possible to manufacture components of high geometrical complexity in a simplified production process, with the positive effect of drastically increasing overall production capacity. Large quantities of small precision components can be produced, saving time, material and, as a result, cost," stated Zatta. MIM eyewear applications include bridges, shown in Fig. 2, and arm components, shown in Fig. 3 in the green state following automated removal from a mould, and in Fig. 4 on ceramic plates after sintering.

Zatta believes that this combination of fortuitous timing for the adoption of the technology, an advantageous geographical position and high-quality customer support during product development and manufacturing were the key factors that won over clients and pushed Matrix to its strong position in the precision components market. "What we are most proud of is the way the company deals with clients and the services offered. Our experienced technicians and engineers

sit together to interpret their needs and intentions; a crucial part of the service is a high level of flexibility when it comes to joint product development and the move towards production.”

This is achieved in part through three distinct services: rapid product development and prototyping, thorough testing, and a close attention to the specific finishing requirements of the eyewear sector. For the rapid prototyping of precision parts, the company uses lost wax casting technology. A 3D Systems ProJet MJP 2500W machine, designed for the jewellery industry, is used to make the required precision patterns and through this route metal sample parts can be available in as little as 72 hours. Whilst the samples do not have the same mechanical properties as sintered components, and the materials are generally limited to brass and bronze, the company believes that they are an effective way to evaluate form and function of components used in the eyewear industry.

Application development is supported by Matrix’s R&D laboratory, whose facilities include hardness and density testing and metallographic analysis as well as a focus on finishing operations. Here the specifications for finishing parts with certain aesthetic requirements, via manual or mechanical processes, are established. Post-processing options include lapping, tumbling, manual polishing, sanding, and welding – including laser welding.

The significant reduction in waste that MIM offers when compared with conventional production methods represents a significant step forward towards an ethical and environmentally friendly approach to production. Zatta stated, “MIM is proven to be highly effective and convenient when it comes to the processing of expensive materials and special alloys such as copper, gold, silver, cobalt-chrome, titanium alloys and tungsten carbides. Part of this is the minimisation of waste, which makes of MIM and CIM truly green technologies.”



Fig. 3 MIM eyewear ‘side arm’ components as moulded and with the sprue still attached. The parts are removed from the mould by a robotic arm and, prior to debinding and sintering, the sprues are removed and re-ground for re-use

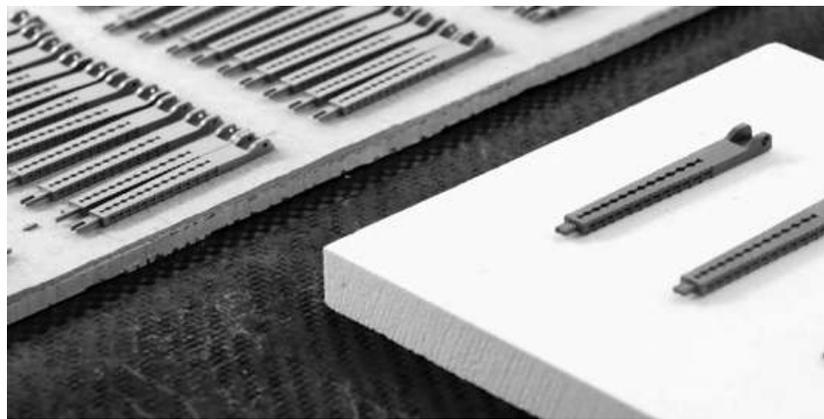


Fig. 4 The parts shown in Fig. 3 after debinding and sintering

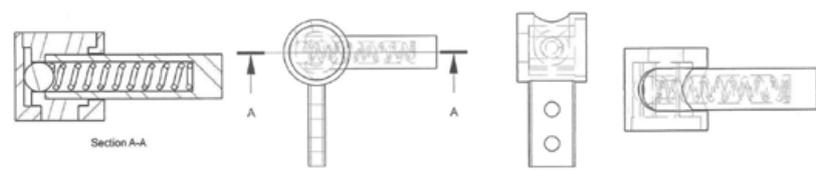


Fig. 5 Matrix s.r.l.’s Easyflex patented screwless hinge was developed in-house and maximises the benefits and capabilities of the MIM process whilst also offering a new degree of customisation to eyewear designers

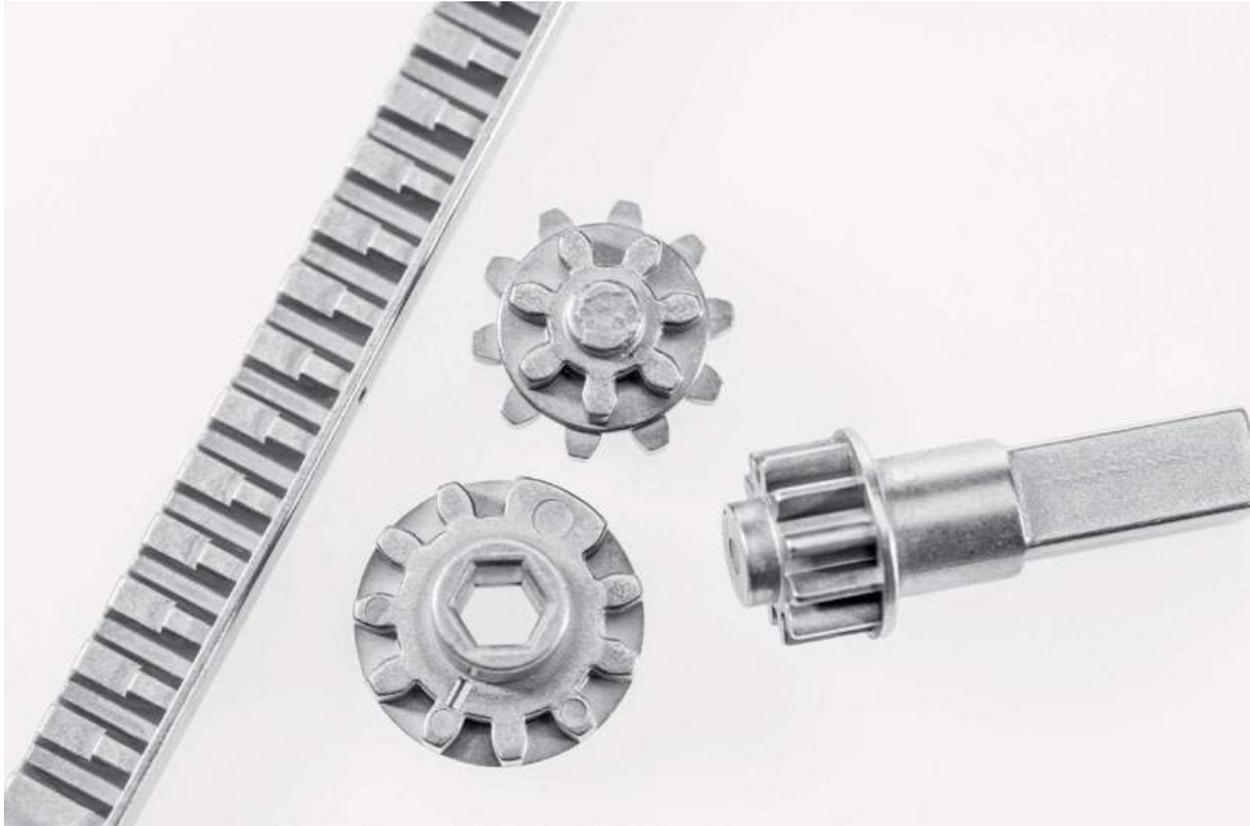


Fig. 6 Component used in automation devices for domestic doors and windows. The largest gear has a diameter of 20 mm and the parts are produced from MIM 17-4 PH stainless steel

Matrix also develops technology for sale to the eyewear sector, with its Easyflex screwless hinge being one example (Fig. 5). This patented hinge design maximises the benefits and capabilities of the MIM process

customer. In the example shown, the hinge is adapted to plastic glasses. However, thanks to the flexibility of the operating principle, nothing prevents it from being used on any other front for glasses. In fact, being

The power of 'Made in Italy' and market diversification

At the turn of the millennium, suppliers to the eyewear industry in Belluno faced an uncertain future. Many eyewear manufacturers decided to relocate to China to reduce manufacturing costs and, as a consequence, orders placed with local third-party suppliers suffered a dramatic decrease. Despite the challenges of the years that followed, the company was able to reorganise itself and to survive the eyewear industry's relocation through a process of diversification.

Recent years, however, have seen a reshoring of a number of brands and product lines. "Many important brands now recognise that to be able to state that their products are completely 'Made in Italy' carries certain associations such as quality and design flair, and, as such, is a great marketing tool," explained Zatta.

" Matrix also develops technology for sale to the eyewear sector, with its Easyflex screwless hinge being one example. This patented hinge design maximises the benefits and capabilities of the MIM process..."

whilst offering a new degree of customisation to eyewear designers. "Easyflex can be defined as an 'elastic' hinge. It has no screws, it can be made of steel, bronze, ceramic or many other materials, but above all it can be customised by the

able to adjust the size of the Easyflex hinge's cylinder means that it can be easily adapted to the customer's specific needs, thus being able to be used to create countless new models of glasses, with more types of materials," explained Zatta.

Even though the eyewear sector remains to this day the company's biggest market, accounting for 60–70% of all part production, Matrix has been able to explore and develop other markets, including fashion, medical devices, food production and electronics. "Today MIM and CIM technologies have applications that span sectors from eyewear to biomedical and automotive, from the fashion luxury market to aerospace, expanding the production of components to virtually every industry sector. We expect that MIM and CIM will be ever more and more present in an increasingly wide range of markets."

Matrix reports particular interest from the fashion and luxury market. "The fashion industry constantly demands sophisticated metal accessories to be featured on clothing, handbags, purses, shoes and more. MIM is perfect for manufacturing highly-precise renderings of, among others, logos, buckles, zips, components for shoulder straps, and parts for high-end shoe heels. We are already collaborating with the biggest brands of the fashion market and predict an expansion in the volume of such products where MIM can find application."

"The end-product has to be flawless and of great visual impact. No matter the complexity of the design, step-by-step monitoring alongside an attentive, detailed care for finishes result in parts of exemplary aesthetic quality. The precision in the smallest details, the impeccable finish and the constant quality of the products, obtained with expertise acquired over the years of continuous development, contribute to increasing the perceived value of the final item and improving the emotional experience of the purchase."

Another promising sector is that of medical devices. Matrix believes that MIM will continue to have a fundamental impact on the medical sector and declares itself ready for new challenges in this area. "Dealing with hospitals and medical companies usually means a high degree of bureaucracy is involved in



Fig. 7 A jewellery carabiner manufactured from 316L stainless steel



Fig. 8 A case for a diving watch. The original was made of bronze, but the change was made to MIM 316L for improved salt water corrosion resistance



Fig. 9 Fashion bracelet components made by MIM



Fig. 10 A dentistry device made from 316L stainless steel. The application is 130 mm in length and 30 mm wide

the process. To be able to fulfil their requests demands a high degree of flexibility and a capability to adjust to the demands of the client, a skill that Matrix's employees have honed throughout years of practising the technology and tending of relationships with clients," added Zatta.

"Relying on ongoing research and careful material selection, we are able to supply MIM and CIM solutions to the highest quality standards while allowing room for the creativity of the client. Combining this with expertise in the finishing processes associated with conventional production methods, overall production speed is increased, and delivery times optimised," he explained.

The opportunities for CIM in the luxury sector

Ceramic Injection Moulding finds application in a diverse range of markets, from dentistry to industrial manufacturing to luxury watches.

Matrix reports increasing interest in the process for certain types of jewellery and fashion accessories. "In the fashion market, ceramic is now often preferred to metal. While metal decorative parts may well receive some form of surface finishing to create a desired colour, there is a trend towards the purity and simplicity of naturally coloured ceramics. Whilst many companies still use pigments for colouring ceramics, many like to leave their designs with a 'natural' polished appearance," stated Zatta.

New ownership brings further opportunities

In 2017, Matrix became part of a larger family of businesses when Ookii, a leading Italian company in the micromechanics sector, founded by Michele De Biasi, acquired a majority stake. Earlier in the same year Visottica

Comotec, a global leader in metal components for the optical sector, acquired a 50% share in Ookii.

For over thirty years, Ookii specialised in cold forging technologies applied to materials such as titanium, steel, aluminium and nickel silver, as well as milling from bar stock, turning, the die casting of zamak, aluminium and magnesium, and the injection moulding of plastics.

Visottica Comotec has been a worldwide leader in metal components for the optical sector since 1947. Established in Conegliano in the 1980s, it has since expanded its operation in the Far East. Today the company has two plants, one in Italy and one in China, with a thousand employees, a production of over one billion components a year, forty international patents and over a thousand customers in fifty countries.

Together, the businesses now benefit from a workforce with a far more diverse range of expertise in the production of precision metal

components. For Visottica Comotec, the benefit of in-house MIM expertise is regarded as a major advantage, while Matrix and Ookii are benefitting from the opportunity to reach a wider market.

"The partnership recognises the seemingly limitless application potential for MIM and CIM technology and it is ready to undertake future challenges. We recently developed and produced components for industrial and commercial oxygenation and ventilation systems [Fig. 11] and are now ready to supply these types of metal components for respirators and ventilation systems in the fight against COVID-19. We are open to new requests and opportunities in this area and are making our skills and knowledge available to contribute to the fight against the pandemic. So far we have only produced plastic components for masks, but we remain eager to do more in the area of hospital equipment and machinery," stated Zatta.



Fig. 11 MIM ventilator components produced by Matrix. The part diameters are 10, 15 and 20 mm

Conclusion

"It is clear to me that MIM and CIM technologies are going to take an increasingly substantial slice of the precision components market. The opportunities are certainly there," says Zatta. "The challenge is to acquire the means to enter in as many sectors as possible while maintaining the highest standard of product and service quality. It is fundamental to keep in mind that production capacity, expertise, cost-effectiveness and responsiveness of the service are at the core of the business. Further steps will then need to be taken to keep our curiosity alive, so as to keep learning and acquiring skills and capabilities. MIM manufacturers have to remain up-to-date to be able to identify

each sector's specific requirements and meet them. A challenge that is massive in scope, but ever more reachable for us now that Matrix is not alone."

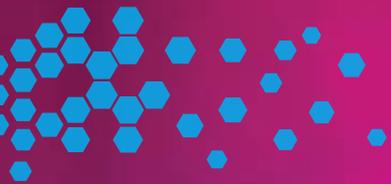
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Acknowledgments

Thanks to Luca van der Heide and Romina Bernard for their work in the preparation of this article. Luca is a writer and English teacher, published both at an academic and personal level. He's the author of four novels, the last one published in June 2020. Romina is a marketing consultant collaborating with Visottica Comotec and has specialised in the eyewear business since 2004.



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Desktop Metal's Live Sinter™: How simulation software is mitigating sintering distortion

Sintering distortion is a fact of life in the Metal Injection Moulding industry. However, through the combination of an experienced eye, the 'trial and error' iteration of a part's design, and the use of sintering supports when needed, stable high-volume production is achieved. With the growth of processes such as metal Binder Jetting, however, the need to manufacture a much wider range of parts at lower production volumes and in a shorter time frame means that a more efficient and streamlined approach is required. Andy Roberts, VP Software at Desktop Metal and the inventor of Live Parts™, presents the simulation software along with a number of case studies illustrating its capabilities

With the ability to eliminate tooling, dramatically reduce manufacturing timelines and create more complex parts than ever before, Binder Jetting (BJT) is quickly revolutionising the way many metal parts are produced. To reach its full potential, though, there is one hurdle that is often overlooked – sintering.

As with Metal Injection Moulding (MIM), BJT parts must be debound and then sintered at temperatures close to the melting point of the alloy being used. The sintering process can cause parts to shrink by as much as 20% and, if not properly supported, there is a real risk of parts slumping and sagging. The result is parts that may emerge from the sintering furnace cracked or deformed beyond usability. Even when not cracked, such parts are typically produced to tight tolerances and any requirement to correct the dimensional accuracy of the parts through post-processing creates additional overhead and expense.

For MIM suppliers, the low-tech solution has for decades been simply a mix of having an experienced

eye for appropriate part design and basic trial-and-error: testing various combinations of part geometry, ceramic setters and rafts, then locking in the combination that works for mass production. However, what if, instead of fighting against sintering-based deformation, we joined forces with it?

The need for a sintering simulation tool

A first-of-its-kind software application, Live Sinter is capable of simulating, in just minutes, the deformation parts undergo as they sinter, allowing manufacturers to predict how parts will change shape as they densify. Developed over a year in



Fig. 1 A Desktop Metal Production System installed at Indo-MIM's metal Binder Jetting operation in San Antonio, Texas, USA (Courtesy Indo-MIM Inc)

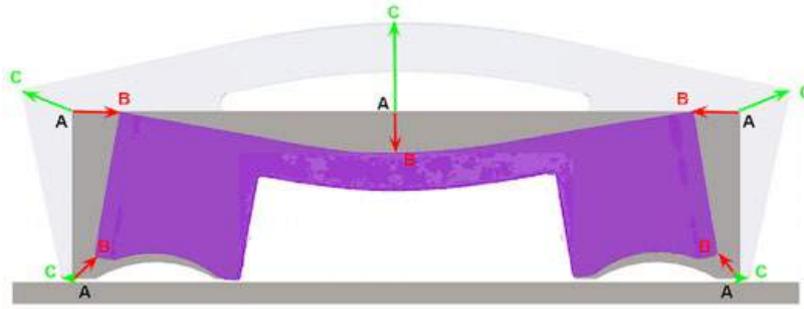


Fig. 2 This image shows three parts – the original CAD part (dark grey), a scan of the sintered straight part (purple), and the negative offset part generated by Live Sinter (light grey). The geometry of the sintered straight part matches the shape that Live Sinter produces after its sinter simulation (Courtesy Desktop Metal)

collaboration with Desktop Metal's materials scientists, the software uses iterative simulation operations to create 'negative offsets' – pro-actively deforming parts by specific amounts in specific directions that allow them to achieve their intended shape as they sinter. Importantly, though, these negative offsets are not simply inversions of the deformation that parts experience during sintering. On the contrary, once the

geometry of the sintered straight part matches the shape that Live Sinter produces after its sinter simulation. The software uses the red vectors to derive green vectors that transform original points A to negative offset points C, thus forming the negative offset part. Importantly, the green negative offset vectors are not the negatives of the red vectors. Both the magnitudes and directions of the vectors are different. Live Sinter can

“Developed over a year in collaboration with Desktop Metal's materials scientists, the software uses iterative simulation operations to create 'negative offsets' - pro-actively deforming parts by specific amounts in specific directions that allow them to achieve their intended shape as they sinter.”

offsets are created, they represent an entirely new simulation challenge.

Fig. 2 shows three parts – the original CAD part (dark grey), a scan of the sintered straight part (purple), and the negative offset part generated by Live Sinter (light grey). The

generate the green negative offset vectors by using its sintering simulation engine. It is also noteworthy that, in performing a negative offset, Live Sinter not only transforms the geometry from points A to C, it also transforms the amount of mate-

rial (metal powder) and the build orientations of cells. The negative offset process creates an entirely new physics problem that has its own sintering simulation results. The goal of these results is to produce a part represented by points C that sinters to the shape represented by points A.

The need for accurate, automatic, high-speed simulation tools such as Live Sinter is undeniable – in large part because a significant increase in part throughput is among the primary benefits that comes with Additive Manufacturing. If manufacturers hope to capitalise on the speed and agility of mass-production via AM, the rest of the manufacturing design process, as it ramps up to production, must be equally fast, and making sintering more predictable is a critical step.

Creating rafts and supports to hold parts during sintering is time-consuming, certainly, but the process is also expensive. In some cases, supports use more material than the parts themselves and, at scale, it can be the difference between a part that makes economic sense and one that does not. By predicting shrinkage and distortion during sintering, Live Sinter can reduce or fully eliminate the need for supports. The end result, despite sintering with minimal or even no rafts or supports, is parts that emerge from the furnace at near-net shape, reducing waste from failed builds and the time needed to post-process parts to meet specific tolerances.

While Live Sinter works across all Desktop Metal platforms, it is primarily targeted for use with the company's Binder Jetting systems. Initially, Live Sinter will be available as a standalone application for download and local installation. In a future release, Desktop Metal may also offer a cloud-hosted version of the software. Live Sinter may also be bundled with the sale of certain Desktop Metal Additive Manufacturing systems and will have features specifically tailored to Desktop Metal's own technology and material offerings, but the technology is compatible with any sinter-based Powder Metallurgy process, including MIM.

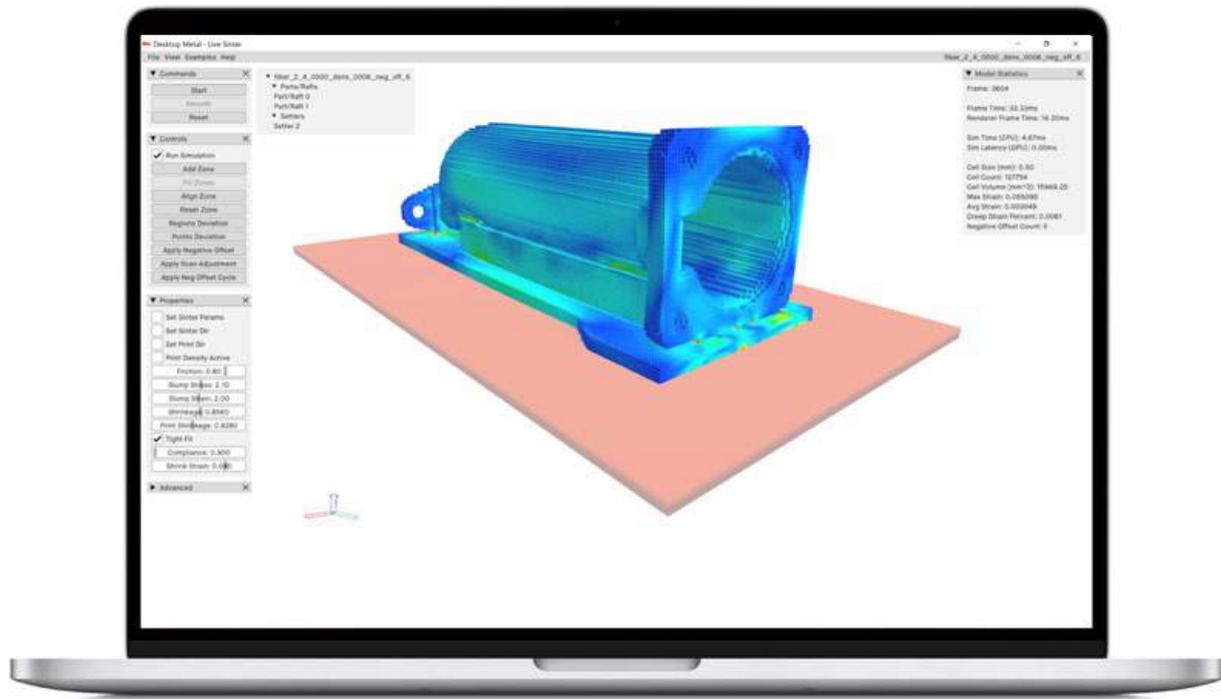


Fig. 3 A screenshot of the Live Sinter software (Courtesy Desktop Metal)

Additive Manufacturing presents new sintering challenges

As the adoption of metal Additive Manufacturing, and, in particular, binder jet systems which deposit liquid binder onto metal powder to build parts layer-by-layer, has grown in recent years, so too has the demand for the sintering of metal powder parts. Whilst MIM and BJT parts share many similarities, including the requirement for debinding and sintering at near-melting point temperatures, in many ways the comparison between the two processes is limited to this step of the process.

Creating a MIM part begins by creating a mould. Metal powder and binder are then mixed and injected into this mould to create what are referred to as 'green' parts, which go through a debinding process before being sintered in a furnace. Additively manufacturing

parts, by comparison, eliminates the need for moulds and other tooling or fixturing, allowing manufacturers to quickly create parts, opening the door to highly-complex parts as well as mass customisation from one build to the next.

While AM reduces part turnaround time and increases new part throughput, the lengthy trial-and-error process of finding a sintering solution becomes ever more impractical. To keep up, manufacturers need simulation tools that can quickly predict how parts will behave in the furnace.

In addition, AM enables parts larger than those typically supported by MIM, meaning distortion during sintering can have a larger effect on their final shape. These factors and many others point to the need for a product like Live Sinter – a powerful simulation engine capable of modelling the complex physics at work as metal parts reach temperatures as high as 1,400°C.

The challenge in modelling sintering behaviour

The notion of simulating how materials respond to gravity, shrinkage, density variations, elastic bending, plastic deformation, friction drag and more is not a new idea, but it is an incredibly difficult one. Part of what makes sintering so difficult to model is the fact that it involves both thermodynamic and mechanical transformations that take place under intense heat, making them difficult to observe.

To monitor those changes, manufacturers have only two real options – either halting the sintering process mid-stream and examining parts after they cool, or installing windows in the furnace to observe distortions from images taken at high temperature.

With few other options, the goal has long been to find a way to simulate the process and, though attempts have been made to do just

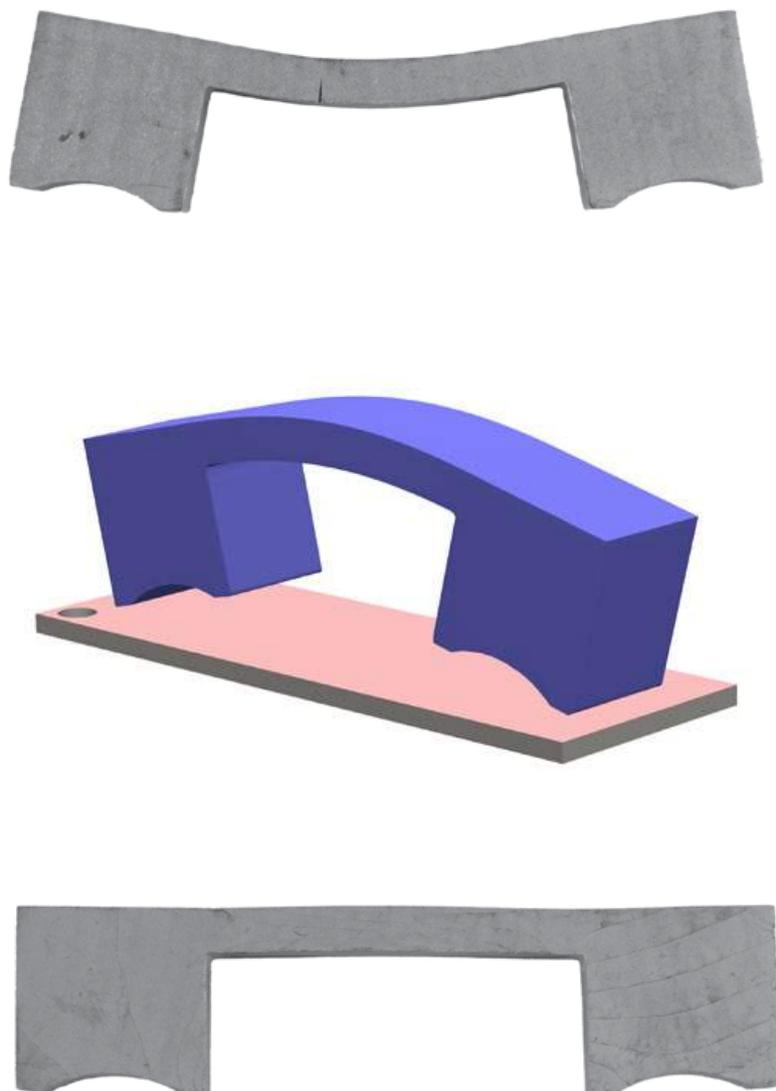


Fig. 4 Without the negative offsets generated by Live Sinter, this drape bar test part shows a pronounced droop in the middle (top). To counteract the deformation, Live Sinter arches the top bar and tips the feet outward (middle) allowing the part to return to straight after sintering (bottom) (Courtesy Desktop Metal)

that, those models must replicate a host of factors, including material properties, density, stress, strain – both elastic and plastic, and friction contact, to name just a few.

Further complicating those efforts, simulating the process based on first principles means other factors such as the micro-behaviour of the material at the particle level, models of heat transfer, chemical

reactions to heat and the mechanics involved in simulating the shrinkage and plastic deformation caused by factors like creep strain, must also enter the equation.

The difficulty of creating a model that incorporates all these factors means that, to date, most attempts to simulate sintering behaviour have come from academia and have relied on custom code. Ultimately, though,

the vast complexity of the models, combined with a lack of data from inside hot furnaces, has made the process virtually impossible.

A novel, integrated approach to simulation

Live Sinter, however, takes an alternative approach. Rather than working entirely from first principles, it uses a multi-physics engine borrowed from the gaming world which runs on NVIDIA GPUs – the same processors found in high-end gaming PCs. Capable of modelling 700,000-plus particles with mass and radii, the multi-physics engine can simulate how particles collide with each other, as well as with the rigid bodies of arbitrary shapes. In addition, the engine models both body and directional forces as they are applied to the particles.

The result is an extremely fast approximation – simulations are run in just minutes – of the physics inside the furnace, including shrinkage, plastic deformation, friction interaction and more. To refine the engine's approximations, Live Sinter also employs a meshless FEA engine, which analyses the model at regular intervals to provide Von Mises stress based on data derived from the physics engine.

Complex physics, complex models

In order to simulate the complex behaviour of parts as they sinter, Live Sinter uses a number of approaches. Simulation of the elastic behaviour of solid parts during sintering builds on a model developed by researchers at NVIDIA. By connecting a collection of simulated particles together with position constraints and dampers, Live Sinter can simulate behaviour such as stretching and compression, both of which are critical to understanding how metal parts change shape during sintering.

At the same time, the software can model both static and dynamic

friction, including the way in which the resulting reaction forces may change from part to part, either due to material differences or the presence of anti-sintering agents. By overlaying a model of plastic deformation on the elastic behaviour of the position constraints, Live Sinter can model how creep strain leads to non-uniform deformation of parts.

The system applies creep strain by relaxing the resting lengths of the position constraints over time, which indirectly changes the strain. In areas of higher stress and temperature, that change rate will be higher, leading to more deformation in some areas and less in others.

Fast simulation and excellent accuracy

Armed with its unique, dual-engine approach and highly complex models, Live Sinter can create a simulation of a furnace run in as little as three to seven minutes, as opposed to simulations using complex, dynamic physics which require hours to run. Based on that simulation, the software generates negative offsets in fifteen to twenty minutes, something that other approaches to sintering simulation are unable to do.

The design of Live Sinter allows the system to strike a balance between speed and accuracy – the GPU-based physics engine provides a quick approximation of the sintering process, which can then be tuned to give more accurate results. The premise is that, while it may not be possible to know the coefficients for every property such as friction, compliance, grain size, diffusion rates or activation temperatures, it may be possible to tune the physics engine to get the correct resulting shapes and produce successful parts.

To ensure the simulations are as accurate as possible, the first step in using Live Sinter is to tune the system using a series of test parts and scans of these parts after sintering. Once that tuning process is complete, an unlimited number of

parts can be processed, simulating sintering distortion and producing negative offset geometry that results in straight sintered parts. Additionally, Live Sinter retains the high level of detail that makes metal AM an attractive manufacturing technology.

Simulating macro and micro distortion effects

Generally speaking, the factors that affect how a part might behave during sintering fall into two main categories: macro factors, which cause distortion to the entire part, and micro factors, which might only occur in a small portion of the larger part. Importantly, Live Sinter compensates for both.

The bulk of the distortions compensated for by Live Sinter are related to macro factors, such as gravity and friction drag, which typically affect the entire part. In the case of the drape bar shown in Fig. 4, parts built without negative offsets showed a pronounced droop in the

shape. The two outside feet would be planted flat. Instead, those feet are cocked inward far enough to lift the outside edges. Rather, the distortion is the result of the middle portion of the drape bar shrinking as it sinters. As that middle section moves, however, the part's feet remain immobile – friction drag prevents them from sliding inwards as far or as fast as the top of the bar, resulting in its characteristic distortion. While much of this distortion is caused by elastic bending during shrinkage, plastic creep strain takes over and causes the release of stress and freezing of the part in this final drooped shape.

The negative offsets created by Live Sinter instead arch the top of the bar up and tip the feet out, allowing the part to return to straight as it sinters. Because friction drag prevents the feet of the drape bar from sliding very much, the negative offset compensates for this by allowing the part to pivot around its largely immobile feet as it shrinks. Interestingly, this places most of the

“Generally speaking, the factors that affect how a part might behave during sintering fall into two main categories: macro factors, which cause distortion to the entire part, and micro factors, which might only occur in a small portion of the larger part. Importantly, Live Sinter compensates for both.”

middle. This is caused not primarily by gravity as one might guess, but rather the friction drag that prevents the bar's feet from moving – the bottom portions remain fixed to the setter while the top regions are pulled together, causing a pivoting of the feet.

Were gravity and plastic distortion alone responsible for the distortion, the bar would not have this

part in compression as it sinters, rather than subjecting certain regions, such as the underside of the cross member, to tension, which would likely cause cracks.

For other parts, such as the heater body component shown in Fig. 5 from Desktop Metal's Fiber™ machine, it became important to compensate for other issues. When built without negative offsets and

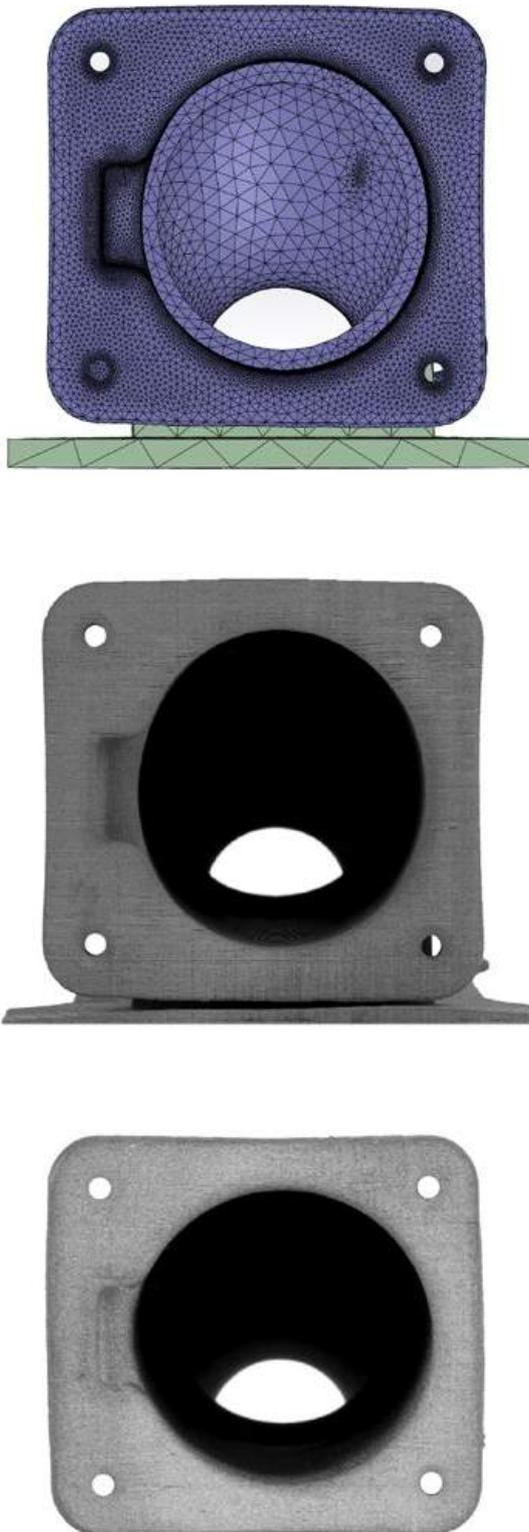


Fig. 5 Three images of a fibre heater body part. Live Sinter generates the CAD model (top) which is used to generate a green part (middle). As it sinters, the oval shape of the green part returns to its intended, circular shape (bottom). The images shown are not to scale. The slight warping in the flange is due to tiny density differences that occur during powder spreading. Algorithms to address those density changes are being developed for Live Sinter (Courtesy Desktop Metal)

minimal supports on the sides, the cylindrical part either warps or – in extreme cases – simply collapses on itself during sintering. Rather than build the part as a cylinder, the negative offset generated by Live Sinter creates an oval-shaped part. As it sinters, the combination of gravity and unsupported sides causes the oval shape to drop slightly, returning the part to its proper, circular shape.

In the case of the part known as a ULA bracket (Fig. 6), however, both of these factors – friction drag and gravity – are working at the same time to produce different effects in different regions of the part. When sintered without negative offsets, the feet of the bracket, as with the drape bar, tend to tip inward due to the shrinkage of the upper cross member combined with friction drag of the feet. At the same time, gravity, combined with an uneven weight distribution on the feet, causes the part to warp into a distinctive ‘duck-footed’ posture.

To compensate for these deformations, Live Sinter creates a part whose feet are tipped inward and arches the middle of the bracket, allowing the parts to return to straight during sintering. These macro effects, though, are just one type of feature that can lead to deformation of parts. The second is far more localised and stems from subtle differences in the density of the metal powder used in certain BJT processes.

Due to their symmetrical geometry, parts like the fuel swirler shown in Fig. 7 are far less susceptible to problems such as friction drag. If they do experience drag, their symmetrical shape means the entire part experiences it, so warping seen from looking down on the part is minimised. The pull of gravity also causes little, if any, changes during sintering. However, when parts do exhibit problems, they may be related to density variations due to powder spreading or compaction in the powder bed.

Though this phenomenon is not completely understood, it is believed that changes in part density can occur as the powder spreading mechanism applies layers of metal powder over

the build surface. Slight changes in density, built up through a part layer-by-layer, can cause a part to warp because areas of lower density shrink more than areas with higher density. In MIM, an equivalent scenario is when density variations arise as a result of powder/binder separation during the injection moulding process. Live Sinter, however, can compensate for these density variations and create negative offset designs that, when sintered, will result in straight parts.

Future outlook

Though it already shows great promise as a tool for making the sintering process more predictable, additional improvements to Live Sinter are planned for the future. One project, which will be undertaken in collaboration with Desktop Metal's software engineers and material scientists, will add a layer of machine learning to identify correlations between changes to certain input parameters and changes in the deformation results in certain regions of a part. For example, if changing the friction coefficients for a part like the drape bar could lead to the part's feet tilting in to a greater or lesser degree, a machine learning algorithm could spot the association, allowing the system to automatically tune these parameters to correct it.

A second project would add the ability for users to calibrate Live Sinter for even more precise results. Parts produced with negative offsets should emerge from sintering with straight geometry, but there may be cases where the geometry is not perfect, due to the software's inability to accurately model some aspect of the shrinkage and deformation.

In these cases, users would be able to scan the finished part and identify areas that require fine tuning and the software would recalibrate the negative offsets to produce even more accurate results.

While the ultimate goal of Live Sinter is to eliminate deviations from specified part geometries that neces-

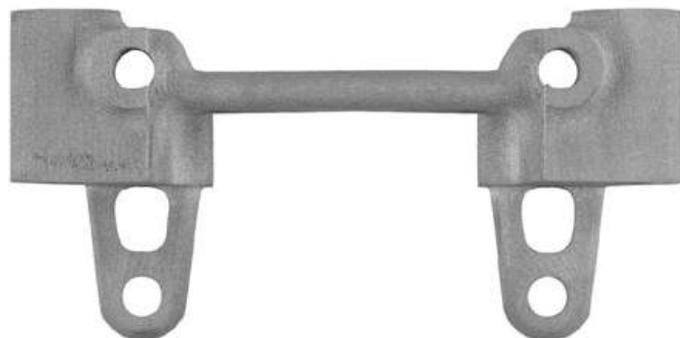
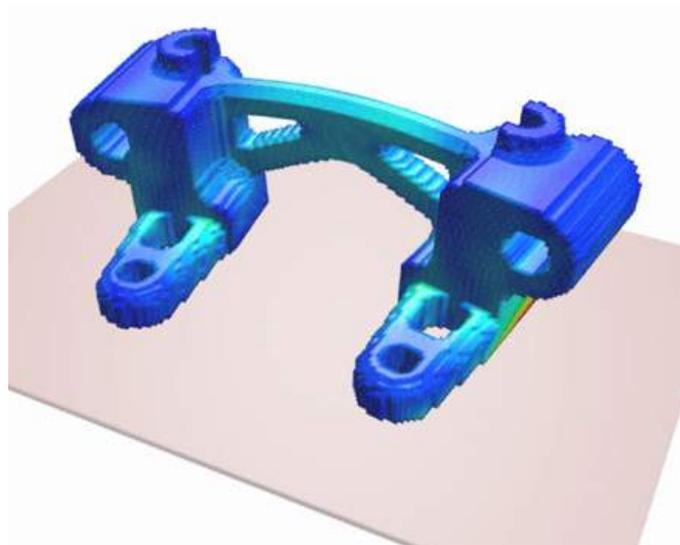


Fig. 6 When built without negative offsets (top) this bracket tips inward and sags, while gravity and uneven weight distribution combine to produce a distinctive 'duck-footed' warping. To correct these issues, Live Sinter tips the feet inward and arches the middle of the bracket (middle), causing the part to return to its intended shape (bottom) as it sinters (Courtesy Desktop Metal)



Fig. 7 When sintered without using Live Sinter, tiny density variations in the metal powder cause the fins of this fuel swirler to warp in one direction or the other. Live Sinter compensates for those variations and produces a part that emerges from the furnace with straight fins (Courtesy Desktop Metal)

sitate additional machining steps for BJT parts, the software today is unable to model sintering behaviour that emerges from different heat or gas flow patterns in furnaces or other complex thermodynamic transformations that take place in the furnace environment.

To address these issues, future versions of Live Sinter will include tools designed to allow users to scan finished parts, in which any number of parameters (related to different furnace runs, different production runs and more) were altered. The

software can then automatically tweak the negative offsets to produce parts with usable results.

While Live Sinter is compatible with MIM parts, initially Desktop Metal will support materials offered on Desktop Metal AM systems and will continue to develop support for new materials in-house. In a future release, material optimisation capabilities will be made available externally, so customers can use Live Sinter to improve the accuracy of parts manufactured using their own novel materials.

Answering a decades-old challenge

By making the sintering process more understandable and repeatable across multiple part designs, Live Sinter could offer benefits not just to individual manufacturers but to the Additive Manufacturing industry as a whole. For decades – even before the emergence of Binder Jetting technology – the Powder Metallurgy industry has struggled with questions of how to create supports that prop up parts in the furnace and, for decades, the answer has been to rely on the intuition of the relatively few engineers with years of hands-on sintering experience. With Live Sinter, however, the process becomes far more controllable – something that will likely help to assuage concerns of potential users.

For many companies, particularly those who have never used a furnace and have no experience with sintering, the notion of additively manufacturing hundreds – or even dozens – of parts is a daunting one. While companies with MIM experience may have standard support structures they can turn to for Binder Jetting, many more are entering the process with limited exposure to Powder Metallurgy, so a product like Live Sinter is a critical tool that enables them to adopt metal Additive Manufacturing with confidence that they will be able to deploy the technology for mass production.

It has often been said that Additive Manufacturing will change the face of industry – Live Sinter is a crucial step in making it happen.

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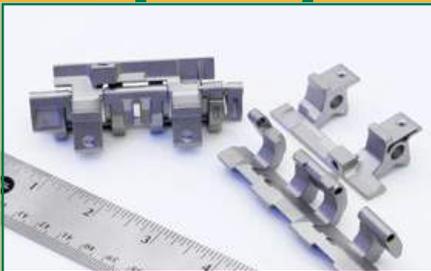
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High-Cycle Fatigue response of MIM 8620 and 100Cr6 steels and their sensitivity to mean stress, notch sharpness and weld line position

Case-hardened MIM 8620 and hardened MIM 100Cr6 are two typical high-strength steel grades used widely for automotive applications produced by Metal Injection Moulding (MIM). In a comprehensive study by GKN Sinter Metals, the notch sensitivity of both these grades is investigated under both static and cyclic loading conditions. Of particular interest was the impact of weld lines – an often unavoidable feature of complex injection moulded components. What is the effect on a component's High-Cycle Fatigue (HCF) response when weld lines are located in highly-loaded regions? Here, Dr.-Ing. Markus Schneider and colleagues present conclusions that will be of value to MIM producers and users alike

Industrialised in the 1980s, the Metal Injection Moulding process allows industry to combine the high geometrical degree of design freedom offered by plastic injection moulding with the high strength properties of fully dense steels. Using the MIM process, which is divided into the injection moulding, debinding and sintering stages, it is possible to achieve the highest possible sintered density ρ for demanding applications. Because of this, high static and cyclic strength values are expected; moreover, the high dimensional accuracy, low surface roughness and high degree of geometrical freedom are key reasons for the widespread use of MIM steel grades for highly-loaded components in the automotive, firearms and medical device industries.

For such parts, with quantities that range from 20,000 to over one million parts a year, it is essential to estimate the fatigue strength at the knee point σ_A . Because MIM components are less porous than

conventional 'press and sintered' PM components, material behaviour is influenced more by single defects than by the whole pore size distribution. For this reason, it is important to understand the influence of critical MIM defects on the fatigue strength at the knee point σ_A . It is known that

internal defects have a higher effect on the cyclic properties than on the static properties because the material plasticity is suppressed. High-Cycle Fatigue (HCF) experiments are recommended to identify the effects of defects such as non-metallic inclusions from feedstock impurities,



Fig. 1 A view of the continuous debinding and sintering facilities at GKN Sinter Metals' MIM operation in Bad Langensalza, one of the largest in Europe

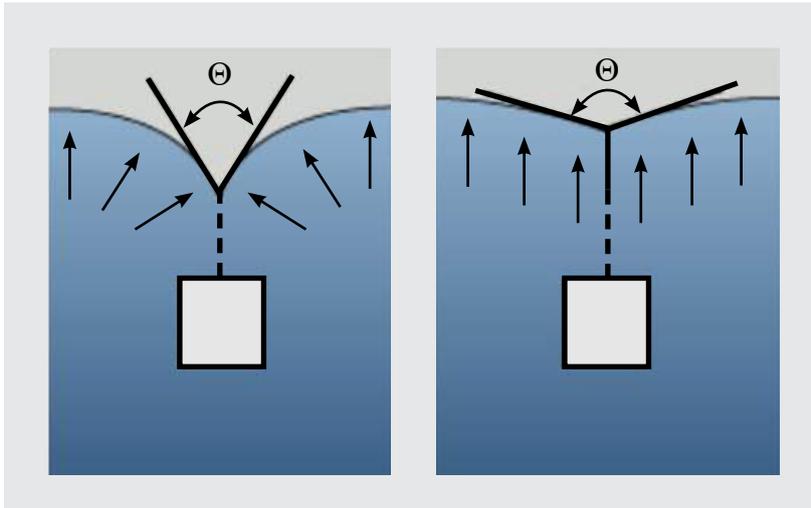


Fig. 2 Internal weld line above an injection moulding tool inlet and characteristic superficial sink mark angle Θ of two welded fill fronts (Image from [2])

shrinkage cavities and weld lines. This is due to the suppressed plastic strain component ϵ_p during the stress-controlled HCF experiments.

The combination of a purely elastic loading and a high number of cyclic repetitions N will bring all issues of concern to light. However, reliable

other design software. The determination of these characteristics, in particular fatigue properties, is costly and time consuming. Only limited data are available, for instance for the precipitation hardening stainless steel MIM-17-4PH and the low alloy steel MIM-4340, which is gener-

“ The combination of a purely elastic loading and a high number of cyclic repetitions N will bring all issues of concern to light. However, reliable information on material properties, especially cyclic material properties, are rare for MIM steel grades.”

information on material properties, especially cyclic material properties, is rare for MIM steel grades. The European Powder Metallurgy Association (EPMA) stated in its current 'Introduction to Metal Injection Moulding' promotional brochure: "The European MIM industry is undertaking great efforts to provide design engineers with comprehensive material property data as required by finite element analysis (FEA) and

ally heat treated by a conventional quench-and-temper process" [1]. Therefore, an internal programme was initiated in 2016 at GKN Sinter Metals to investigate the static and cyclic material properties of a few common MIM steel grades.

MIM 8620 (20NiCrMo2-2) and MIM 100Cr6 are two common MIM steel grades which have found wide application, including for the production of automotive upvalve rockers for

Variable Valve Timing (VVT) systems. Because of their geometric complexity, MIM components typically feature many notches, along with inevitable weld lines because of a combination of the injection moulding step and part complexity. A material's property response to these notches and weld lines is of critical importance for the MIM industry.

Moreover, it should be mentioned at this point that fully-reversed (loading ratio $R=-1$, often realised via rotating bending) fatigue strength at the knee point σ_A values are insufficient for a fatigue assessment and a precise fatigue lifetime calculation. This is due to the fact that most MIM components are loaded with static pre-loads (interference fits, bolts or screws) and superimposed cyclic operating loads. Consequently, higher loading ratios than $R=-1$, which are more damaging at a similar stress amplitude σ_a , must be tested. This study therefore focuses on three specific areas:

- Providing full fatigue data sets for FEA fatigue lifetime calculations (both HCF and Long Life Fatigue (LLF)), including static properties, mean stress and notch sensitivities and scatter
- Comparison between different strongly notched fatigue specimens
- Investigation of the interface strength of weld lines

Tool design related weld lines

Weld lines are the result of the meeting of two or more fill fronts where the feedstock flow splits and joins together during the filling process [2]. Such weld lines can occur behind drillings (injection moulding tool inlets) or if the component is injection moulded with more than one gate. A good overview regarding the avoidance and the improvement of weld lines can be found in [3]. A few literature sources discuss weld lines as a MIM defect that can influence mechanical properties [4, 5, 6, 7].

R M German differentiates between moulding defects (part sticking, short shots, air pockets and voids, sink marks and internal cracks) and debinding defects (large pores, warpage, distortion, cracks, porosity, rounded edges, carbon issues, surface finish of melted component). Moreover, he concludes that sintering amplifies defects which were introduced earlier in mixing, moulding or debinding [8]. This defect compilation is an extract from a larger overview of defect sources and cures from [9].

The plastic injection moulding industry has a lot of experience with weld lines. They differentiate weld lines formed due to different feedstock flow temperatures ϑ during the fill front formation and weld lines formed by differently angle-orientated fill fronts. If two fill fronts meet each other with a certain angle Θ , a blurred weld line could arise [2]. The resulting part surface shows a local sink mark, which can be interpreted as a notch. In the plastic injection moulding industry, a characteristic sink mark angle of $\Theta=135^\circ$ is used to differentiate between a merged ($\Theta > 135^\circ$) and conventional ($\Theta < 135^\circ$) weld line. Fig. 2 shows a schematic of the corresponding weld line formation. Well-welded fill fronts are assumed to be non-critical [2].

Besides the local sink mark formation, another feature is assumed to be critical: a sharp angle between the meeting fill fronts will also reduce component quality [3]. The damaging effect of weld lines could be dramatic in the plastic injection moulding industry if an anisotropic orientation of a reinforced filling material, such as glass or carbon fibre, is provoked.

In the past, designers of MIM tools moved the gates to positions that ensured weld lines were as far away as possible from highly-loaded regions of a component. Fig. 3, however, shows that this is not always possible. In this case, the weld line is located on a hub which is loaded with a fracture opening mode 1 during the interference fitting. Another option is to vary the gate diameter d or the



Fig. 3 Weld line and superficial sink mark on a hub of an injection moulded MIM component. Circumferential tensile stresses will load the weld line with fracture opening mode 1 during the interference fitting

volumetric injection feedstock flow rate Q to guarantee a quick injection moulding process without a rapid cooling of the feedstock.

Furthermore, the feedstock flow temperature ϑ or the tool temperature ϑ_{tool} can be increased to decrease the feedstock viscosity η . In general, smaller components with shorter feedstock flow paths are favoured since the resulting temperature gradient $\Delta\vartheta$ from the injection gate to the formed weld

Fig. 4 (a-e) shows the filling evolution and the final weld line position of a twin-gated notched fatigue specimen according to DIN EN ISO 3928 (notch radius $r=0.45$ mm, stress concentration factor $K_t=3.42$, axial loading mode) simulated with Sigmasoft Mould Flow. With this procedure, the resulting weld line position can be simulated. As a result, the tool designer can vary the gate position. However, the shifting of the weld line to non-critical component regions is

“In the past, designers of MIM tools moved the gates to positions that ensured weld lines were as far away as possible from highly-loaded regions of a component...”

line is lower. To analyse the injection moulding process in general, and to investigate the resulting feedstock flow paths, a mould flow simulation is an often-recommended procedure [4, 5].

not always possible, because of the complexity of the injection moulding tool; in particular, the location of cooling channels, other cavities and the length of the runner. It is, therefore, necessary to assume the worst-

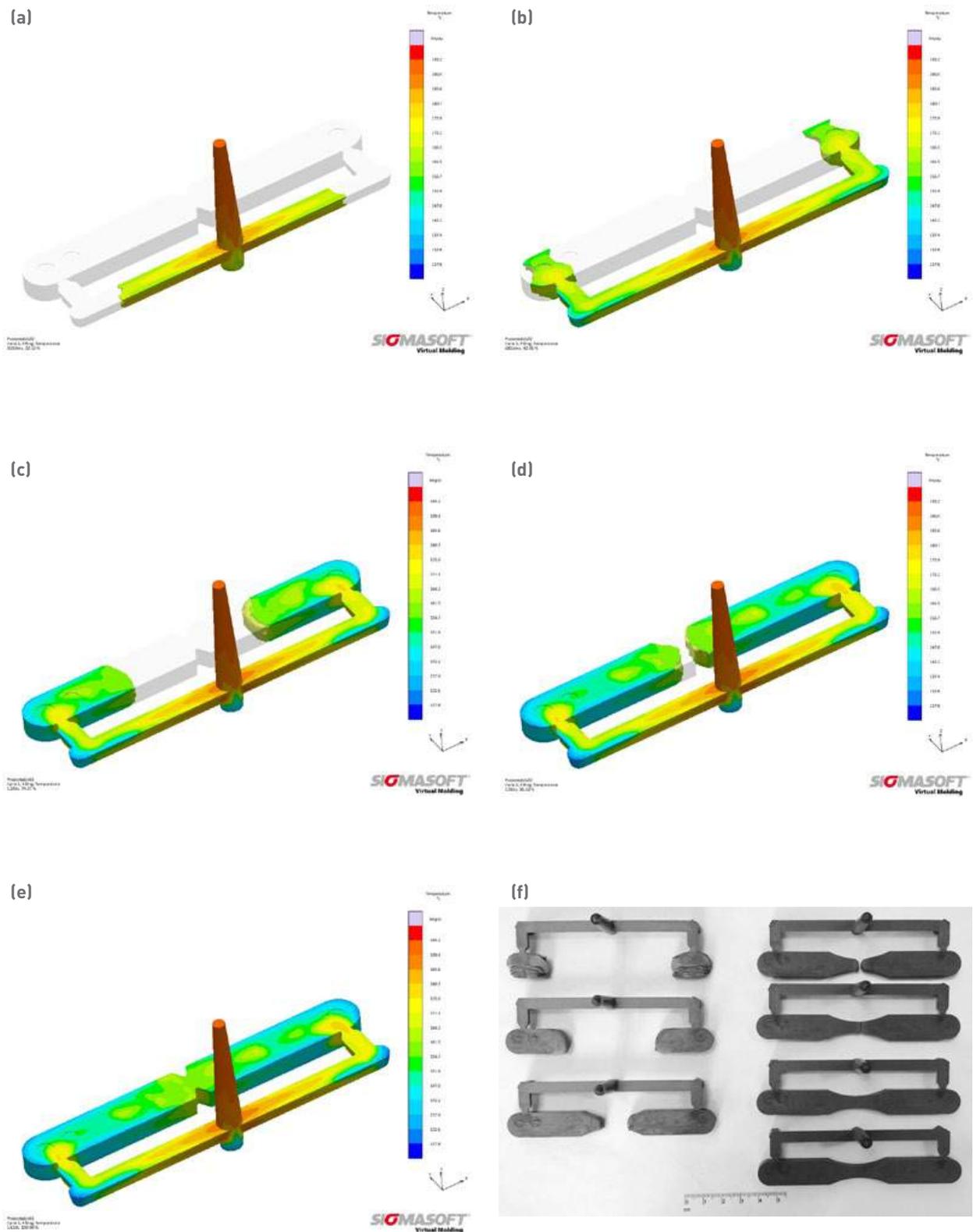


Fig. 4 Filling evolution and final weld line position of a twin-gated notched fatigue specimen according to DIN EN ISO 3928 (notch radius $r=0.45$ mm, stress concentration factor $K_t=3.42$, axial loading mode). In this case, the gate diameters were slightly varied to investigate the symmetry of the resulting feedstock flow paths [a-e]. f shows an injection moulding study of an unnotched fatigue specimen according to DIN EN ISO 3928 (notch radius $r=30$ mm, stress concentration factor $K_t=1.06$, axial loading mode)

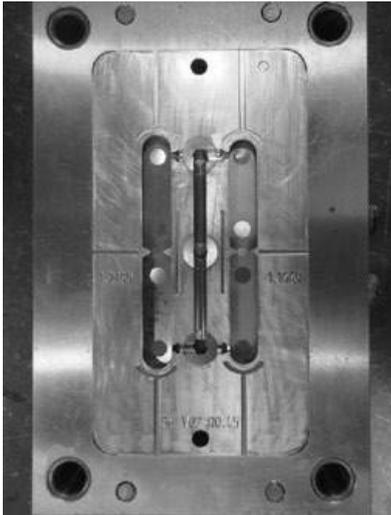


Fig. 5 Tool cavity for the fatigue specimens according to DIN EN ISO 3928 with a notch radius of $r=0.45$ mm for two different offset factors OF and special adjustable valves

case scenario where the weld line is located in the highly-loaded component region and the weld line is loaded with fracture opening mode 1.

High cycle fatigue experiments are rare in the MIM industry. To determine material properties and to investigate the effect of weld lines, a new tool design for fatigue specimens was developed. As a result, there is no standardised fatigue specimen geometry for MIM steel grades available or recommended. Most of the existing fatigue experiments were conducted on turned and ground MIM preforms (cylindrical bars) without consideration of the weld line position. The machining operations are the dominant cost drivers which make fatigue testing expensive. Moreover, the effects from machining, such as providing a smoothing effect, densification, work hardening and the introduction of residual stresses, are not discussed. These effects must be considered, however, since most MIM components are used with as-sintered surfaces.

Therefore, in addition to DIN EN ISO 2740 tensile test specimens, DIN EN ISO 3928 fatigue specimens were also injection moulded with two different gate variants. For the investigation of notch sensitivity and



Fig. 6 Overview of the tensile test and fatigue specimens used (from top to bottom): tensile test specimen according to DIN EN ISO 2740 (notch radius $r=\infty$, stress concentration factor $K_t \approx 1$, axial loading mode), unnotched fatigue specimen according to DIN EN ISO 3928 (notch radius $r=30$ mm, stress concentration factor $K_t=1.06$, axial loading mode), notched fatigue specimen according to DIN EN ISO 3928 (notch radius $r=0.9$ mm, stress concentration factor $K_t=2.53$, axial loading mode) and notched fatigue specimen according to DIN EN ISO 3928 (notch radius $r=0.45$ mm, stress concentration factor $K_t=3.42$, axial loading mode). Note that the stress concentration factor K_t depends on the applied load. The defined stress concentration K_t factors above are valid for the axial loading mode (tensile loading mode, Table 1). They are not to be confused with the stress concentration factors from the bending loading mode (Table 2 and Table 3)

to derive the resulting support factor n_x , three different tools with different cavities were designed. The unnotched DIN EN ISO 3928 fatigue specimen has a waist with a notch radius of $r=30$ mm ($K_t=1.04$ for bending loading). Moreover, two further fatigue specimens with a respective notch radius of $r=0.9$ mm ($K_t=1.91$ for bending loading) and $r=0.45$ mm ($K_t=2.47$ for bending loading, slightly varying from DIN EN ISO 3928) were produced. The corresponding stress concentration factors K_t were calculated numerically via Finite Element Analysis (FEA). The worst-case scenario discussed above was achieved with the tool cavity shown in Fig. 5. With this injection moulding cavity, it is possible to produce single-gated and twin-gated fatigue specimens by adjusting the valves.

Because of the symmetry of the runners, the resulting weld line of the twin-gated injection moulding

process is located at the notch root, as can be seen in Fig. 4. The tool cavity dimensions were corrected with an offset factor $OF=1.2160$ for MIM 8620 [Catamold 8620 from BASF, 20NiCrMo2-2] and $OF=1.1669$ for MIM 100Cr6 [Catamold 100Cr6 from BASF] to match the required dimensions of DIN EN ISO 3928.

Specimen production

The two low-alloyed MIM steel grades selected (MIM 8620 case-hardened vs MIM 100Cr6 hardened) were compared, with a focus on the static and cyclic material properties, respectively. The injection moulding of all specimens was undertaken with plant-specific injection moulding parameters. Fig. 6 shows the four manufactured geometries in the as-sintered condition. A more detailed overview of the formed weld lines

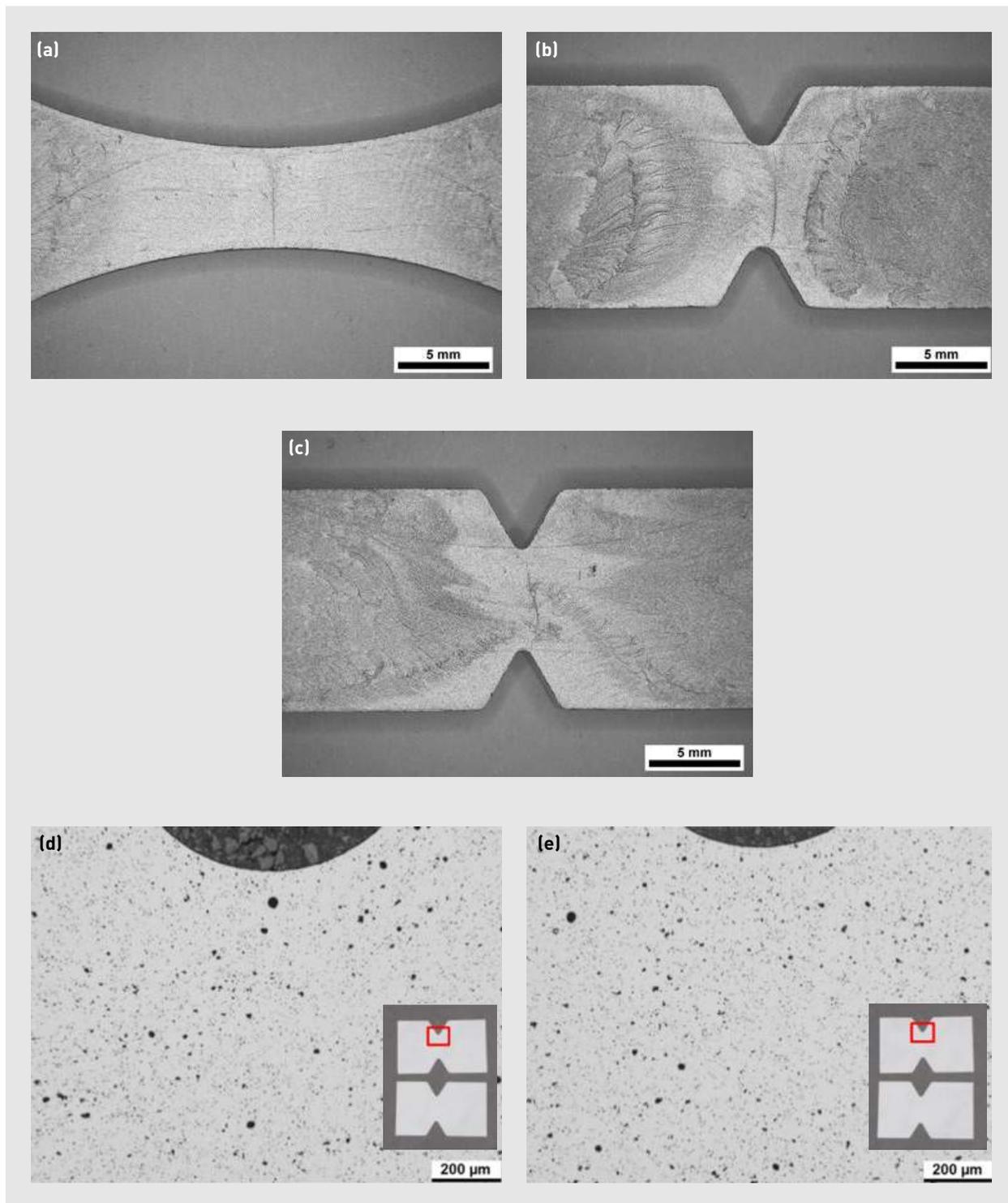


Fig. 7 Visible weld lines and superficial sink marks of twin-gated fatigue specimens according to DIN EN ISO 3928 (from top to bottom) of MIM 8620 as-sintered specimens: unnotched fatigue specimen according to DIN EN ISO 3928 (notch radius $r=30$ mm, stress concentration factor $K_t=1.06$, axial loading mode), notched fatigue specimen according to DIN EN ISO 3928 (notch radius $r=0.9$ mm, stress concentration factor $K_t=2.53$, axial loading mode) and notched fatigue specimen according to DIN EN ISO 3928 (notch radius $r=0.45$ mm, stress concentration factor $K_t=3.42$, axial loading mode) [a-c]. Unetched microstructures of MIM 100Cr6 hardened taken in the notch root of a notched fatigue specimen according to DIN EN ISO 3928 (notch radius $r=0.45$ mm, stress concentration factor $K_t=3.42$, axial loading mode). d is from a single-gated specimen (maximum Feret diameter $d_{\max, \text{Feret}}=33$ μm) and e is from a twin-gated specimen (maximum Feret diameter $d_{\max, \text{Feret}}=24$ μm). A difference regarding the porosity f , its shape or distribution cannot be observed. This indicates that a recognition of weld lines is more likely from the optical visible impress (colouring) than from the microstructure

is shown in Fig. 7. The single-gated and twin-gated fatigue specimens were injection moulded with the same filling and packing parameters (volumetric injection feedstock flow rate Q , filling pressure p_f , packing pressure profile p_p , filling time t_f and packing time t_p) to ensure similar material properties.

After injection moulding, the densities of the right-hand and left-hand gripping ends were measured by the Archimedes method to guarantee comparable green part densities ρ_g . All specimens were then peened with a plastic granulate to remove the injection moulding burrs. Potential residual stresses σ_R were eliminated by the subsequent sintering process above the recrystallisation temperature of both the MIM steel grades.

Both MIM steel grades were sintered together to achieve the targeted sintered density of $\rho=7.4 \text{ g/cm}^3$. Debinding and sintering were performed in a continuous debinding and sintering walking beam furnace. The catalytic debinding of the specimens was carried out in a low temperature atmosphere of HNO_3 and N_2 for $t=390 \text{ min}$. The parts were sintered at a sintering temperature of $\Theta=1251^\circ\text{C}$ for a sintering time of approximately $t=90 \text{ min}$ in a 100% N_2 atmosphere with an atmospheric pressure of $p=10 \text{ mbar}$. The cooling-rate $\Delta\Theta/\Delta t_{300^\circ\text{C}-600^\circ\text{C}}$ was not recorded. After sintering, the specimens made of MIM 8620 were carburised, case-hardened and tempered at an external company.

The carburising atmosphere consisted of natural gas, CH_4O (methanol) and N_2 with a carbon level of $C=1\%$. The carburising temperature Θ and the carburising time t were not communicated; however, a value of $\Theta\approx 950^\circ\text{C}$, the recommended value from the feedstock supplier, BASF SE [10], can be assumed. The quenching medium was oil. Afterwards, the specimens were tempered at $\Theta=170^\circ\text{C}$ for $t=2 \text{ h}$.

The sintered MIM 100Cr6 specimens were processed using a different route. They were austenitised, quenched and tempered by an external company. The austenitisation

temperature Θ and the austenitisation time t were not communicated. The quenching medium was oil. Further details regarding the tempering were not communicated. The nitrogen, oxygen and carbon contents were measured after sintering and after the heat treatments.

The complete carbon profile $C(d)$ of MIM 8620 case-hardened was not measured. The surface carbon content C_0 of MIM 8620 case-hardened cannot be measured precisely with the Leco carbon combustion technique. Therefore, a local equilibrium was assumed with $C_0\approx C\text{-level}=1\%$. The core carbon content was measured as $C_\infty\approx 0.146\%$. Therefore, a sigmoidal carbon profile $C(d)$ with an asymptotic plateau in the core region can be assumed.

MIM 100Cr6 hardened exhibits a value of $C_0\approx C_\infty\approx 0.85\%$. Moreover, both MIM steel grades show a small nitrogen pick-up of approximately $N_0\approx N_\infty\approx 0.03\%$. This could be explained by the chemical compositions of both the MIM steel grades and the affinity of chromium for nitrogen. MIM 8620 contains $\text{Cr}=0.5\%$ and MIM 100Cr6 contains $\text{Cr}=1.5\%$, respectively.

Static properties and resulting notch-strength ratios γ

Material toughness is an important property because it characterises a material's resistance to crack growth and rupture as well as its ability to absorb energy in the form of plastic deformation. This is a very general definition. However, several metrics are used to characterise material toughness, for example:

- Plastic strain ε_p from the stress-strain curve
- The equivalent strain energy density ESED from the stress-strain curve (integral of the stress-strain curve)
- The fracture toughness K_{Ic} and the cyclic stress intensity threshold ΔK_{th} from static and cyclic fracture mechanics tests

- The impact strength W or toughness W/A from Charpy or Izod impact strength tests and special drop-weight tests to imitate the behaviour of welded sheets (Pellini and Battelle drop-weight tests)

Unfortunately, the correlation between all these toughness metrics is not very good. This leads to the conclusion that there is no single 'material toughness'. Therefore, the testing method should be as close as possible to the real application and the real loading, with special consideration of the environment (humidity, temperature and pH value), the strain rate $\Delta\varepsilon/\Delta t$ (impact), the geometry (notches) and the existence of defects (cracks, flaws or welding seams).

MIM components are filigree and very complex in shape. From the mechanical point of view, they are notched in multiple ways. As a consequence, a toughness metric is needed to characterise its response on multiaxial stress states and on the local peak stresses $\sigma=K_t\cdot\sigma_n$ ('stress raisers') with sharp stress gradients $\chi^*\sim 1/r$. An additional and very easy testing method is based on a comparison between the ultimate tensile strength σ_u of unnotched tensile test specimens ($\sigma_{u,smooth}$, $K_t\approx 1$, axial loading mode, smooth condition) and notched fatigue specimens ($\sigma_{u,notched}$, $K_t>1$, axial loading mode, notched condition). The ratio is called the notch-strength ratio γ and depends on the material, the heat-treatment condition and on the notch geometry (flat or circumferential notch and sharpness of the notch/notch radius r) and is defined as [11]:

$$\gamma = \frac{\sigma_{u,notched}}{\sigma_{u,smooth}}$$

For perfectly brittle materials, the notch-strength ratio γ follows the perfectly brittle limit hyperbola as a function of the realised stress concentration factor K_t :

$$\gamma_{brittle} = \frac{1}{K_t} = \frac{\sigma_{u,notched}}{\sigma_{u,smooth}}$$

Material	Geometry	r (mm), K _t (1), axial	Condition	σ _u (MPa), 1 gate	σ _u (MPa), 2 gates
MIM 8620	DIN EN ISO 2740	∞, K _t ≈1	As-sintered	397	Not realised
MIM 8620	DIN EN ISO 3928	30, K _t =1.06	As-sintered	418	417
MIM 8620	DIN EN ISO 3928	0.9, K _t =2.53	As-sintered	458	447
MIM 8620	DIN EN ISO 3928	0.45, K _t =3.42	As-sintered	432	441
MIM 8620	DIN EN ISO 2740	∞, K _t ≈1	Case-hardened	1102	Not realised
MIM 8620	DIN EN ISO 3928	30, K _t =1.06	Case-hardened	915	947
MIM 8620	DIN EN ISO 3928	0.9, K _t =2.53	Case-hardened	802	781
MIM 8620	DIN EN ISO 3928	0.45, K _t =3.42	Case-hardened	703	725
MIM 100Cr6	DIN EN ISO 2740	∞, K _t ≈1	As-sintered	1076	Not realised
MIM 100Cr6	DIN EN ISO 3928	30, K _t =1.06	As-sintered	1035	1063
MIM 100Cr6	DIN EN ISO 3928	0.9, K _t =2.53	As-sintered	1045	1048
MIM 100Cr6	DIN EN ISO 3928	0.45, K _t =3.42	As-sintered	923	939
MIM 100Cr6	DIN EN ISO 2740	∞, K _t ≈1	Hardened	1106	Not realised
MIM 100Cr6	DIN EN ISO 3928	30, K _t =1.06	Hardened	1033	1022
MIM 100Cr6	DIN EN ISO 3928	0.9, K _t =2.53	Hardened	629	610
MIM 100Cr6	DIN EN ISO 3928	0.45, K _t =3.42	Hardened	470	432

Table 1 Static tensile test results as a function of the material (MIM steel grades), material condition (heat treatment condition), notch radius r and the weld line position (1 gate vs 2 gates)

The notch-strength ratio γ correlates with the plastic strain ϵ_p and the macro-hardness H of the material. Harder materials exhibit a lower ductility. They show a stronger drop of the notch-strength ratio γ [11]. This means that those materials are more sensitive to peak stresses $\sigma = K_t \cdot \sigma_n$ ('stress raisers') and a shape optimisation of the MIM component (e.g. Baud curve, Mattheck's tensile triangles or other splines) is highly recommended to reduce the peak stresses $\sigma = K_t \cdot \sigma_n$. However, for most material and notch geometry combinations, the notch-strength ratio is $\gamma < 1$. This indicates the assumed notch weakening effect. In the case of very soft and ductile materials, the plastic constraint effect can be recognised. In this case, the notch-strength ratio is $\gamma > 1$ and a notch strengthening can be observed.

The static material properties were characterised in terms of the stress-strain and the stress-displacement response. As a reference, single-gated tensile test specimens according

to DIN EN ISO 2740 were tested in the as-sintered and the case-hardened (MIM 8620 case-hardened) or hardened (MIM 100Cr6 hardened) conditions. These static tensile tests were conducted according to the existing standards and correct stress-strain curves could be derived.

Additionally, non-conforming static tensile tests on notched (waist with a notch radius of $r=30$ mm, $r=0.9$ mm and $r=0.45$ mm) fatigue specimens according to DIN EN ISO 3928 were conducted to investigate the interface strength and the notch sensitivity (in terms of the notch-strength ratio γ). Moreover, the difference between the single-gated and the twin-gated specimens can be allocated to the weld line position.

The two MIM steel grades exhibited almost the same surface macro-hardness H after the heat-treatment. The surface macro-hardness was found to be $H=631$ HV 30 for MIM 8620 case-hardened and $H=626$ HV 30 for MIM 100Cr6 hardened, respectively (averaged values between all realised

geometries given in Table 1). This indicates a comparable apparent surface carbon content C_0 after the heat-treatment and comparable quenching conditions, because the maximum achievable surface hardness H_{max} is just a function of the surface carbon content C_0 and shows no strong effect from the alloying element content.

This finding agrees well with the applied carbon level of C-level=1% of the carburising atmosphere (MIM 8620 case-hardened) and the alloyed carbon content of C=1% (MIM 100Cr6 hardened). Even if MIM 8620 case-hardened must be assumed as a multilayer material (in contrast to the homogeneous MIM 100Cr6 hardened material variant) with location-dependent material properties due to the continuous carbon profile C(d), it is interesting to note that the ultimate tensile strength σ_u values are almost identical.

However, case-hardened (in general surface treated) materials should be characterised by their micro-hardness profile H(d) because of their

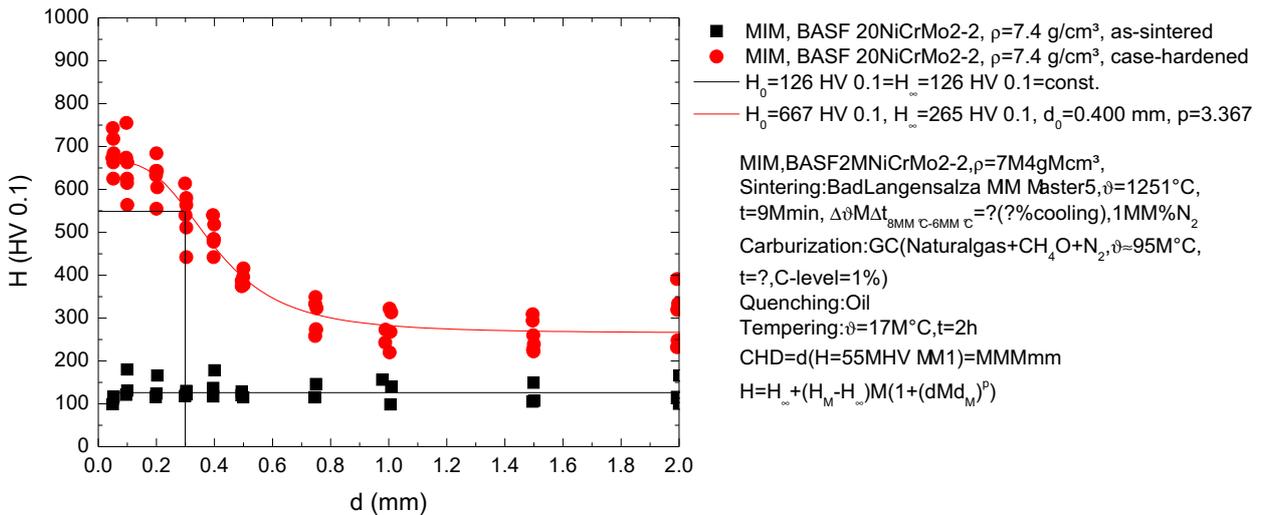


Fig. 8 Micro-hardness profiles $H(d)$ of MIM 8620 (here denoted as 20NiCrMo2-2) with a sintered density of $\rho=7.4 \text{ g/cm}^3$ before (as-sintered condition) and after the case-hardening (case-hardened condition). The carburising time t was not communicated (marked with a question mark)

gradient material properties. Fig. 8 shows the micro-hardness profiles $H(d)$ of MIM 8620 case-hardened with a sintered density of $\rho=7.4 \text{ g/cm}^3$ before (as-sintered condition) and after the case-hardening (case-hardened condition). The micro-hardness profile $H(d)$ according to DIN EN ISO 4507 was approximated with a sigmoidal power-law as:

$$H(d) = H_{\infty} + \frac{(H_0 - H_{\infty})}{\left(1 + \left(\frac{d}{d_0}\right)^p\right)}$$

In this equation, the first asymptote H_{∞} denotes the core micro-hardness, the second asymptote H_0 denotes the surface micro-hardness, d_0 is the inflection point of the sigmoidal function and p is the slope. The derived parameters are given in Fig. 8. It can be seen that a surface micro-hardness of $H_0=667 \text{ HV } 0.1$, a core micro-hardness of $H_{\infty}=265 \text{ HV } 0.1$ and a case-hardening depth of $\text{CHD}_{550}=d(H=550 \text{ HV } 0.1)=0.3 \text{ mm}$ were achieved after the case-hardening. In the as-sintered condition, the sigmoidal shaped curve decreases to a line with identical surface micro-hardness H_0 and core micro-hardness H_{∞} values with $H_0=H_{\infty}=126 \text{ HV } 0.1=\text{const.}$

Due to its homogeneous alloyed carbon content of $C=1\%$, MIM 100Cr6 hardened was actually through-hard-

ened. This results in identical surface micro-hardness H_0 and core micro-hardness H_{∞} values with $H_0=H_{\infty}=705 \text{ HV } 0.1=\text{const.}$ However, even in the macro-hardness domain, both MIM steel grades exhibit similar surface macro-hardness H values ($H=631 \text{ HV } 30$ for MIM 8620 case-hardened vs $H=626 \text{ HV } 30$ for MIM 100Cr6 hardened). The effect from the load ($\text{HV } 30$ vs $\text{HV } 0.1$) can be allocated to the sintered density of $\rho=7.4 \text{ g/cm}^3$ (porosity f). The macro-hardness H is an apparent hardness value in the sense of a combination of the metallic matrix hardness and the porosity hardness. Therefore, those macro-hardness H values ($\text{HV } 30$) are lower.

The ultimate tensile strength σ_u of MIM 100Cr6 hardened is $\sigma_u=1106 \text{ MPa}$ and the ultimate tensile strength σ_u of MIM 8620 case-hardened is $\sigma_u=1102 \text{ MPa}$ (Table 1), respectively (tensile test specimen according to DIN EN ISO 2740, 1 gate). This could indicate a through-hardening effect for the MIM 8620 case-hardened material variant due to the small cross-section of the DIN EN ISO 2740 specimen. However, the corresponding case-hardening depth was found to be $\text{CHD}_{550}=0.3 \text{ mm}$, whereas the DIN EN ISO 2740 specimen diameter is $d \approx 3 \text{ mm}$ ($d=3.8 \text{ mm}$ in the green state). This means that the generated micro-hardness profile $H(d)$ is close to the through-

hardening condition $2 \cdot \text{CHD}_{550}=d$. In comparison to the achieved high surface macro-hardness H values after the heat-treatments, the derived ultimate tensile strength σ_u values seem to be too low. According to the often-proposed $\sigma_u \approx 3 \cdot H$ correlation, ultimate tensile strength σ_u values of approximately $\sigma_u \approx 1800 \text{ MPa}$ were expected.

It is interesting to note that the ultimate tensile strength σ_u of MIM 100Cr6 remains the same in the as-sintered and the hardened material condition, respectively ($\sigma_u=1076 \text{ MPa}$ for the as-sintered condition vs $\sigma_u=1106 \text{ MPa}$ for the hardened condition, tensile test specimens according to DIN EN ISO 2740, 1 gate). Nevertheless, the ductility (in terms of the fracture strain ϵ_f) has changed dramatically ($\epsilon_f=7.43\%$ for the as-sintered condition vs $\epsilon_f=0.88\%$ for the hardened condition, tensile test specimens according to DIN EN ISO 2740, 1 gate). This is remarkable because the often-proposed $\sigma_u \approx 3 \cdot H$ correlation fails [12]. The surface macro-hardness of MIM 100Cr6 could be increased from $H=273 \text{ HV } 30$ in the as-sintered condition to $H=626 \text{ HV } 30$ in the hardened condition.

In this context, it is worth considering a potential correlation between the unnotched fully reversed bending fatigue strength at the knee point σ_A

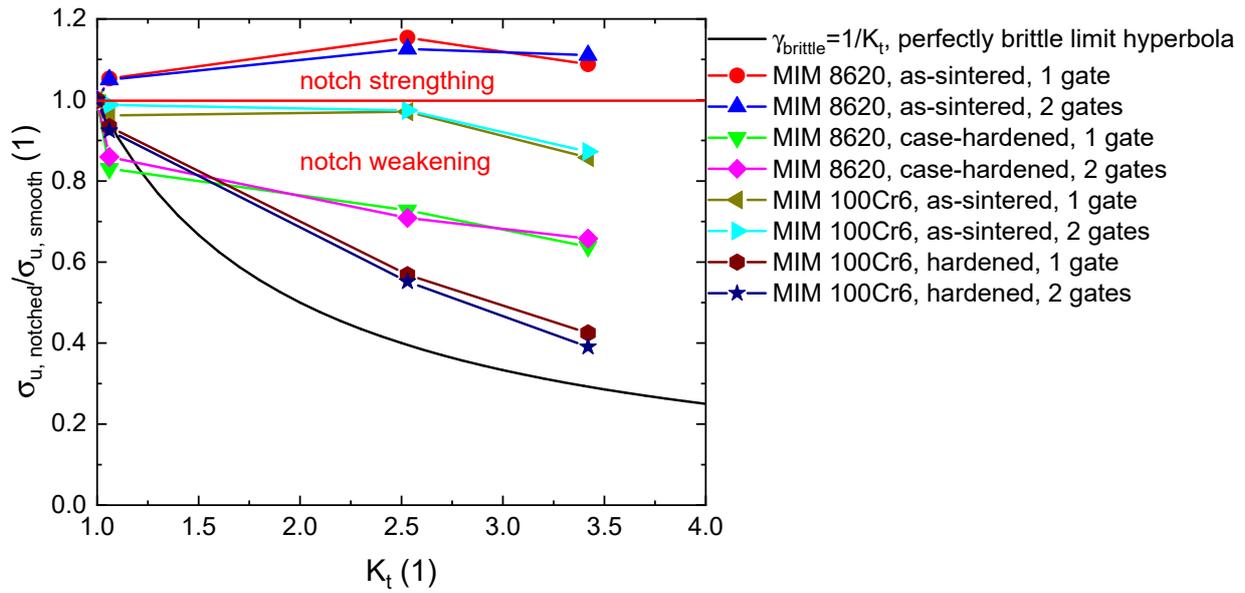


Fig. 9 Notch-strength ratios γ of the tested MIM steel grades. MIM 8620 as-sintered exhibits a notch strengthening effect due to its low macro-hardness H and low-alloyed carbon content of $C=0.2\%$ in the as-sintered material condition. MIM 100Cr6 as-sintered shows a neutral behaviour and a slight notch weakening effect at higher stress concentration factors K_t in the as-sintered material condition. Both MIM steel grades show a notch weakening effect after the heat treatments (case-hardening and hardening), whereas MIM 100Cr6 hardened shows a dramatic drop towards the perfectly brittle limit hyperbola. The tensile test specimens according to DIN EN ISO 2740 were only produced without a weld line (single gate). Since a difference regarding the weld line position (single-gate vs twin-gated) tensile test specimens on the static tensile test results cannot be found, the same value was taken as a reference for the unnotched tensile test specimens ($\sigma_{u,smooth}$, $K_t \approx 1$, axial loading mode, smooth condition) which were produced with a weld line (twin-gated)

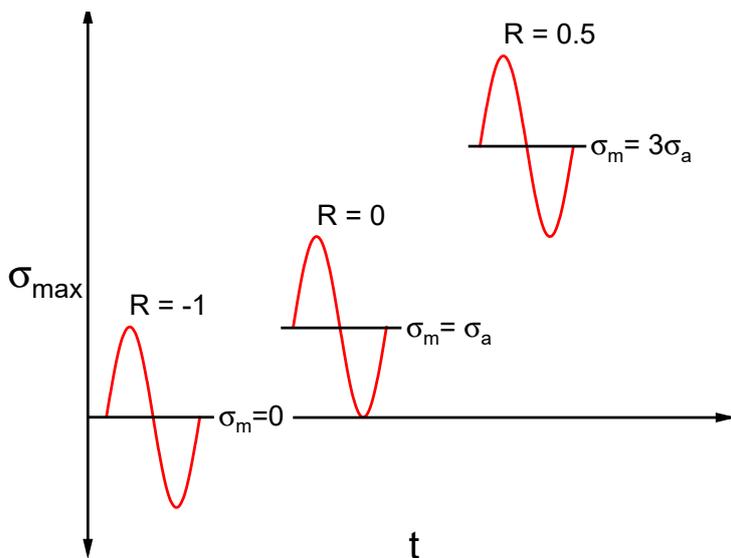


Fig. 10 Loading ratios R during the cyclic bending fatigue experiments. The maximum stress σ_{max} is the sum of the mean stress σ_m (static stress component) and the stress amplitude σ_a (cyclic stress component). The loading ratio R indicates the ratio between the static and the cyclic stress component. Positive loading ratios R indicate positive (tensile) mean stresses σ_m , which are more damaging than negative (compression) mean stresses σ_m with the same stress amplitude σ_a

and a static strength parameter, for example the surface macro-hardness H or the ultimate tensile strength σ_u . If there is a correlation between the unnotched fully reversed bending fatigue strength at the knee point σ_A and the ultimate tensile strength σ_u , similar unnotched fully reversed bending fatigue strengths at the knee point σ_A values would be expected for the two different material conditions (as-sintered vs hardened). This will be not the case. Therefore, it is assumed that a correlation with the surface macro-hardness H will deliver a better agreement. A systematic trend regarding the weld line position (single-gated vs twin-gated tensile test specimens) on the static tensile test results cannot be found. A dramatic difference between the two investigated MIM steel grades occurs in the case of notches or other stress concentrations.

R (1)	K_t (1)	k (1)	N_K (1)	σ_A (MPa)	S_{SAFD} (MPa)	k (1)	N_K (1)	σ_A (MPa)	S_{SAFD} (MPa)
1 gate					2 gates				
-1	1.04	-19.227	3303592	610.78	7.99	-14.745	3072990	565.55	18.82
0	1.04	-6.213	172096	362.49	15.08	-7.560	309596	333.49	9.58
0.5	1.04	-6.981	198094	195.48	8.72	-4.228	128227	194.46	10.30
-1	1.91	-6.520	146430	468.72	10.59	-5.643	138222	470.39	18.29
-1	2.47	-5.673	124389	423.18	13.02	-5.405	140835	397.07	12.84

Table 2 Basquin parameters for MIM 8620 case-hardened with a sintered density of $\rho=7.4 \text{ g/cm}^3$ of the derived bending s-N lines (each bending s-N line was derived with $n=50$ specimens) as function of the weld line position (1 gate vs 2 gates)

R (1)	K_t (1)	k (1)	N_K (1)	σ_A (MPa)	S_{SAFD} (MPa)	k (1)	N_K (1)	σ_A (MPa)	S_{SAFD} (MPa)
1 gate					2 gates				
-1	1.04	-22.540	521870	624.90	13.13	-0.582	28913	600.85	12.88
0	1.04	-5.901	42219	361.24	9.44	-13.792	102833	382.32	9.63
0.5	1.04	-10.396	88671	215.00	8.34	-6.360	39089	221.04	10.30
-1	1.91	-4.328	41391	412.85	15.55	-4.448	48305	370.68	18.28
-1	2.47	1.398	11503	308.67	9.19	-3.751	67069	301.09	8.54

Table 3 Basquin parameters for MIM 100Cr6 hardened with a sintered density of $\rho=7.4 \text{ g/cm}^3$ of the derived bending s-N lines (each bending s-N line was derived with $n=50$ specimens) as function of the weld line position (1 gate vs 2 gates)

The notch-strength ratio γ (for the sharpest produced notch with a notch radius of $r=0.45 \text{ mm}$ and a corresponding axial stress concentration factor of $K_t=3.42$ for the axial loading mode, 1 gate) of MIM 100Cr6 hardened reduces to $\gamma=\sigma_u(K_t=3.42)/\sigma_u(K_t\approx 1)=470 \text{ MPa}/1106 \text{ MPa}=0.42$, whereas MIM 8620 case-hardened exhibits a value of $\gamma=\sigma_u(K_t=3.42)/\sigma_u(K_t\approx 1)=703 \text{ MPa}/1102 \text{ MPa}=0.64$. In general, the notch-strength ratio γ of MIM 100Cr6 hardened follows the expected progression [11]. From Fig. 9, it can be seen that its behaviour is closer to the perfectly brittle limit hyperbola $\gamma_{\text{brittle}}=1/K_t$. This means that the behaviour of MIM 8620 case-hardened differs from expectations. It seems that the higher core ductility and the compressive residual stresses σ_R^- on the surface of MIM 8620 case-hardened effectively decelerate the crack growth in the static loading case. This important effect remains undetected if only standard-conforming static tensile tests are performed.

The conclusion for the practical static strength assessment is that MIM 100Cr6 hardened will show a much higher sensitivity to notches or other stress concentrations. This is a clear disadvantage, especially for complex-shaped MIM components.

Cyclic properties

The cyclic material properties were evaluated exactly as described in [13]. Both MIM steel grades were cyclically tested (bending loading mode) with three different loading ratios R (R=-1, R=0 and R=0.5) as shown in Fig. 10.

The notched fatigue specimens according to DIN EN ISO 3928 ($K_t=1.91$ and $K_t=2.47$ for the bending loading mode) were only tested with a loading ratio of R=-1 because the Haigh damage lines will be shifted in a more or less parallel manner [14]. Two different batches were produced with a special injection moulding

cavity. With this injection moulding cavity (Fig. 5), it is possible to produce single-gated and twin-gated fatigue specimens by adjusting the valves. Further details can be found in [13]. It was the goal to investigate the interface strength of the twin-gated weld lines because weld lines are a common feature of injection moulded MIM components. Moreover, weld lines are assumed to be a MIM defect (critical hot spot) which affects (lowers) the static and cyclic material properties.

The results are summarised in Table 2, with values taken from [13] and Table 3 in terms of the Basquin parameters of the corresponding bending s-N lines where k denotes the slope and N_K the cut-off point. For each bending s-N line, a total number of $n=50$ specimens ($n=25$ specimens for the staircase test domain/LLF domain and $n=25$ for the HCF domain) were used. The bending s-N lines were approximated with the Basquin power-law as:

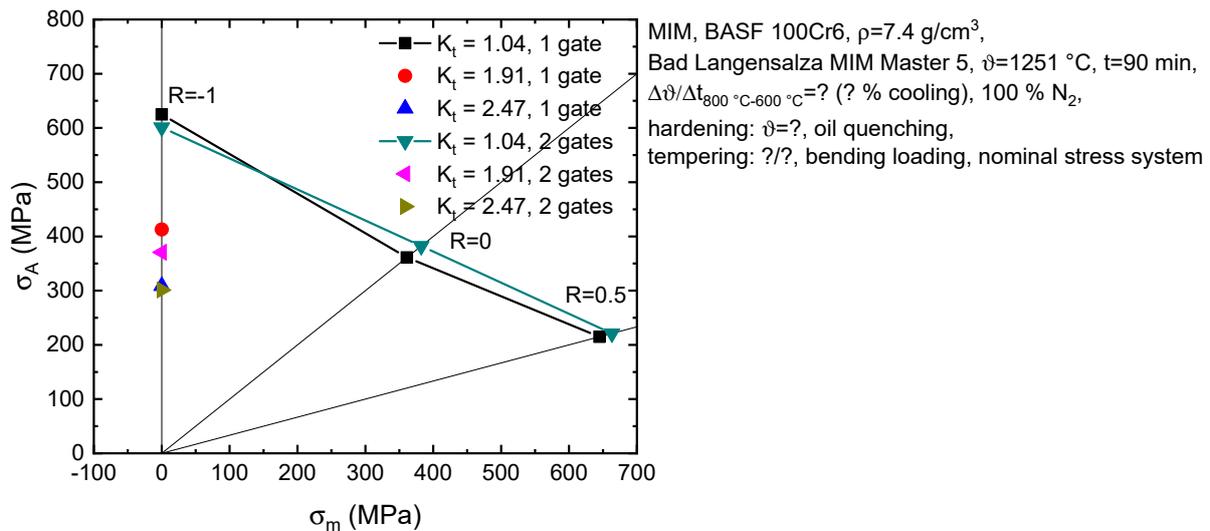


Fig. 11 Haigh damage lines for MIM 100Cr6 hardened (1 gate vs 2 gates) according to the presented values from Table 3 (the cooling-rate $\Delta\vartheta/\Delta t_{800^{\circ}\text{C}-600^{\circ}\text{C}}$, the austenitisation temperature ϑ , the austenitisation time t and the tempering conditions were not communicated)

$$\sigma_a = \left(\frac{N}{N_K} \right)^{\frac{1}{k}} \sigma_A$$

The bending fatigue strength at the knee point σ_A was derived for a survival probability of $P_s=50\%$. With the help of the standard deviation of the strength s_{SAFD} (note this is only the material scatter without the consideration of the process scatter), the measured bending fatigue strength at the knee point $\sigma_A=\sigma_A(P_s=50\%)$ and a tabulated parameter (Gaussian quantile u), a conversion into all other required survival probability levels P_s is possible:

$$\sigma_A(P_s) = \sigma_A(P_s = 50\%) + u \times s_{SAFD}$$

The unnotched fatigue specimen according to DIN EN ISO 3928 exhibits a waist with a notch radius of $r=30$ mm ($K_t=1.04$ for the bending loading mode). Moreover, two further fatigue specimens with a notch radius of $r=0.9$ mm ($K_t=1.91$ for the bending loading mode) and $r=0.45$ mm ($K_t=2.47$ for the bending loading mode, slightly varying from DIN EN ISO 3928) were produced, respectively.

From the presented values from Table 2 and Table 3 it is evident that

both MIM steel grades exhibit a similar material scatter. This material scatter is defined in terms of the standard deviation of the strength s_{SAFD} as described in [15, 16]. The overall variants averaged values, $\bar{s}_{SAFD}=12.52$ MPa for MIM 8620 case-hardened and $\bar{s}_{SAFD}=11.53$ MPa for MIM 100Cr6 hardened, are very similar. This indicates a comparable material and manufacturing quality without larger defects or value variations.

The values are, however, significantly higher than those for conventional 'press and sintered' PM steel grades. As proposed in [15], it seems that there is a rough trend, even if statistically insignificant, that the standard deviation of the strength s_{SAFD} increases with an increasing surface macro-hardness H . A possible explanation for this observation could be the finding that, for most statistical probability density distributions, the mean value μ (here: fatigue strength at the knee point σ_A) and the corresponding standard deviation s (here: the standard deviation of the strength s_{SAFD}) are not completely independent of each other.

A comparison between the two types of gates (single gate vs twin-gates) exhibits only a small effect of

the weld lines. Only an averaged drop of the fatigue strength at the knee point σ_A of $\Delta\sigma_A=-4.3\%$ can be observed for MIM 8620 case-hardened and of $\Delta\sigma_A=-1.6\%$ for MIM 100Cr6 hardened, respectively, whereas this effect is not systematic. This means that not all twin-gated bending fatigue strengths at the knee point σ_A values exhibit a drop of the cyclic material properties. This observation is based on small injection moulded fatigue specimens and means that the effect of weld lines can be neglected for smaller MIM components if the difference between the feedstock flow temperatures ϑ is small and a sufficient welding can be assumed.

The remaining Basquin parameters of the corresponding bending s-N lines should be discussed very briefly. The slope k and the cut-off point N_K are essential for damage accumulation calculations if a load spectrum with varying stress amplitudes σ_a is considered. MIM 8620 case-hardened exhibits very flat bending s-N lines for the unnotched ($K_t=1.04$ for the bending loading mode) fully reserved loading case ($R=-1$). This holds true for both weld line positions (1 gate vs 2 gates). As a result, the slopes k are very small (1 gate: $k=-19.227$ and 2 gates: $k=-14.745$) and the cut-

off points N_K are shifted to very high numbers (1 gate: $N_K=3303592$ and 2 gates: $N_K=3072990$). A variation, in terms of the loading ratio R or in terms of the stress concentration factor K_t , change the observed tendencies completely. The resulting bending s-N lines are much steeper with much higher slopes k and smaller cut-off points N_K .

The other slopes k vary between $k=-4.228$ and $k=-7.560$. However, MIM 8620 case-hardened behaves in a tolerant manner, because all cut-off points are larger than $N_K=124389$. Therefore, damage accumulation calculations seem to be possible. MIM 100Cr6 hardened behaves more unpredictably. In general, the cut-off points N_K are much smaller than those from MIM 8620 case-hardened. As a result, damage accumulation calculations must be avoided. Moreover, two slopes k (1 gate/ $R=-1/K_t=2.47$: $k=1.398$ and 2 gates/ $R=-1/K_t=1.04$: $k=-0.582$) are wrong. Even if $n=25$ specimens were available for the HCF domain, the SAFD software algorithm [15] was not able to approximate a best fit line for the data points.

This means that, for MIM 100Cr6 hardened, there is only a small transition zone between the HCF domain and the LLF domain. Therefore, MIM components made of MIM 100Cr6 hardened should be designed for LLF loadings only. From the data values presented in Table 2 and Table 3, the corresponding Haigh damage lines can be constructed, and the corresponding mean stress sensitivities M can be calculated according to the FKM guideline [17].

For MIM 8620 case-hardened, the mean stress sensitivities M can be quantified as $M_2=0.69$ (1 gate) and $M_2=0.70$ (2 gates) and $M_3=0.75$ (1 gate) and $M_3=0.56$ (2 gates), respectively. MIM 100Cr6 hardened exhibits similar values with $M_2=0.73$ (1 gate) and $M_2=0.57$ (2 gates) and $M_3=0.52$ (1 gate) and $M_3=0.57$ (2 gates), respectively. Fig. 11 exhibits the Haigh diagram for MIM 100Cr6 hardened. This Haigh diagram can be compared with its MIM 8620 case-hardened counterpart from Fig. 12. If the averaged (between the two gate variants) values are

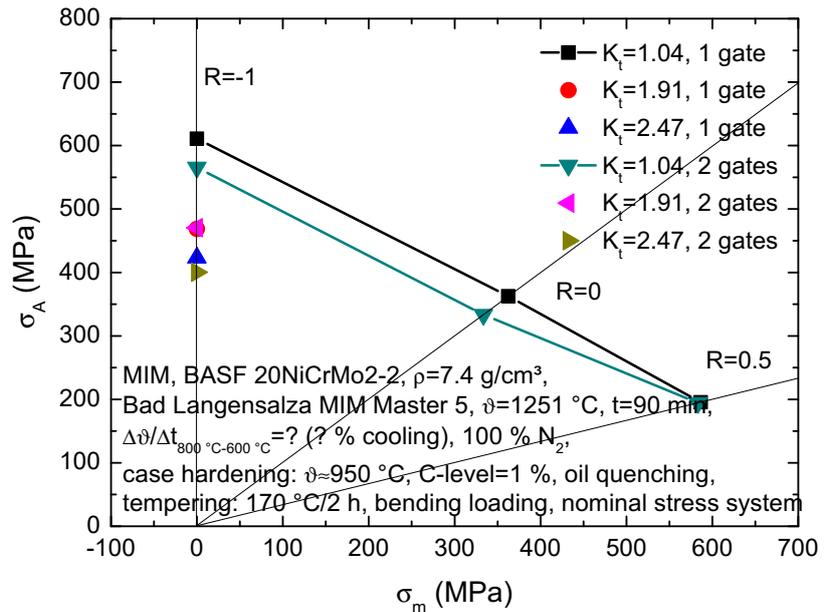


Fig. 12 Haigh damage lines for MIM 8620 (here denoted as 20NiCrMo2-2) case-hardened (1 gate vs 2 gates) according to the presented values from Table 2 (the cooling-rate $\Delta\theta/\Delta t_{800^\circ\text{C}-600^\circ\text{C}}$, the austenitisation temperature θ , the austenitisation time t and the tempering conditions were not communicated)

compared, it is found that MIM 8620 case-hardened behaves with slightly more mean stress sensitivity beyond M_2 . However, the unnotched bending fatigue strength at the knee point σ_A values are very similar for the three tested loading ratios R ($R=-1$, $R=0$ and $R=0.5$).

A clear difference between the two tested MIM steel grades arises if the notched bending fatigue strength at the knee point σ_A values are compared. It is evident that MIM 100Cr6 hardened shows a stronger reaction to notches or other stress concentrations. For example, for a stress concentration factor of $K_t=2.47$, the bending fatigue strength at the knee point σ_A values of MIM 8620 case-hardened are approximately $\Delta\sigma_A \approx 100$ MPa higher than those of MIM 100Cr6 hardened. This means that there is a high support effect for MIM 8620 case-hardened.

Contrary to expectations, the MIM 8620 case-hardened material is not perfectly notch sensitive. Due to the high sintered density of $\rho=7.4$ g/cm³ and the high surface micro-hardness of $H_0=667$ HV 0.1 a high notch sensitivity was expected.

The notch factors are $K_t(K_t=1.91)=1.30$ (1 gate), $K_t(K_t=1.91)=1.20$ (2 gates), $K_t(K_t=2.47)=1.44$ (1 gate) and $K_t(K_t=2.47)=1.42$ (2 gates). Obviously, the notch sensitivity and the resulting support factors n_z are in the same range as for conventional PM steel grades [14]. It must be investigated whether the material itself (hard surface with soft core) or the resulting compressive residual stresses σ_R^- after the case-hardening are responsible for this observation.

MIM 100Cr6 hardened shows a completely different behaviour. This MIM steel grade was through-hardened to a surface micro-hardness of $H_0=H_\infty=705$ HV 0.1=const. As a result, there is no soft core, which could act as a fatigue crack arrester. Moreover, due to its homogeneous alloyed carbon content of $C=1\%$, the martensitic transformation occurs at the same temperature θ . As a result, no beneficial compressive residual stresses σ_R^- will be established on the surface. However, the notch factors K_t are much higher than those from MIM 8620 case-hardened and closer to the linear elastic limit, which is given by the stress concentration factor K_t .

The notch factors are $K_t(K_t=1.91)=1.51$ (1 gate), $K_t(K_t=1.91)=1.62$ (2 gates), $K_t(K_t=2.47)=2.02$ (1 gate) and $K_t(K_t=2.47)=2.00$ (2 gates). The final conclusion regarding the cyclic material properties is very similar to that from the static material properties: MIM 8620 case-hardened shows a much lower notch sensitivity than MIM 100Cr6 hardened. Therefore, this material and material condition is to be favoured. The derived cyclic material properties and model parameters can be used for FEA fatigue lifetime calculations. Only a small modification is needed to transform the bending fatigue strength at the knee point σ_A values into its axial and stress gradient free counterpart. This procedure is described in [14].

Outlook and future work

The values presented above were experimentally derived under the special consideration of the weld line position and the achieved sintered density of $\rho=7.4 \text{ g/cm}^3$. The weld line was assumed as a MIM defect without the definition of its size. Therefore, the location was defined but not the size. This is incomplete information. As a result, an inter- or extrapolation to other defect sizes is not possible. However, a quick prediction or estimation method is needed to approximate the fatigue response in the case of larger defects. The Murakami approach predicts the fully reversed properties (most of the underlying experiments from Murakami were derived during rotating bending fatigue experiments ($R=-1$)), therefore, the predicted fully reversed fatigue strength at the knee point σ_A is (for the bending loading mode) bending fatigue strength at the knee point σ_A as a function of the material macro-hardness H (Vickers hardness) and the projected defect area in the first principal direction $(AREA)^{0.5}$.

The position of the defect (surface defect or internal defect) affects a model-inherent factor. Surface cracks, having the same projected defect area $(AREA)^{0.5}$ in the first principal direction, are more critical than

comparable internal defects. As a result, the model-inherent factor varies between $X=1.43$ (surface defect) and $X=1.56$ (internal defect). Therefore, the predicted bending fatigue strength at the knee point σ_A is lower in the case of a surface defect. The definition of 'defect' is very wide and incorporates cracks, pores, non-metallic inclusions, soft domains in a harder matrix, grain boundary precipitations and surface roughness [18, 19, 20]. An intermediate position is also defined in [18].

Internal defects in contact with the surface should exhibit a factor of $X=1.41$. It is not clear why this value should be smaller than that from the surface defect ($X=1.43$). As a result, the factor of $X=1.41$ is rarely used in practice [19]. However, A. Bergmark assumes $X=1.41$ for edge defects [20]. The Murakami approach predicts the bending fatigue strength at the knee point σ_A for a fully dense material exhibiting a single defect. The macro-hardness H is a common metric to define the corresponding hardness H of fully dense materials ($H_{\text{macro}} \approx H_{\text{micro}}$).

However, two modifications are needed to tailor the Murakami approach for sintered and porous PM and MIM steel grades. The effect of the porosity f , which is characteristic for sintered and porous PM and MIM steel grades, has not yet been covered. The first modification is in regard to the required macro-hardness H value. The macro-hardness H is the apparent hardness (superimposition of the porosity and the metallic matrix hardness) in the case of sintered and porous PM and MIM steel grades. Therefore, it does not describe the micro-hardness H_0 of the metallic matrix solely.

As a consequence, the micro-hardness H_0 (metallic matrix hardness), e.g. the HV 0.1 micro-hardness, should be used for the Murakami approach [20]. The second modification is with regard to the effect from the porosity $f=1-\rho/\rho_0$. A. Bergmark [20] had proposed an additional term to reduce the predicted bending fatigue strength at the knee point σ_A value as function of the porosity f . In general, that approach is known as the Balshin equation:

$$P = P_0 \left(\frac{\rho}{\rho_0} \right)^m$$

In this equation, P is a material property, which is affected by the porosity f . P_0 is the fully dense material property ($f=0$), ρ is the corresponding density, ρ_0 is the full density and m is a characteristic exponent. In the case of Young's modulus E , the Balshin equation is called the Mac-Adam equation and the characteristic exponent is $m=3.4$. A Bergmark had applied that term to incorporate the effect (superimposition of the porosity and the single defect) from the porosity f as:

$$\begin{aligned} \sigma_A &= \frac{X(H + 120)}{\sqrt[12]{AREA}} \\ &\times \\ \frac{E}{E_0} &= \frac{X(H + 120)}{\sqrt[12]{AREA}} \\ &\times \\ &\frac{E_0 \left(\frac{\rho}{\rho_0} \right)^m}{E_0} \\ &= \\ &\frac{X(H + 120)}{\sqrt[12]{AREA}} \times \left(\frac{\rho}{\rho_0} \right)^m \end{aligned}$$

However, this seems to be valid with one exception. The corresponding Balshin exponent must be set as $m \approx 5$ since the Balshin exponent of $m=3.4$ is only valid for the evolution of Young's modulus E . Further research had shown that a Balshin exponent of $m \approx 5$ is more typical for cyclic fatigue properties. With the two mentioned modifications, the Murakami approach should be able to predict the bending fatigue strength at the knee point σ_A of sintered and porous PM and MIM steel grades. As illustrated in Fig. 13, it must be understood as a superimposition of the bending fatigue strength at the knee point σ_A of a fully dense material with a single defect, together with a porous material without a defect. For a calibration of the Murakami prediction model, the projected defect area $(AREA)^{0.5}$ in the first principal direction should be varied as long as the experimentally

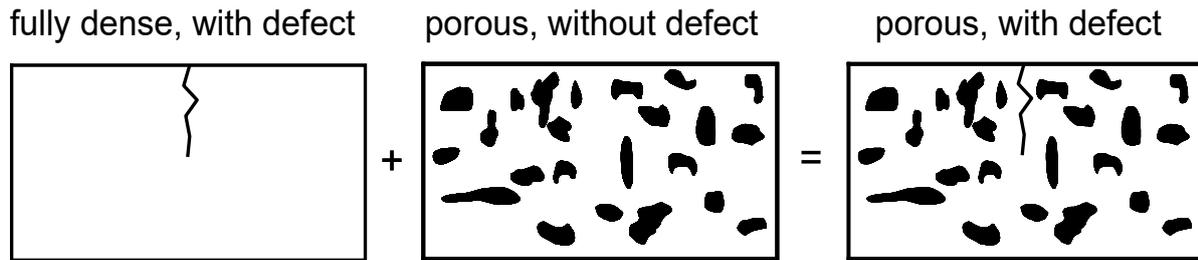


Fig. 13 Superimposition of a fully dense material with a single defect (Murakami approach) together with a porous material without a defect (Balshin approach)

derived bending fatigue strength at the knee point σ_A values are correctly approximated. If a surface defect ($X=1.43$) is assumed to be critical, a spherical defect with a diameter of $d=a \approx 44 \mu\text{m}$ (MIM 8620 case-hardened, $H_0=667 \text{ HV } 0.1$) or $d=a \approx 51 \mu\text{m}$ (MIM 100Cr6 hardened, $H_0=705 \text{ HV } 0.1$) must be assumed to match the experimental values from Table 2 and Table 3 (1 gate). This first estimation neglects the effect of the porosity f (Balshin equation). In other words, here it was assumed that the defect $d=a$ dominates the material and porosity behaviour. The final calibration of the Murakami prediction model requires the adjustment of both influencing factors (defect size effect according Murakami and porosity effect according Balshin). In practise, a clear differentiation between 'defect' and 'pore of the porosity population' will be difficult due to the wide and skewed probability density distribution of the pore size.

Those predicted defect diameters $d=a$ are in a reasonable range for the two tested MIM steel grades with a sintered density of $\rho=7.4 \text{ g/cm}^3$. The maximum Feret diameters $d_{\text{max. Feret}}$ were measured using optical image analysis software for all four specimen geometries, gate variants and for both MIM steel grades as metrics for the largest defect size (without a further differentiation between surface and internal defects). They vary between $d_{\text{max. Feret}}=13 \mu\text{m}$ and $d_{\text{max. Feret}}=46 \mu\text{m}$. However, the mean value (averaged over all variants) is $d_{\text{max. Feret}}=26 \mu\text{m}$. This value is approximately half of the predicted spherical defect diameter $d=a$. After a proper calibration, the Murakami prediction model can be

used for further estimations. The Murakami approach also exhibits a mean stress correction term. After our experiences this mean stress correction term is too optimistic. Therefore, the derived mean stress sensitivities M according to the FKM guideline are more representative.

Conclusions

A systematic analysis of twenty in-house derived bending s - N lines of MIM 8620 case-hardened and MIM 100Cr6 hardened materials was undertaken to investigate the pure material behaviour as well as the effect of weld lines and notches.

- The filling and the formation of weld lines were numerically investigated with Mould Flow simulations.
- A twin-gated cavity was designed and built to shift the weld line into the notch root of unnotched and notched fatigue specimens according to DIN EN ISO 3928 with different notch radii r ($r=30 \text{ mm}$, $r=0.9 \text{ mm}$ and $r=0.45 \text{ mm}$) to investigate the interface strength.
- A sintered density of $\rho=7.4 \text{ g/cm}^3$ was achieved for all four specimen geometries and for both MIM steel grades.
- A case-hardening depth of $\text{CHD}_{550}=0.3 \text{ mm}$ was achieved on MIM 8620 case-hardened (measured on the unnotched specimen with the waist radius of $r=30 \text{ mm}$) which agrees with the requirements. The surface micro-hardness was estimated as $H_0=667 \text{ HV } 0.1$ and the core micro-hardness as $H_c=265 \text{ HV } 0.1$, respectively.
- MIM 100Cr6 hardened was through-hardened to a constant micro-hardness of $H_0=H_c=705 \text{ HV } 0.1=\text{const}$.
- Moreover, the macro-hardness H values are comparable ($H=631 \text{ HV } 30$ for MIM 8620 case-hardened vs $H=626 \text{ HV } 30$ for MIM 100Cr6 hardened). This indicates comparable surface carbon contents C_0 , because the maximum achievable surface hardness H_{max} (hardenability) depends only on the surface carbon content C_0 (and in the case of porous MIM and PM steel grades on the sintered density ρ).
- A systematic trend regarding the weld line position (single-gated vs twin-gated) tensile test specimens on the static tensile test results cannot be found. Differences between the two benchmarked MIM steel grades occur in the case of notches or other stress concentrations. The notch-strength ratios γ of MIM 8620 case-hardened are much better.
- Four complete Haigh diagrams (two MIM steel grades and two gate variants) and the corresponding Haigh damage lines were derived for the fatigue assessment and the fatigue lifetime prediction. The mean stress sensitivities M_2 and M_3 are high and all above $M_{2/3}=0.52$, due to the case-hardened or hardened surface condition.
- The unnotched Haigh damage lines of the two benchmarked

MIM steel grades are very similar. This means that the unnotched bending fatigue strength at the knee point σ_A values are comparable. This statement holds true for all of the three tested loading ratios R (R=-1, R=0 and R=0.5).

- Huge differences occur if notches are present. Similar to the static notch-strength ratios γ (axial loading mode), the cyclic notch factors K_f (bending loading mode) are much better for MIM 8620 case-hardened. Contrary to expectations, MIM 8620 case-hardened is not perfectly notch

presented to incorporate the effect of a single defect. After a calibration, the Murakami approach can be used to predict the bending fatigue strength at the knee point σ_A as a function of the micro-hardness H_0 and the projected defect area (AREA)^{0.5} in the first principal direction.

Due to their low and comparable alloying element contents of Cr+Ni+Mo=1.2% for the MIM 8620 material and of Cr+Ni+Mo=1.5% for the MIM 100Cr6 material, the raw material (feedstock) prices are almost comparable. A difference in the

strong advantage arises for MIM 8620 case-hardened in the presence of notches or other stress concentrations. In this case, and which is always the case for mechanical engineering components, MIM 8620 case-hardened exhibits much higher static and cyclic material properties. Therefore, the usage of MIM 8620 case-hardened is to be favoured against the usage of MIM 100Cr6 hardened.

Moreover, a clear HCF domain cannot be recognised for MIM 100Cr6 hardened. Therefore, MIM components made of MIM 100Cr6 hardened should be designed for LLF loadings only. The reliability of each MIM component will be enhanced from these findings, if the additional costs for a case-hardening treatment are accepted. The derived results must be examined carefully if the MIM component is subjected to rolling contact fatigue and wear.

Further static and fatigue experiments are planned for 2021 with MIM 17-4PH precipitation hardened and MIM 8740 hardened steels.

“A clear and very strong advantage arises for MIM 8620 case-hardened in the presence of notches or other stress concentrations. In this case, and which is always the case for mechanical engineering components, MIM 8620 case-hardened exhibits much higher static and cyclic material properties.”

sensitive, possibly because of the multilayer material structure (hard surface and soft core). This is remarkable because both surface micro-hardness H_0 values are comparable ($H_0=667$ HV 0.1 for MIM 8620 case-hardened vs $H_0=705$ HV 0.1 for MIM 100Cr6 hardened).

- Both MIM steel grades discussed are typically chosen for rolling contact fatigue and wear applications (Hertzian pressure loading mode/bearing applications). Those loading modes were not tested in this study. Therefore, there is an uncertainty as to how the tested bending loading mode correlates with the Hertzian pressure loading mode.
- An extension of the classical fatigue strength prediction was

production costs can be allocated to the different heat treatment strategies. The carburisation step during the case-hardening of the MIM 8620 material requires some extra time and a better controlled carburising atmosphere. As a rule of thumb, the heat treatment costs per kilogram for a case-hardening treatment are three times those for a more traditional hardening treatment. However, typical MIM components are small and low weight. Therefore, the additional costs for a case-hardening treatment will be a few euro cents more (the cost structure in general depends strongly on the component quantities to be produced and to be treated).

In essence, it can be summarised that both MIM steel grades (MIM 8620 case-hardened vs MIM 100Cr6 hardened) are very similar in the unnotched condition. A clear and very

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Perspectives on extrusion-based metal Additive Manufacturing: From bionic design to hollow structures and foams

Not so many years ago, the idea of taking a Powder Injection Moulding feedstock and adapting it to create filaments for use in an extrusion-based Additive Manufacturing machine would have sounded far-fetched. Today, however, a variety of sophisticated systems are available, along with metal and ceramic filaments from a range of manufacturers. Here, Dr Uwe Lohse, from XERION BERLIN LABORATORIES GmbH, considers how the unique combination of feedstock extrusion and sintering presents a range of component design concepts that enable previously impossible forms and functions.

Additive Manufacturing is penetrating ever further into numerous areas of industry. While it has already become widely used in plastics, other materials – not only metal and ceramics, but also construction materials and biological tissues – are becoming hotspots for further development.

With metals in particular, it is vital to ensure that additively manufactured components do not differ in any essential parameters from conventionally produced ones. Thus, in nearly all applications, a component density of > 99% of the theoretical value is desired, i.e. a density equivalent to the parameters achieved in wrought metallurgy, or that are possible in Metal Injection Moulding (MIM) when combined with a post-processing step such as Hot Isostatic Pressing (HIP). Likewise, the surface quality of metal AM parts must be comparable with that achieved by subtractive processes such as turning, milling or grinding. In most cases, a post-processing step such as polishing is obligatory.

This article presents an overview of some of the design opportunities presented by Material Extrusion (MEX), also known as Fused Filament Fabrication (FFF) or Fused Deposition Modelling (FDM). From the incorporation of 'bionic' design principles to the use of hollow cavities, it is now possible to design and manufacture

highly sophisticated components using MEX in far greater quantities than before and to tailor them to a far greater extent to a particular use.

When it comes to the application of bionic nature-inspired design principles, the concept is not to directly adopt natural structures

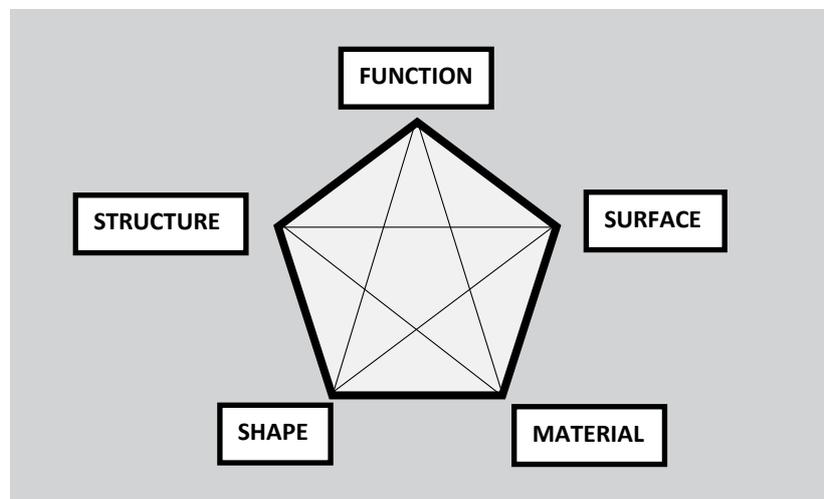


Fig. 1 To achieve the desired characteristics for metal AM parts, five major properties of the component to be manufactured need to be determined

within a technical application [1], but about looking for analogies and inspiration from the natural world in order to improve a component's performance and effectiveness. In this respect, the application of bionic principles to metallic components is justified. In biological structures, the tendency to minimise the metabolic energy required for growth is omnipresent. Closely related with this is a strict drive towards low-mass construction, meaning that many parallels with lightweight component design are apparent.

To achieve the desired characteristics for metal AM parts, five key component properties need to be

determined. This pentagon of properties is shown schematically in Fig. 1 and will be further explained below.

The MEX of metallic and ceramic components is well on its way to becoming an established process and, as with all processes, it has advantages and disadvantages. The process is particularly suitable for nature-inspired methods of manufacture as it allows extensive freedom in the choice of material and the design of the part's interior, such as internal features like hollow spaces or channels within the part.

After a part has been built by MEX using one of the many systems available on the market – some of which are 'open platform' to deploy

filaments from various manufacturers [2, 3] – a debinding and sintering stage is required. During this process parts will shrink by up to 20% by volume.

Materials for MEX

One of the advantages of extrusion-based Additive Manufacturing is the wide variety of materials that can be processed. In principle, it is possible to extrude a whole range of metal and ceramic powders. These have to be mixed with the right proportion of binders and shaped into filaments that can then be processed by MEX. Another decisive advantage is the complete use of the powder within the filament; 100% of the powder input into the process makes up the finished component, in contrast to powder bed processes such as Powder Bed Fusion (PBF) and Binder Jetting (BJT) where only selected parts of a layer of powder are used to form the final part. Table 1 shows a selection of materials that are currently available as filaments.

From this broad palette of metallic and ceramic materials, the intended application will inevitably drive material choice. Because of the various atmospheres required by these materials, sintering is best achieved using a multi-atmosphere sintering furnace. This makes it possible to process a range of materials for research or small series production [2].

Multi-material components

The manufacture of multi-material components can be achieved using MEX machines with two or more filament extrusion nozzles. The join between the two materials can be designed with relative freedom and does not have to run along a fixed plane, as is required in other processes. For multi-material component sintering, at least four of the physical parameters of the materials used must lie within the same ranges:

- Sintering temperature
- Sintering atmosphere
- Shrinkage
- Coefficient of thermal expansion

Material	Sintering temperature	Sintering atmosphere	Source
316L stainless steel (1.4435)	1,340–1,390°C	Hydrogen	[4,5]
17-4 PH stainless steel (1.4542)	1,320–1,370°C	Hydrogen	[4]
42CrMo4 heat treatable steel (1.7225)	1,300–1,330°C	Nitrogen	[5]
Titanium Ti6Al4V (3.7165)	1,100–1,400°C	High-vacuum	[4]
Alumina (Al ₂ O ₃)	1,475–1,650°C	Air	[4,6,7]
Zirconia (ZrO ₂)	1,450–1,500°C	Air	[4,6,7]
Silicon carbide (SiC)	2,100–2,200°C	Argon	[6]

Table 1 A selection of metal and ceramic materials currently available for MEX

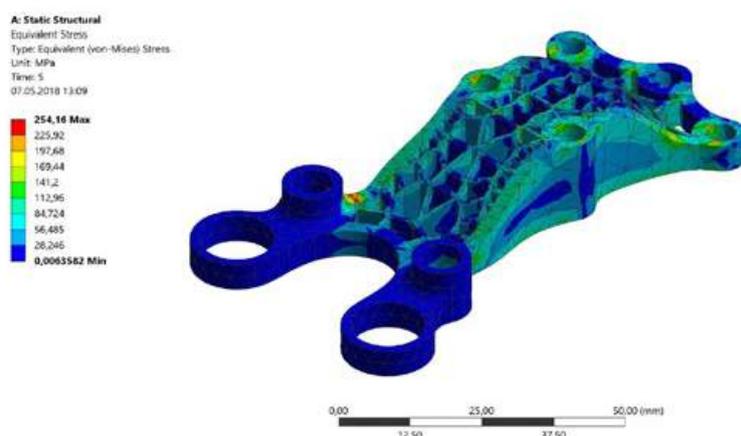


Fig. 2 Calculation of the von Mises stress in a 'bionically inspired' supporting element



Fig. 3 Supporting element manufactured by MEX in 17-4 PH stainless steel after debinding and sintering

These are challenging requirements, which is, in part, why such components cannot yet be manufactured on an industrial scale.

Unique part design opportunities

Because AM is a toolless manufacturing process, a wide degree of freedom is possible in designing the external shape of components. This freedom is already being used extensively, with a long list of example applications. As a rule, the shapes developed can often combine nature-inspired design principles with conventional approaches to lightweight construction. It is to be expected that components in such shapes will find ever wider use. In certain cases, they go against our habitual expectations for what a robust mechanical component looks like; for this reason, it is not only technical considerations that play a role in the use of these bionically inspired forms.

Internal spaces and cavities

A great advantage of MEX, in contrast to PBF, is the ability to manufacture closed hollow cavities. From this, it is also evident that it is extremely well suited to imitating the hollow or porous structures found in nature. Often, these can be achieved without the use of support structures. This

of such cavities, or macroporosity, is achieved in the build process itself and can thus be locally differentiated.

Microporosity as an opportunity

The sintering process can offer some interesting opportunities. Initially, sintering is perceived as a disadvantage by those new to the

“A great advantage of MEX, in contrast to PBF, is the ability to manufacture closed hollow cavities... Often, these can be achieved without the use of support structures.”

results in an extensive range of possibilities for determining the ‘macroporosity’ of components using filament-based processes.

To build hollow spaces within a component, the lower limit is one or two times the diameter of nozzle used, from 0.5–1.0 mm. The creation

various metal AM processing routes, with the impression that it ‘complicates’ the manufacturing process chain. However, what some see as a disadvantage can be turned into an advantage, with an example being managing sintering parameters to control microporosity.

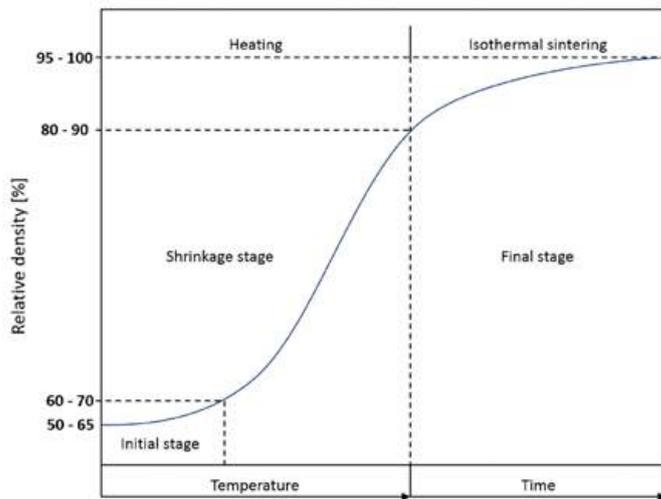


Fig. 4 Density changes during sintering (schematic) [8]

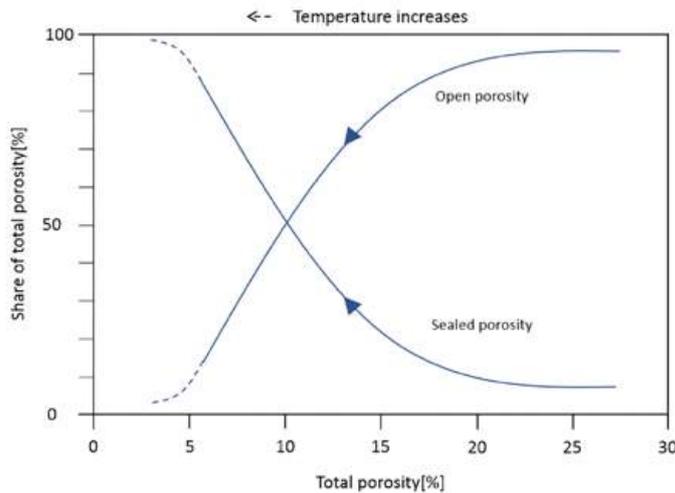


Fig. 5 Changes in open and closed porosity during sintering (schematic) [8]

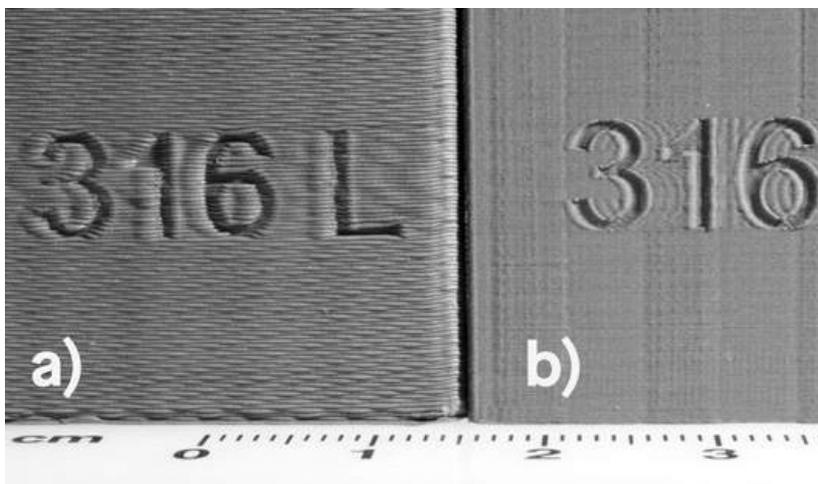


Fig. 6 Surface structure comparison of components built using a) a nozzle diameter of 0.8 mm and layer height of 0.25 mm, and b) a nozzle diameter of 0.4 mm and layer height of 0.05 mm

Here, sintering temperature and heating rate are the key parameters. If the sintering temperature is lowered, the sintering process will be 'incomplete' and the density of the component reduced. This can be advantageous, for example, for increasing the resistance to temperature changes of ceramics used in thermal applications. Naturally, this modification applies globally to the entire component. Fig. 4 shows how density is affected by sintering time and temperature and Fig. 5 shows the changes between open and close porosity during sintering.

There is particular potential here for the development of binder materials that can enable adjustments to post-sintered porosity or can be processed without shrinkage [9]. For this reason, in contrast to the routines developed so far, sinter-based Additive Manufacturing requires and makes it possible for completely new paths to be discovered. Only in this way can the full potential of this innovative manufacturing method be fully exploited.

Surface considerations

The design of surface structures is subject to relatively narrow tolerances. It is in the nature of all metal Additive Manufacturing processes that, to a greater or lesser extent, a rough surface results. This is particularly apparent in comparison with MIM, where the use of a highly-polished mould and the selection of finer powders can deliver extremely smooth surfaces.

With MEX, the structure of the surface can, to some extent, be managed. This can happen in two different ways. The first option is to set the build parameters in this area: for example, layer height, level of extrusion or speed of extrusion. The second option is to use multiple nozzle widths. For this, machines with two or four nozzle systems could be used. The use of a fine nozzle (e.g. with diameter of 0.4 mm) on the surface leads to a fine structure. For certain applications, of course, a coarser surface may be desirable, such as to make the surfaces of control elements non-slip.

Fig. 6 shows two different surface structures built using machines with a nozzle diameter of 0.8 mm and layer height of 0.25 mm and a nozzle diameter of 0.4 mm and layer height of 0.05 mm. The respective build times were 30 and 150 minutes.

To build infill structures, a much larger nozzle diameter can be used to speed up the process. Of course, there is also the option of using a surface made of a different material altogether, as described earlier in this article.

Functions that lead to applications

Hydraulic and pneumatic functions

The flow of fluids within structures is a well understood geological and biological principle. This is why it has been applied in the Additive Manufacturing of bionically inspired components from the very beginning. What can now be regarded as a 'classic' example of this is the production of cooling or flow channels close to the surface of a part, something traditional manufacturing processes can only achieve with enormous effort (Fig. 7). The MEX route is also well suited for this, even if it does have drawbacks when compared with binder jet Additive Manufacturing processes.

Electrical functions

The integration of electrical conductors in non-conductive matrices opens up huge possibilities; this principle is also inspired by the natural world. The MEX process is well suited for this, as it is intrinsically easy to build two different materials in parallel using extrusion-based processes. One approach is to combine 17-4 PH stainless steel as the conductor with zirconium oxide as the ceramic matrix [10]; this combination fulfils the requirements given earlier in this article for material pairings with the same sintering parameters. However, the stainless steel used is unsuitable as a heating element material for temperatures above 1,000°C. For



Fig. 7 Ring shower head with interior water channel and various nozzle exit angles (Courtesy Aloys F Dornbracht GmbH & Co. KG)

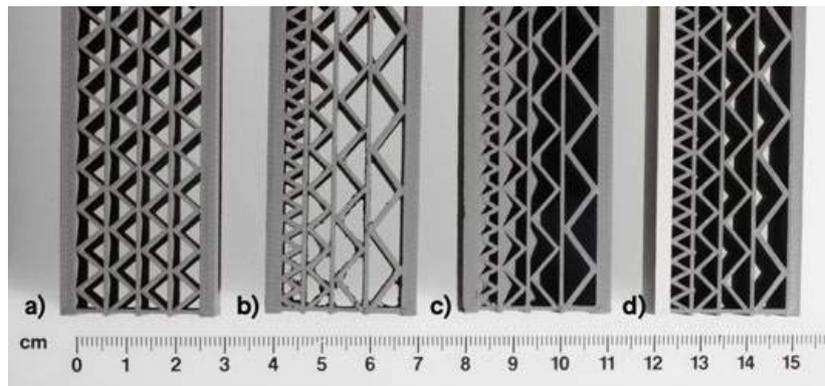


Fig. 8 Component evolution through design of hollow spaces and material selection, showing a) evenly distributed cavities, b) cavities whose size decreases from top to bottom, c) a variant with closed inner spaces, and d) a gradation in cavity size with a surface made of a different material, in this case aluminium oxide ceramic

this reason, rather than using 'pure' metal and ceramic materials for both components, filaments containing a blend of metal-ceramic mixtures can be used with gradual differentiation between each other. Combinations of tantalum and niobium are currently being tested [9].

Combining MEX's advantages

The MEX process allows a broad spectrum of options in designing components, as per the pentagon

of properties outlined earlier. Fig. 8 shows the four-stage evolution of a 17-4 PH stainless steel component design produced by MEX. In a) the cavities are evenly distributed, while in b) their size increases from the left. Both a) and b) have open cavities, while c) shows a variant with closed inner cavities. In variant d), alongside the gradation in cavity size, the surface is made of a different material, in this case an alumina oxide ceramic.

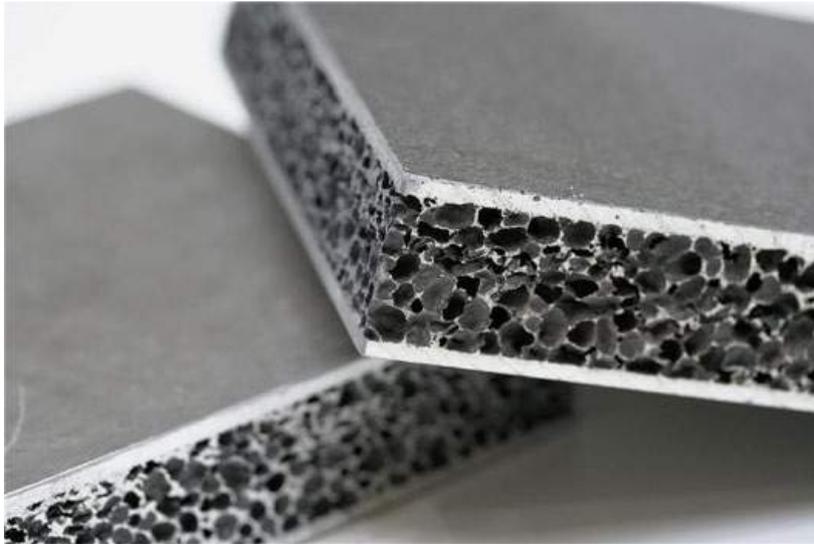


Fig. 9 Conventional closed-pore aluminium foam in a sandwich construction [Courtesy Fraunhofer IWU, Metallschaumzentrum Chemnitz]

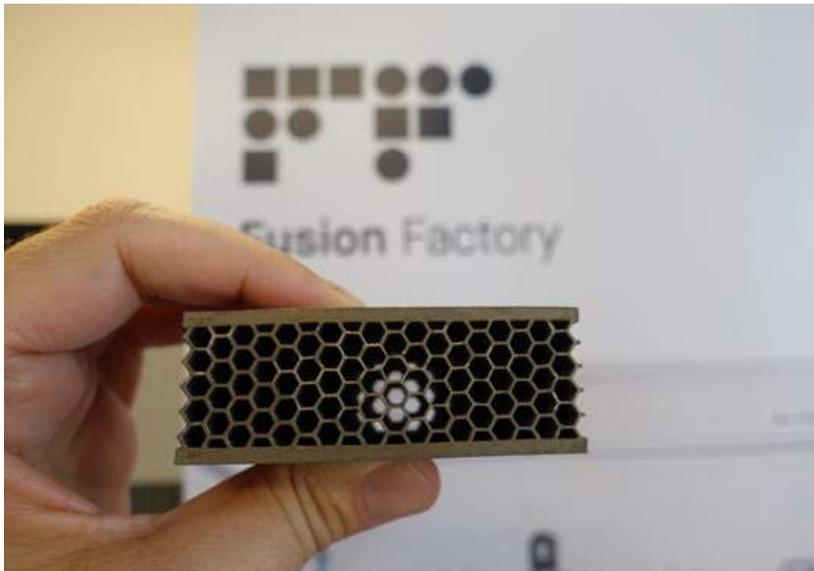


Fig. 10 Additively manufactured sandwich plate in stainless steel [Courtesy XERION]

**MEX metal foams:
combining open and closed
porosity in one component**

Metal foams are enjoying increased interest thanks to their range of applications, from use in industrial machines and automotive design to ballistic protection. Conventional manufacturing processes lead either to closed-pore or open-pore foams.

A combination of both types is only possible through joining at a later stage. For this reason, the MEX process is particularly useful as it allows the free but defined distribution of cavities or hollow spaces in the component. The closed areas can be clearly separated from those that allow through-flow and it is also very easy to integrate channels for liquid and gas entry into the component.

Outlook

Additive Manufacturing is far more than a new addition to the list of manufacturing technologies. On a far greater scale than previously possible, it allows the nature-inspired design of components. The type and means of manufacture almost inevitably leads to an organic approach. However, it is not to be ruled out that the inspiration may run in the opposite direction, with anthropogenic construction principles discovered at a later point in geological or organic structures. This occurred in spectacular fashion in the work of the visionary architect and mathematician R Buckminster Fuller [11]. It is to be expected that the various AM processes will change component design to a significant extent and this change will enormously increase the efficiency and ergonomic behaviour of human-made objects. To this end, it is necessary to ‘cast off the shackles’ of traditional habits of thought and perception and use the comprehensive possibilities of Additive Manufacturing to the fullest.

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Acknowledgements

Thanks to Tobias Stenzel and Florian Schulz for manufacture the samples shown in Figs. 3, 6, 7, 8 and 10.

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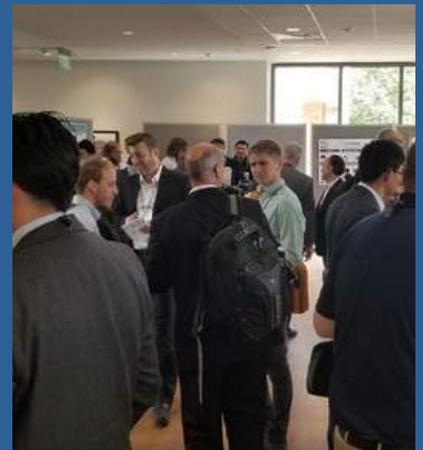
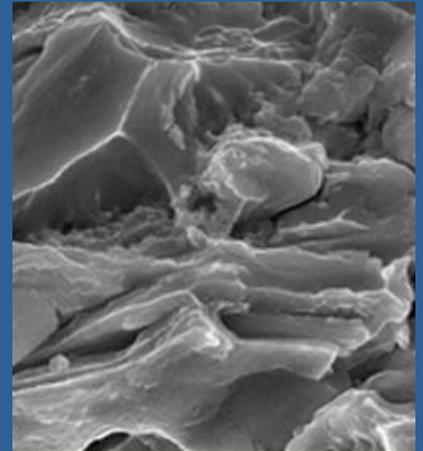
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How on-site gas generation supports the integration of sintering facilities into MIM and sinter-based AM operations

Metal Injection Moulding and industrial-scale sinter-based Additive Manufacturing facilities require a secure supply of industrial gases for use as sintering atmospheres. In addition to cost considerations, a strategic view needs to be taken of how these gases are supplied or generated, what infrastructure is required to store them, and what the risks are in terms of health & safety and supply stability. In this article, David Wolff, Stefan Joens, Bryan Sherman, Mike Montesi and John Boyle outline the challenges and the solutions.

Both Metal Injection Moulding and sinter-based metal Additive Manufacturing require a sintering step during which a functional, low-oxygen protective atmosphere, consisting of inert and active gases, must be used. These gases can be purchased externally or generated on-site.

MIM has an established and large market for the production of a wide variety of parts at high volumes worldwide, particularly in the consumer electronics, medical device, firearms and automotive sectors, to name just a few. When setting up any MIM operation, the integration of an on-site sintering facility is crucial, given the associated high production volumes.

Sinter-based metal AM, by contrast, is a more recent development that is receiving attention from parts manufacturers worldwide thanks to the unique geometric capabilities that the various processes offer, in parallel with their potential for low to medium production volumes without the need for tooling. Leading sinter-based AM

technologies currently include metal Binder Jetting (BJT) and Material Extrusion (MEX). The latter is the ISO/ASTM process category for material extrusion-based processes that are also referred to as Fused Filament Fabrication (FFF) or Fused Deposition Modelling (FDM).

Whilst MEX systems for metal parts fabrication are seeing rapid adoption for prototyping and small volume production, it is currently metal Binder Jetting that is seen as the most promising technology for medium and high-volume part production. In this process, a thin

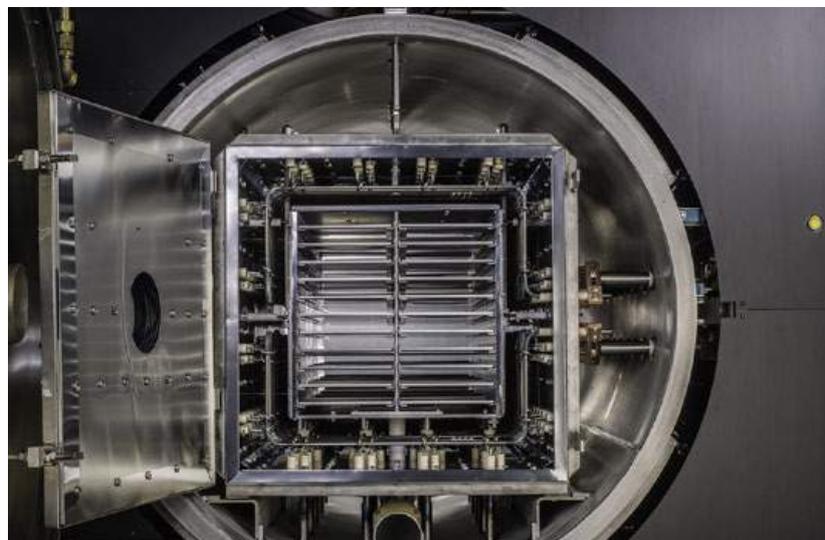


Fig. 1 An industrial-scale sintering furnace for MIM and sinter-based AM parts (Courtesy Elnik Systems LLC)



Fig. 2 An on-site nitrogen generator (Courtesy ON-Site Gas Inc.)

layer of metal powder is deposited onto a build platform and a binder jetted into the powder bed, causing selected areas of powder particles to be bound together in the desired geometry. A new layer of powder is then deposited and the process repeated, layer by layer, until the 'green' part is built. This green part must then be debound and sintered in order to achieve its full strength and density.

Whilst the sintering steps for MIM and sinter-based AM are more or less identical, with the volume of binder involved being the main varying factor, the lower production volumes expected for AM – at least in the near term – allow for alternative approaches to manage a company's sintering capacity requirements, including the use of off-site 'toll sintering' services.

Gas infrastructure considerations

A number of new MIM and sinter-based AM producers have emerged in recent years. Some are startups, whilst others are experienced sintering specialists or have a wide

range of other manufacturing expertise. The resulting new operations may be sited alongside an existing operation, or opened as a new, standalone facility. In most cases, these companies are having to add industrial gas supply infrastructure to buildings that did not previously have it.

When the need for a new sintering facility is decided upon, there are two ways to provide for the industrial gases required: they must be delivered and stored as a gas supply, or generated on-site. Which gases are required depends on the metal powder being processed. Hydrogen, used pure or blended with nitrogen or argon, is used in the sintering furnace atmosphere for a large proportion of MIM and sinter-based AM parts made from stainless steels, superalloys and copper alloys. Metals that react with hydrogen are sintered in pure nitrogen or argon.

In industrial locations, part producers might start their operations using gases delivered by an industrial gas supplier, with liquefied or compressed gases stored in a storage vessel on the user's site. Generally, the user in this case will enter into an industrial gas supply

contract with a local supplier. In less industrialised areas, this approach may not be possible, particularly for hydrogen and argon gas supply, as the local industrial gas industry may not be capable of providing a reliable gas supply and suitable storage equipment.

As an alternative, therefore, gas users may choose on-site gas generation. Of the three gases which may be used in the sintering of MIM and sinter-based AM parts, two – hydrogen and nitrogen – can be made cost-effectively on-site, eliminating the requirement for most or all gas storage. A summary of the advantages and disadvantages of delivered and on-site generated gas is presented in Tables 1 and 2.

Sintering gases overview

Argon

Argon has the fewest supply options. It comprises just 1% of the Earth's atmosphere, too low for cost-effective small-scale production, and cannot be generated on-site by users. It is often only widely available in highly industrialised locations and, where an operation requires this gas, it will generally use delivered liquefied argon stored in an on-site tank. Limited argon availability may mean that production lines for parts that may, for example, require Hot Isostatic Pressing (HIPing) in argon as a post-processing step might be best suited to geographies where argon is readily available.

Nitrogen

Nitrogen comprises 78% of the Earth's atmosphere and liquefied nitrogen is made worldwide in large air-separation units. The use of delivered liquid nitrogen can be a great way to start a new sintering facility – low fixed-cost tank rental and acceptable product cost are ideal for the early, low-volume startup stage. Customers charges for delivered nitrogen typically include the cost of the gas, storage rental and various fees associated with delivery.

Once a process is operational and a company's nitrogen requirements have become relatively steady and well understood, nitrogen users may wish to progress from delivered and stored liquid nitrogen to on-site nitrogen generation in order to reduce costs (Fig. 2). On-site nitrogen generation uses specially designed equipment to adsorb and remove non-nitrogen impurities from compressed air, providing an inert pressurised gas stream comprising a blend of nitrogen with about 1% argon plus low amounts of oxygen, water and carbon dioxide. Since argon is even more inert than nitrogen, for most applications the inclusion of 1% argon is not a problem, but users should ensure that this small amount of residual argon in on-site generated nitrogen does not create an issue in their particular application.

The purity of nitrogen produced by on-site equipment can be specified when the equipment is procured. For on-site nitrogen generation, the lower the purity required, the more cost savings are available compared to cryogenically-generated, delivered and stored nitrogen. Most sintering operations use nitrogen at 99.99% or higher purity. On-site generated nitrogen can save up to 75% of costs as compared with delivered bulk liquid nitrogen and it is not unusual to see a one- or two-year payback with on-site nitrogen generation equipment.

Some companies choose to use both supply options, using liquid nitrogen for the processes at their site that require the highest purity and using less pure nitrogen generated on-site to supply the purging, inerting and pressurisation that often comprises the bulk of the nitrogen volume consumed in a thermal processing facility. This 'hybrid' approach can ensure the highest quality results at the lowest overall costs, but users should be aware that this approach requires two sets of nitrogen distribution piping – one for low-purity nitrogen and a smaller header system for the few high-purity nitrogen requirements. Users with a

DELIVERED GAS	Advantages
	Delivered gas is flexible in use rate if the actual usage schedule and flow rate requirements are not yet understood
	The startup capital cost with delivered gas may be relatively low, especially for nitrogen and argon
	Delivered gas can be treated as a utility – a convenience that is necessary for operation
	Disadvantages
	Supply chain risk – will the truck show up?
	Customers may be required to enter into a multi-year gas supply contract with specific terms and requirements – ensure that you understand the contract before signing
	The supply chain of gas production, delivery and storage is expensive, resulting in high costs for both the rented storage equipment and for the gas(es)
	Infrastructure for gas delivery, storage and gas distribution at a customer's site must be paid for by the customer – adding large up-front costs that are fixed to the site and unrecoverable
	Hydrogen delivery and storage can be a particular challenge because local safety authorities are concerned about large volumes of a hazardous material in their community
The large area of space required for the gas delivery and storage area and the required 'safety zone' surrounding the storage (especially for hydrogen)	

Table 1 Advantages and disadvantages of traditional, delivered gas

ON-SITE GAS GENERATION	Advantages
	Eliminates supply chain risk for industrial gas supply off-site production and delivery
	Often less expensive and complex to install, as it eliminates the need for gas delivery and storage infrastructure and simplifies gas piping, by producing gas nearer its point of use
	Eliminating the safety compliance issues that are a particular challenge with stored hydrogen
	Predictable pricing and no gas contract to deal with
	Gas cost will drop as your usage rises, due to the benefit of fixed-cost generation equipment
	Significant gas cost savings are possible, especially for generating nitrogen
	Much less space is required, due to elimination of the safety buffer required for stored hydrogen
	Gas generation equipment is easily relocatable if a gas user moves to a new building
	Challenges
	Customer must understand the requirements of their use, to define the capacity and characteristics of the gas generation equipment required – flow rate, purity and pressure
	Must provide facility space and utilities for installing gas generation equipment in your building
	Must properly maintain gas generation equipment to ensure reliable gas generation

Table 2 On-site production offers several advantages (and some challenges)



Fig. 3 An on-site hydrogen generator (Courtesy Nel Hydrogen)

gas contract will need to negotiate the contract implications of this approach with their industrial gas supplier, as many standard gas contracts are based on 100% of requirements and specifically prohibit self-generation.

Hydrogen

Hydrogen is required for the successful sintering of many parts in MIM and sinter-based AM. It is widely used as a furnace atmosphere component in thermal

appearance. In metal powder-based processes such as MIM and sinter-based AM, hydrogen acts to protect the powder particles, ensuring a bare, oxide-free surface that contributes to successful sintering. Hydrogen may be used in a continuous furnace, or, together with vacuum, in a batch furnace.

It is, however, more challenging to add hydrogen gas to a facility than to add argon or nitrogen. While argon and nitrogen are inert, hydrogen is

“While argon and nitrogen are inert, hydrogen is highly flammable, leak-prone, has a low activation energy and very high chemical energy content. A single hydrogen cylinder contains the energy equivalent of 15 kg of TNT.”

processing operations because, in a high-temperature, low-oxygen environment, it will ‘clean’ the surface of parts undergoing thermal treatment, enhancing processing and

highly flammable, leak-prone, has a low activation energy and very high chemical energy content. A single hydrogen cylinder contains the energy equivalent of 15 kg of TNT.

Because of these risks, the storage and use of hydrogen is governed by a web of overlapping regulations and authorities. In most industrialised locations, local government plays a key role in permitting or prohibiting the storage and use of hydrogen. In the US, the relevant National Fire Protection Association (NFPA) standards generally define a local ‘Authority Having Jurisdiction’ – AHJ. The AHJ is the organisation which can permit, or prevent, the use of hydrogen. In the US, your AHJ may be your local fire marshall.

The AHJ will require compliance with recognised codes and standards for construction and operation of hydrogen-utilising systems. In the US and Canada, that means NFPA and American Society of Mechanical Engineers (ASME) Fuel Gas codes. Companies should be careful to do things right and meet these codes and standards the first time they apply for AHJ approval, as it may be difficult to appeal a negative decision.

Beyond the local AHJ, a company’s plan to use hydrogen will be of interest to its insurance provider. Depending on the current risks at a company’s facility, the addition of hydrogen may meaningfully change its risk profile. However, since it is widely accepted that storage drives risk, on-site hydrogen generation may be considered safer.

The risks of hydrogen are primarily around its tendency to leak, due to its extremely small molecule size, and its explosivity. Hydrogen has different physical characteristics to many gases of more widespread use – it is lighter than air, so tends to collect on the underside of roofs, where it may not be immediately noticeable, and, because it has no colour or odour to aid in leak detection, a leak may go undetected for some time. Hydrogen safety in thermal processing facilities generally uses a combination of carefully designed exhaust systems and hydrogen sensors, interlocks and alarms.

The EPA defines hydrogen as a Highly Hazardous Chemical requiring additional care and scrutiny in storage and use. Amounts of hydrogen over

a certain threshold quantity require specific reporting to both EPA and OSHA at the Federal level, as well as required local and regional reporting.

The primary means utilised to ensure the safety of stored hydrogen is to maintain a large enough distance between hydrogen storage and any operation, facility or neighbour. This way, if a fire or energy release does occur, injuries will be prevented and facility damage will be minimised. Unlike nitrogen and argon bulk storage, which may be located in close proximity to a building, bulk hydrogen storage is required to be located remotely from buildings and generally away from parking, roads, site boundaries and areas of assembly. This means that storing hydrogen requires a larger site and considerably more space than would be needed if hydrogen were not stored.

If hydrogen storage is required, a site for a new MIM or sinter-based AM operation must offer sufficient space to enable hydrogen storage at a safe distance and underground hydrogen piping must be installed from the hydrogen tank to the building. It can be especially challenging to store hydrogen for operations located in leased, urban, old or crowded facilities, as well as sites such as business incubators and science parks. Many new metal AM operations are set up in leased facilities, but rental landlords are averse to hydrogen storage; not only is the tenant digging up their parking area to run piping, but it is taking parking spaces and restricting use of part of the real estate. Additionally, and worse yet, the delivery of hydrogen requires that a wide area for truck trailer manoeuvring be provided, further reducing parking availability. The necessity for hydrogen storage can turn a manufacturer into an undesirable tenant.

Delivered industrial gases must be distributed to a building and, within the building, they must be transmitted from the storage vessel to the point(s) of use. For stored hydrogen, where the storage vessel must be remote from the building to

Line size	Estimated cost per metre in the US			
	Copper	316 stainless steel, Industrial Grade	316 stainless steel, UHP Grade	Underground added cost
20 mm (1/2") ODT	\$100-115	\$190-225	\$270-320	\$160-195
25 mm (3/4") ODT	\$145-175	\$275-300	\$410-450	\$190-240
32 mm (1") ODT	\$190-225	\$335-370	\$480-510	\$250-320

Table 3 Piping cost comparison table (Courtesy John Boyle)

comply with safety regulations, piping costs can be high. The cost per metre of installed piping varies, based on location, line size, pressure, joining methodology and construction material, but can range from \$110 per metre to as high as \$320 per metre for corrosion-protected underground piping. These costs are unrecoverable (Table 3).

Unlike hydrogen delivery and storage, zero-inventory Proton Exchange Membrane (PEM) water electrolysis hydrogen generation can

Hydrogen generators that bear 'Nationally Recognized Testing Laboratories' (NRTL) markings such as TÜV, UL, CSA and other NRTL authorised certifiers will be easier and faster to permit with local AHJs and will reassure insurance providers. CE certification can be helpful as well.

Consider the differences between hydrogen delivery and storage, and PEM onsite hydrogen generation. Each delivered 16.5 MPa (2,400 psig) hydrogen

“Unlike hydrogen delivery and storage, zero-inventory Proton Exchange Membrane (PEM) water electrolysis hydrogen generation can be installed in any building – owned, leased, urban or shared – with minimal interior infrastructure requirements...”

be installed in any building – owned, leased, urban or shared – with minimal interior infrastructure requirements and without foundations, underground outside piping, fencing and security, or restrictions on parking. In general, indoor piping will be short, because the hydrogen generator can be located nearby to the process.

compressed gas cylinder contains 35 to 53 m³ (200 to 300 SCF, Standard Cubic Foot) of hydrogen with enormous chemical and kinetic energy. These cylinders are handled routinely during swap-outs by personnel who may not be highly trained and may be unaware of the hazards. Cylinders are particularly tricky because they are often stored

and handled indoors – bringing the associated risks of high-pressure hydrogen indoors.

Further, a compressed hydrogen tube bank or tube trailer installation may contain from 3,500 to 21,300 m³ (20,000 to 120,000 SCF) of hydrogen. Liquid hydrogen storage starts at about 35,000 m³ (200,000 SCF) of hydrogen. This volume of hydrogen, if released inside a facility due to a component failure or piping leak or damage, will rise to ceiling level, pool across the ceiling until it reaches an ignition source, ignite and potentially level a plant.

A PEM electrolysis hydrogen generator, suitable to replace hydrogen supply as large as served by a liquid hydrogen tank, contains less than 1.2 m³ (7 SCF) of hydrogen, at under 3.4 MPa (500 psig). Because the maximum rate of hydrogen supply is limited by the hydrogen generator capacity, it is much harder to overwhelm building exhaust ventilation and collect an ignitable amount of hydrogen in the facility.

Conclusion

The establishment of effective sinter-based AM and MIM production requires the use of industrial gases appropriate to the materials being processed and the anticipated production volumes. If these gases

are being added to a facility that has not employed industrial gases previously, a manufacturer must factor its supply considerations into the facility project plan and make industrial gas supply decisions that best support its implementation plans.

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Industry events

If you would like to see your PIM/MIM/CIM-related event listed in this magazine and on our websites, please contact Kim Hayes, email: kim@inovar-communications.com. We welcome enquiries regarding media partnerships and are always interested to discuss opportunities to cooperate with event organisers and associations worldwide.

2020

Euro PM2020 Virtual Congress [DIGITAL]

October 5–7, 2020
www.europm2020.com

Formnext Connect [DIGITAL]

November 10–12, 2020
www.formnext.com

2021

MIM2021 [DIGITAL]

February 22–25, 2021
www.mim2021.org

5th Additive Manufacturing Forum Berlin 2021

March 11–12, 2021
 Berlin, Germany
www.am-forum.eu

METAV

March 23–26, 2021
 Düsseldorf, Germany
www.metav.com

Hannover Messe – Home of Industrial Pioneers

April 12–16, 2021
 Hannover, Germany
www.hannovermesse.de

RAPID + TCT

April 26–29, 2021
 Chicago, Illinois, USA
www.rapid3devent.com

Ceramics Expo 2021

May 3–5, 2021
 Cleveland, Ohio, USA
www.ceramicsexpousa.com

Ceramitec 2021

May 17–20, 2021
 Munich, Germany
www.ceramitec.com

PM China 2021

May 23–25, 2021
 Shanghai, China
www.pmexchina.com

AMPM2021

June 20–23, 2021
 Orlando, Florida, USA
www.ampm2021.org

PowderMet2021

June 20–23, 2021
 Orlando, Florida, USA
www.powdermet2021.org

Tungsten2021

June 20–23, 2021
 Orlando, Florida, USA
www.tungsten2021.org

EPMA Powder Metallurgy Summer School

July, 2021 (Dates TBC)
 Ciudad Real, Spain
www.summerschool.epma.com

Formnext + PM South China 2021

September 9–11, 2021
 Shenzhen, China
www.formnext-pm.com

PMTi2021

September 15–17, 2021
 Montréal, Canada
www.pmti2021.org

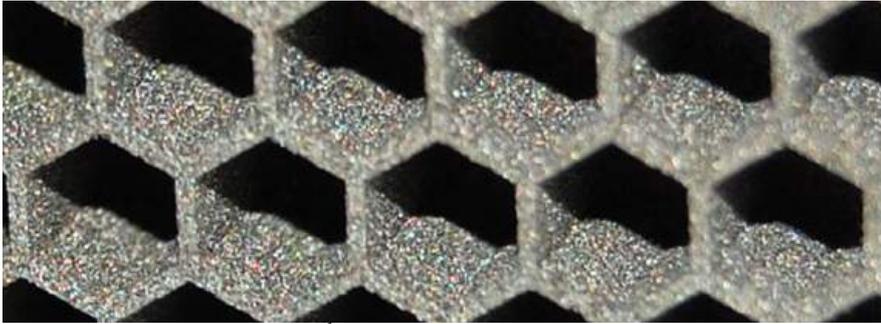
AMTC 2021

October 12–14, 2021
 Aachen, Germany
www.amtc.community/amtc/en/

Euro PM2021

October 17–20, 2021
 Lisbon, Portugal
www.europm2021.com

Call for Papers & Posters



TECHNICAL PROGRAM

Three advanced manufacturing conferences under one roof (AMPM2021—Additive Manufacturing with Powder Metallurgy; PowderMet2021—International Conference on Powder Metallurgy and Particulate Materials; and Tungsten2021—International Conference on Tungsten, Refractory & Hardmaterials) will provide attendees with access to over 200 technical presentations from worldwide experts on the latest research and development.

TRADE EXHIBIT

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SPECIAL CONFERENCE EVENTS

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November 13, 2020

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