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FOR THE METAL, CERAMIC AND CARBIDE INJECTION MOULDING INDUSTRIES

POWDER INJECTION MOULDING INTERNATIONAL

in this issue

BASF: Perspectives on PIM

Company profile: Silcon Plastic

Advances in continuous furnaces

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For the metal, ceramic and carbide injection moulding industries

Innovation set to drive global growth

Welcome to the September 2016 issue of *PIM International*. At 112 pages, this is our biggest issue yet and we are excited to be able to present it at the World PM2016 Congress and Exhibition in Hamburg.

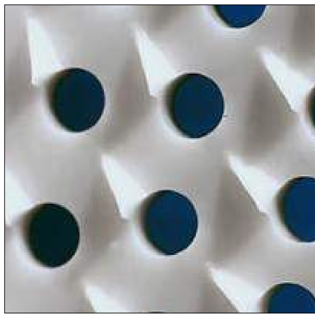
The return of the PM World Congress series to Europe is always an important occasion for the region's PIM community, with so many of the industry's leading materials and technology suppliers based on the continent. What is clear from this issue is that there continues to be a strong drive for innovation in the industry, with materials and technology suppliers working with parts makers to expand the market by pushing PIM's capabilities.

A major area of growth in recent years has been in smartphone applications and there is a belief that there are many new application opportunities in this dynamic market. As one example of the potential of the technology, two leading industry suppliers, BASF SE and Arburg GmbH + Co KG, will be producing prototype smartphone frames and back plates in the World PM2016 exhibition hall.

Such applications, combining large shapes with thin wall sections and the requirement for a perfect surface finish push the capabilities of the technology to new limits. Suppliers are, of course, seeing the opportunities and pressing ahead with innovations. In terms of feedstock, BASF states that it is developing the next generation of its catalytic binder system in order to support the industry's expansion into new markets (page 53). The latest innovations in continuous debinding and sintering furnaces are also presented, dispelling many of the misconceptions that surround continuous debinding and sintering equipment (page 73).

Nick Williams
Managing Editor

Cover image
The final polishing of an injection moulding tool at Silcon Plastic



In this issue

Industry News

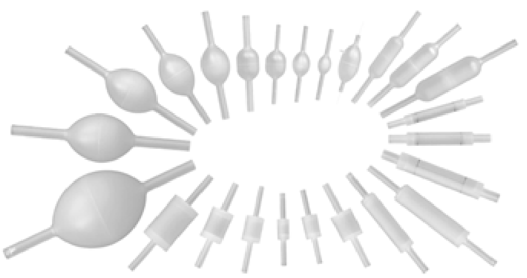
To submit news for inclusion in *Powder Injection Moulding International* please contact Nick Williams, nick@inovar-communications.com

CoorsTek acquires Philips' CIM operation in Uden

CoorsTek, the world's largest engineered ceramics manufacturer headquartered in Golden, Colorado, USA, has acquired Philips' Ceramic Injection Moulding operation in Uden, The Netherlands. Through this acquisition CoorsTek is expanding its ongoing strategic partnership with Philips and will serve both Philips' and other regional customers from Uden."The integration of Uden's people, equipment and technology into CoorsTek extends our regional presence and capabilities even further – a natural fit and complement to our advanced ceramics expertise," stated Timothy Coors, Co-CEO of CoorsTek.

Adding Uden extends the CoorsTek footprint to a dozen European manufacturing locations in the Czech Republic, England, Finland, Germany, Italy, Netherlands, Norway, Scotland and Sweden. "The Uden team will help support our expanding customer base across Europe and around the world," stated Andreas Schneider, Executive VP of CoorsTek in Lauf, Germany. CoorsTek serves over 10,000 technology and manufacturing customers in seventy countries, delivering local service from its network of fifty locations on four continents.

"CoorsTek has known and respected Philips and Uden for decades," added Schneider. "Combining Uden's sixty years of engineering know-how and manufacturing capabilities with the ceramics expertise CoorsTek has developed over the past century – it is a great opportunity to push the frontiers of technology and help make the world measurably better." Using advanced Ceramic Injection Moulding and automated high volume manufacturing, Uden can produce millions of high-purity ceramic parts each year.



CIM translucent alumina burners made by Philips Lighting Uden for HID lighting applications (left). The pre-CIM designs, made by extrusion, are shown on the right

As a part of Philips, Uden was focused primarily on supporting the company's market-leading global lighting business. In addition to securing an exclusive, long-term agreement to supply Philips Lighting, CoorsTek will use these capabilities to serve a broader set of customers and applications beyond lighting, including automotive, electronics, and medical. "Together with our Uden colleagues, the CoorsTek team will help even more companies create and deliver amazing solutions to some of their toughest challenges," concluded Coors.

www.coorstek.com

Leading US MIM producer Phillips-Medisize to be acquired by Molex LLC

Phillips-Medisize Corporation, a provider of design, development and manufacturing services for the medical industry, announced on August 17th that it had entered into a binding agreement to be acquired by Molex LLC. Phillips-Medisize is also one of North America's largest MIM producers and a portfolio company of San Francisco based Golden Gate Capital, a US private equity investment firm with approximately $15 billion of capital under management.

Molex designs and manufactures electronic, electrical and fibreoptic systems, employing over 40,000 people in more than 40 countries. "Molex and Phillips-Medisize share a similar culture and approach to managing the business that creates strong partnerships built on quality and innovation," said Matt Jennings, Chairman, President and CEO of Phillips-Medisize. "Molex's global scale in electronics, coupled with Phillips-Medisize's strength in designing and manufacturing innovative products for medical device customers, will help us become a global leader in connected health solutions."

"Phillips-Medisize has a talented, experienced and innovative team that has strong customer relationships because of its outstanding ability to serve the unique needs of the medical solutions market," stated Tim Ruff, Senior Vice President of Business Development and Corporate Strategy, Molex LLC. "Combined with Molex's expertise in electronics and broad global manufacturing presence, we are confident that together we can significantly expand our medical solutions capabilities globally."

MIM parts made by Phillips-Medisize

Rajeev Amara, a Managing Director of Golden Gate Capital, stated, "In just three years of our ownership, Phillips-Medisize has executed on a transformative vision to become a global leader in the manufacturing of biologics drug delivery devices. We would like to thank all the employees for their hard work and wish them well in the future." Terms of the transaction were not disclosed.

www.phillipsmedisize.com

Alpha Sintered Metals acquires MIM producer Precision Made Products

Private equity firm O2 Investment Partners announced in June that its portfolio company, Alpha Sintered Metals, headquartered in Ridgway, Pennsylvania, USA, has acquired Precision Made Products (PMP), a Metal Injection Moulding business based in Brunswick, Ohio, USA. Terms of the deal were not disclosed.

Founded in 2002, PMP is an established MIM business with CNC machining capability serving the medical, aerospace and firearms markets. Due to certain proprietary elements of its MIM manufacturing process, PMP claims to have significantly shortened the debinding and sintering cycles which creates advantageous product characteristics including low shrinkage rates, better shape stability and very tight tolerances.

Alpha Sintered Metals, LLC is a global manufacturer of high-precision Powder Metallurgy components and assemblies for the automotive, small engine, recreational vehicle, commercial vehicle and agricultural equipment industries. With specialties in high density stainless steels and steel alloys, Alpha has a rich heritage in providing a diverse customer base with innovative material and process solutions for the most demanding applications. "I was seeking a strategic partner that could help us take PMP to the next level. Alpha's experience in powder metal manufacturing coupled with our MIM technology will create exciting opportunities for the future," stated Majid Daneshvar, founder and CEO of PMP.

JoAnne Ryan, CEO of Alpha Sintered Metals agreed, noting "Partnering with PMP will allow us to expand our capabilities, enhance our market position and enter new markets. MIM is an important part of our growth strategy and we are very excited to be partnering with Majid and the PMP team."

Jay Hansen, Managing Partner of O2 Investment Partners, added, "Majid and his team are well respected within the industry and we are excited to work with them going forward. PMP's continuous innovation made it an excellent fit for the Alpha platform and our long-term strategic plan."

www.o2investment.com
www.alphasintered.com
www.pmp-tech.com

PMP manufactures a wide range of MIM components

MIM in China: 2015 MIM part sales estimated at US $725 million

The 2015 China Metal Injection Moulding Industry Status Report, published by the Powder Metallurgy Branch Association of the China Steel Construction Society, provides invaluable insight into the recent development of China's Metal Injection Moulding industry.

Sales of MIM parts were reported to be in the region of CNY ¥4.85 billion (US $725 million), of which sales of CNY ¥3.25 billion (US $485 million) are generated by just five producers or group companies that share 67% of total sales. It was stated that fifteen companies have sales in excess of CNY ¥40 million (US $6 million). The remaining MIM producers were described as small scale.

The report stated that there are now more than 130 MIM part producing companies in China, excluding Taiwan. Of these, the Pearl River Delta is home to 65 producers, the Yangtze River Delta 35 producers and the Beijing, Tianjin, Hebei and Shandong regions 20 producers. The balance of MIM part producers is located in Hunan and other regions.

In terms of application areas, mobile/smartphone parts are the largest market for Metal Injection Moulding in China, followed by computer parts, wearable devices, automobile parts, medical instruments and parts for hardware and power tools, etc.

Material consumption and trends

The total shipment of materials (powders and feedstock) for Metal Injection Moulding was given as between 6,000 and 7,000 tons. The report stated that market share is divided equally between domestic and foreign brands. It was estimated in the report that between 3,000 and 3,500 tons of foreign feedstock was imported in 2015. It was also stated that there are eight domestic producers of MIM powder, each with production capacities in excess of 100 tons per year.

In terms of domestic MIM feedstock production, there are nine manufacturers producing a total of between 800 and 1,000 tons of feedstock per year. The most widely processed MIM materials in China are stainless steels and low alloy steels, accounting for 85% of production. Of the stainless steels, 316L and 17-4PH are the dominant alloys. Tungsten-based materials account for 10% of production, with cemented carbides, copper-based alloys and titanium alloys accounting for the remaining 5%.

It is expected that there will be a diversification of MIM materials in the near future, including nickel free stainless steel, non-magnetic alloys, aluminium alloys and high thermal conductivity alloys.

Industry outlook

The report anticipates that China's Metal Injection Moulding industry will continue to experience high levels of growth, stating that ever more products are being designed as MIM components. As a relatively new precision forming technology, new materials and innovative designs will lead to an expansion of the market for MIM products. It was stated that the technology in China is developing rapidly in response to increasing customer requirements. As a result, both the size and levels of precision of Chinese MIM products are expected to increase.

The largest market for the Chinese MIM industry is the consumer electronics sector. It is expected that automotive, wearable devices and medical instruments sectors will grow significantly.

As the size of the Metal Injection Moulding industry in China continues to increase, it is anticipated that the number of enterprises will, at the same time, decrease steadily because of competition and changes in end-user markets. However, whilst the industry will gradually become more concentrated, the report stated that there will still be opportunities for small, innovative enterprises.

In terms of production technology, the report states that there will continue to be a steady improvement in the quality of domestic production equipment for Metal Injection Moulding, including vacuum sintering furnaces, catalytic debinding systems and feedstock mixers. Exports of these products are also expected to increase. It was stated that the production and development of continuous sintering furnaces in China will also increase.

www.cncscs.org/english/about5.asp

APMA 2017 conference to be held in Taiwan

The 4th International conference on Powder Metallurgy in Asia (APMA 2017) will be held in Hsinchu, Taiwan, from April 9-11, 2017. The event will be organised by the Taiwan Powders and Powder Metallurgy Association. Previously held in Jeju (Korea) in 2011, Amoy (China) in 2013 and Kyoto (Japan) in 2015, the APMA 2017 conference will showcase the capabilities of the Asian Powder Metallurgy industry through technical papers, which will update R&D and recent industry developments and trends.

Professor Kuen-Shyang Hwang, National Taiwan University, is organising the sessions on Powder Injection Moulding. There will also be an exhibition as part of APMA 2017.

apma2017.conf.tw

Metal Injection Moulding in North America: Growth slowed in 2015

In the Metal Powder Industries Federation's annual state of the industry address at POWDERMET2016, June 5-8, Patrick J. McGeehan, MPIF President, stated that North America's MIM industry has managed to sustain modest growth despite a slow-down in the key firearms market.

"Slower growth impacted the US MIM industry in 2015 mainly due to the decline in the domestic firearms market. The annual North American powder market is estimated to range from 1.2 to 1.6 million kg. The decline in the firearms market that began during late 2014 impacted 2015 powder demand. Despite this, 2015 MIM parts sales still grew modestly in the lower-single digits," stated McGeehan.

The 2015 decline in firearms sales drove a shift in the market mix for Metal Injection Moulded parts. By weight of parts shipped medical/dental became the leading MIM market at 32%, followed by general industrial (26%), firearms (21%), automotive (7%), electronics (6%) and miscellaneous applications (6%). Automotive, aerospace and cutting tool applications were reported as key growth areas.

"While the firearms market declined in 2015, knowledgeable observers forecast the market increasing in 2016 to a more normal growth pattern, or possibly spiking again. Recent mass-casualty shootings in North America have impacted firearms sales as citizens seek personal protection options and react to proposed tougher gun controls. Overall, the majority of members of the Metal Injection Molding Association (MIMA) forecast business increasing in the 5%–10% range in 2016," added McGeehan.

It was also reported that the Hot Isostatic Pressing (HIP) business experienced strong growth in demand for the densification of Metal Injection Moulded parts. All powder-related applications, including canned powder shapes, MIM and metal Additive Manufacturing, account for an estimated 20% to 25% of the North American HIP business, with the balance going to castings. The region's HIP industry, it was stated, recently added a substantial amount of new capacity to meet increasing demand through 2018.

Taking a broader view of the North American Powder Metallurgy industry, McGeehan stated, "The entrepreneurial spirit still rings true in the PM industry and confidence remains strong within executive offices and on the shop floors in the majority of PM industry companies. Following a healthy 2015, the year opened on a positive trend with modest growth forecast by most informed observers. Conventional press-and-sinter companies and metal powder producers report good business levels, as well as companies involved with Metal Injection Moulding, metal Additive Manufacturing and Hot Isostatic Pressing. The demand for refractory metals, however, has continued to decline."

www.mpif.org

Metal Injection Moulding in Japan: Growth anticipated after a poor 2015

The Japan Powder Metallurgy Association (JPMA) has reported that sales of MIM parts decreased slightly in 2015 compared with the previous year to reach Yen 10.547 billion (US $99.5 million). This compares with the highpoint of Yen 11.952 billion (US$ 112.8 million) reached in 2010 (Fig. 1).

The data is based on the JPMA's latest annual survey of 21 leading MIM parts producers in Japan. However, respondents to the JPMA survey also indicated that Metal Injection Moulding sales would increase over the next two years, reaching Yen 10.743 billion in 2016 and Yen 11.238 billion in 2017.

A breakdown of the application areas for Metal Injection Moulding in Japan showed that the Industrial Machine segment remained the largest single sector with a 23.5% market share (down slightly on the previous year), followed by medical appliances which was up one percentage point to 19.3% (Fig. 2, left).

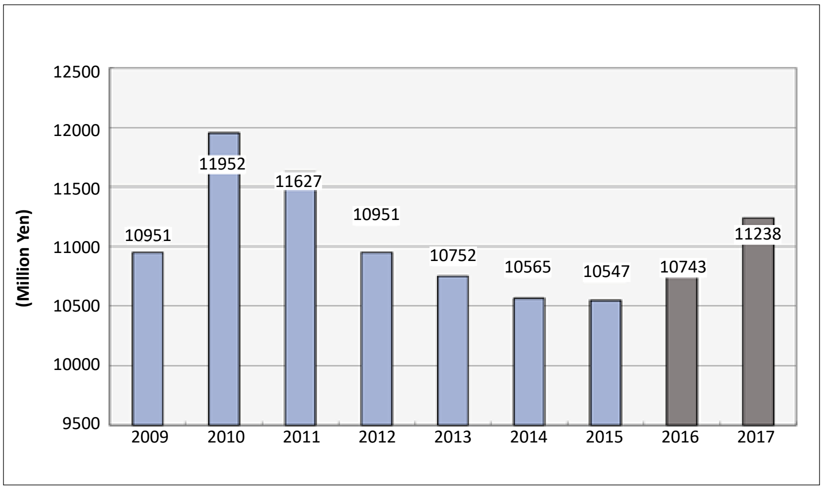


Fig. 1 MIM sales in Japan. FY2009-2015 are results, FY2016-2017 are estimated (Courtesy JPMA)

The automotive and motorcycle sectors have been evaluated separately and show market shares of 17.4% and 6.3% respectively, with the motorcycle sector showing a 2.5% gain over the previous year but the automotive sector showing only a 0.1% increase. The share of the Information Technology sector was shown to be down slightly at 10.7% of the market compared with 11.2% the previous year.

Stainless steel powders still dominate the materials used for MIM parts in Japan with a 65.1% market share (Fig. 2, right). The JPMA reports that stainless steels, ferrous based magnetic materials and Fe-Ni steels account for over 80% of total powder demand for MIM in Japan. The demand for titanium alloy powders for Metal Injection Moulding increased from 1.6% in 2014 to 2.8% in 2015.

The JPMA reports that it is difficult to predict future trends for MIM sales in Japan because each MIM producer has different expectations. However, the producers acknowledge that more needs to be done to promote the benefits of Metal Injection Moulding in comparison with other forming technologies.

www.jpma.gr.jp

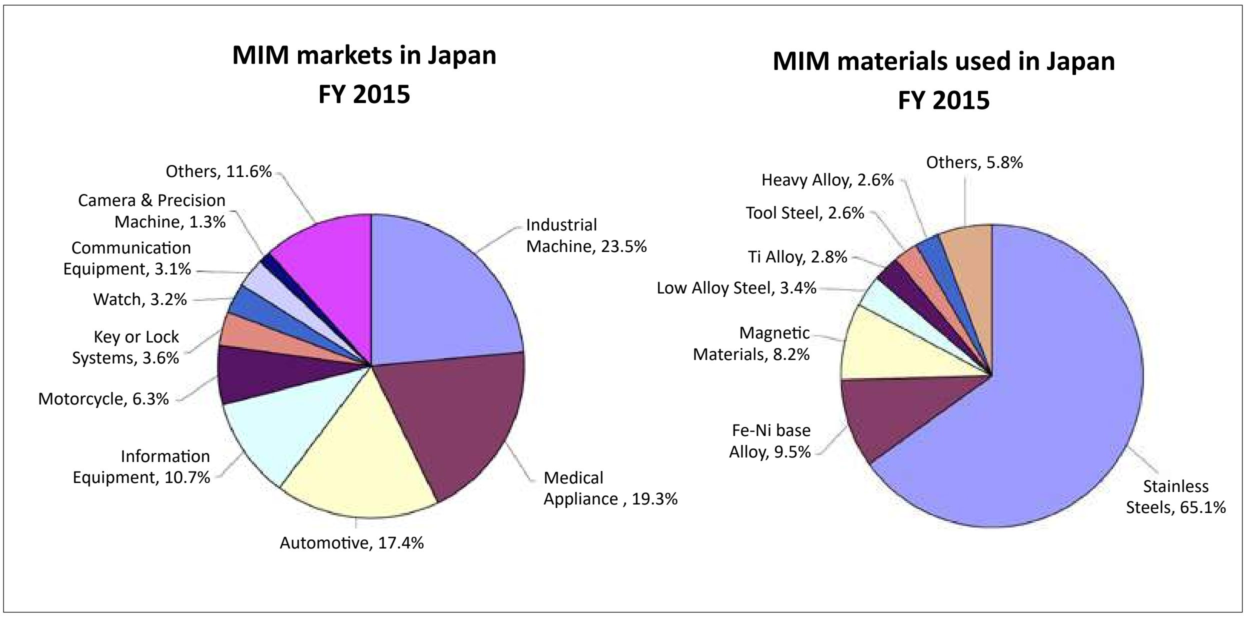


Fig. 2 Markets and materials for Metal Injection Moulding in Japan in 2015 (Courtesy JPMA)

MIM watchcases used for Swatch's latest Irony range, Sistem51

Swatch has been a pioneer in the use of Metal Injection Moulding for the production of high volume watchcases, with its Irony range dating back to 1994. The company has once again used MIM in the latest addition to its portfolio, Sistem51 Irony. Launched in August, the Sistem51 Irony models are an evolution of the original Sistem51 range that uses plastic cases.

Sistem51 features a unique mechanical movement that consists of only 51 parts, assembled in a fully automated process and secured with a single central screw. As it is not a quartz watch, Sistem51 has no need for a battery but is powered by the movement of the wearer. Every movement of the wrist sets the rotor in motion, winding the watch, so Sistem51 features an automatic, or self-winding, movement. Even when not worn, the watch keeps on going for 90 hours. The rear of the watchcase is transparent to expose the movement. Swatch stated, "By taking advantage of the first fully-automated mechanical watch manufacturing process, each elegant model is assembled to the highest level of precision and Swiss quality whilst delivering unmatched value."

For Swatch, Sistem51 Irony represents a major step towards affordable, automatic watches with a classic, up-market appearance. The range is composed of seven models that, suggests the company, can be seen to be moving toward a more sophisticated market. Swatch stated, "Sistem51 is beautiful technology. Conceived, developed and built entirely and exclusively in Switzerland and in less than two years. It is a luxury, an accessible point of entry to high-end mechanical watchmaking - for everyone."

www.swatch.com

The new Swatch Sistem51 Irony watch

Rear of the watch showing the mechanical movement

Epson Atmix to increase amorphous alloy powder production

Epson Atmix Corp., one of the leading global producers of superfine alloy powders at its Kita-Inter plant in Hachinohe, northern Japan, is investing more than Yen 1.25 billion ($12.5 million) to build a new facility for the production of amorphous alloy powders. Construction of the new powder plant will begin in November 2016 and is expected to be completed in January 2018. The plant will eventually increase production from the current 2,000 tonnes/year of amorphous powder to approximately 6,000 tonnes/year by the year 2025.

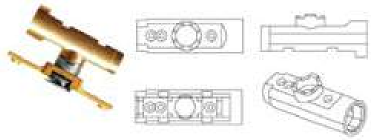
The company began volume production of amorphous alloy powder in 2004 using an original production method called Spinning Water Atomisation Process (SWAP). In the SWAP process, powder is produced by blasting an alloy that has been melted in a high-frequency induction furnace with high-pressure gas and cooling water to create tiny droplets that are then solidified by rapidly cooling at a rate of several tens of thousands of degrees Celsius per second. Amorphous alloy powders are technically challenging to produce in volume, but Epson Atmix has continued to accumulate expertise in this area and is believed to be the first company in the world to mass-produce these powders.

The amorphous alloy powders produced by the SWAP process have high magnetic flux densities and low energy loss in addition to excellent high-frequency characteristics. These characteristics make amorphous alloy powders extremely attractive as performance-enhancing, highly functional material powders that enable small, low-power voltage control components and that support high frequencies and large currents.

Epson Atmix is currently also constructing a new factory for superfine alloy powders, excluding amorphous alloy powders, which are used in the production of high-performance precision Metal Injection Moulded components for numerous sectors including automotive, 3C, wearable products and medical devices.

www.atmix.co.jp

Increasing demand for MIM 3C hinges drives capacity expansion



This MIM camera hinge design offers higher torque, stronger wear-resistance and improved reliability compared with pressing (Photo Shin Zu Shing, Taiwan)

According to the Taiwan-based *Digitimes* newspaper, demand is growing strongly for 3C hinges produced by Metal Injection Moulding. It was stated that despite a year on year decline in PC shipments, sales of hybrid devices that combine the functionality of a tablet with the form factor of a notebook are expected to grow by 13%. Such devices have complex multi-function hinge mechanisms that allow, for example, the removal or rotation of the screen.

It was stated that the Metal Injection Moulded hinges that are expected to be featured on the next generation of Apple MacBooks are also driving capacity expansion amongst leading hinge manufacturers. Taiwan's hinge maker Shin Zu Shing (SZS) was reported to have installed an additional six new sintering furnaces in the first half of the year, with a further six to be installed in the second half of the year, making a total of 38 sintering furnaces at the company by the end of 2016.

It was also reported that Jarllytec Co. Ltd., headquartered in Hsin Chuang City, Taipei Country, Taiwan, is expanding sintering capacity to meet the growth in demand for Metal Injection Moulded hinges. The company was established in Taiwan in 1992 and has been actively developing and manufacturing various MIM hinges for notebooks and two-in-one devices since 2004.

Jarllytec recently reported in August that sales revenue at the company for the period January to the end of July increased to NT$3.253 billion, a rise of 67% compared with the same period last year. The company expects demand to grow strongly in the second half of 2016 as new ultra-thin laptop models will feature MIM hinges. This is in addition to sales of existing two-in-one devices with MIM hinges. Jarllytec has production facilities in Shanghai, Fu-Qing, Dongguan and Changshu as well as in Taiwan and the current monthly capacity for various sets of hinges is said to be more than 3 million.

The use of Metal Injection Moulded hinges for the 3C sector is by no means new, with the hinge mechanisms for clamshell cellphones being early examples.

www.digitimes.com

MIM headphones win prestigious design awards

Reed Heath Ltd (RHA), based in Glasgow, Scotland, has received the prestigious 'Observeur du Design' award 2017 for its flagship T20i Metal Injection Moulded headphones. The award was presented in the product design category, recognising quality in technological and design innovation, with additional criteria including overall value and the corporate responsibility of the product's manufacture.

One of over a hundred entries for the 2017 award, the MIM stainless steel T20i headphones will be exhibited with other winners in prominent galleries and museums across France throughout the second half of 2016. The tour will culminate in Paris in December where the product will compete against other L'Observeur winners for the 'Étoiles du Design' award.

RHA received a further award for its T20i MIM headphone at the Visual Grand Prix in Japan at the end of May 2016. The T20i is certified to High Resolution Audio standard by the Japan Audio Society and features RHA's revolutionary DualCoil™ driver technology as well as the two-piece MIM casing enabling it to outperform traditional drivers in the replication of true-to-life sound.

www.rha-audio.com

The T20i headphones from RHA Audio (Courtesy RHA Audio)

Exploded view of the interior of the T20i headphones showing the features of the stainless steel MIM housing (Courtesy RHA Audio)

High thermal conductivity achieved with boron nitride filled injection moulded plastic heat sinks

Rapid developments in microprocessor technology have led to a need for the efficient high-volume production of advanced heat sink devices. Fin and tube or plate heat exchanger designs are often constructed using copper or copper-tungsten and aluminium-silicon carbide materials and these can be produced by the Powder Injection Moulding process to achieve the complex designs required and to meet the need for high volume production for electronics applications. Many of these applications require the quick and effective dissipation of heat in an extremely small space.

Thermally conductive polymers are also used for applications involving the transfer, propagation or dissipation of thermal energy and modern thermal management composites containing, for example, Al_2O_3 offer extremely good thermal conductivity while retaining the typical properties of plastics such as electrical insulation and low weight. However, even with Al_2O_3 filled compounds, only a maximum thermal conductivity of 2 W/m*K can be achieved.

The 3M Advanced Materials Division, based in St Paul, Minnesota, USA, has introduced boron nitride fillers for thermal management composites, which the company states, can reach thermal conductivity over 15 W/m*K. The high thermal conductivity of 3M™ Boron Nitride Cooling Filler compounds is also supported by the high aspect ratio of the boron nitride particles (approx. 1:30). This allows for thermal conduction paths even at low concentrations. For example, thermal conductivity levels of >5 W/m*K can be achieved even at filling levels of <30 vol.%.

Compounds filled with 3M™ Boron Nitride Cooling Fillers are also reported to have good processing properties. The fillers' dry lubrication properties and low hardness (1-2 on the Mohs scale) ensure non-abrasive processing even at the highest filling levels. The extremely high thermal conductivity in boron nitride filled thermoplastics can also result in shorter cool-down times for injection moulding tools. Overall cycle time reductions of >30% have been achieved. The excellent heating and quick cool-down of these fillers can also be applied economically in compounding. For filling levels of over 30 vol.%, these properties are decisive for process and costs and stability.

www.3m.com

New low pressure injection moulding system suited to PIM feedstocks announced

Extrude to Fill LLC (X2F), based in Loveland, Colorado, USA, recently presented its new low pressure moulding approach at the Molding 2016 Conference held in New Orleans earlier this year. Rick Fitzpatrick, Chief Technology Officer, stated that the new approach essentially takes the injection out of injection moulding by eliminating the reciprocating screw, high pressures and difficult-to-manage temperatures of traditional moulding and replacing them with a continuously extruding fixed screw and precise melt using any compound. The low shear of the system also permits moulding of highly filled compounds such as feedstocks for PIM.

Fitzpatrick stated that, by eliminating conventional rapid injection and by using friction and shear heating to melt material, X2F’s alternative requires far less clamp pressure and achieves far more consistent and uniform melt temperature. This allows the use of aluminium moulds and a very small, lightweight press (horizontal or vertical) with a pneumatically actuated toggle clamp and a servo-driven extruder with a shutoff nozzle.

The company’s largest current machine weighs only 364 kg with a 91 x 12 cm footprint and can run on 208 V single-phase electricity with shot sizes up to 150 g. The company also makes machines that weigh only around 93 kg and run on 110 V household power with shot sizes to 30 g. The smaller press would compare to a 25 ton clamp in a conventional design, but uses only 8.7 tons.

The patent-pending machine design uses electrical heating to melt material via conductive heating rather than frictional shear heating. Thus, the larger machine can heat up from room temperature to 230°C in 5-6 min., thanks to barrel walls as thin as 3.175 mm (owing to low-pressure moulding) and use of special thermally conductive materials in barrel construction. The process reportedly needs only 10% of the energy consumed in conventional injection moulding.

On the controls side, since the process is not rapidly injecting fixed volumes of feedstock, the machine can give real-time pressure and volume feedback to confirm part consistency with sensors in the melt. Controlled melt temperature supports the moulding of heat and shear sensitive materials such as MIM feedstocks and biopolymers.

www.extrudetofill.com

Submitting news..

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

Cost and quality optimisation with intelligent automation systems

The increasingly sophisticated MIM production process makes it possible to produce parts that are ever more complex. There is, however, a requirement to avoid as many machining, coining and finishing operations as possible in order to remain cost-competitive. Automation and inspection systems can help address the requirements of the production process by achieving the highest levels of efficiency in terms of cost and product quality, states Roboworker Automation GmbH, based in Weingarten, Germany.

The modular design of the company's automation systems means they can be flexibly adapted to customer requirements. Corresponding tray handling versions are available for the smallest right up to large batch sizes. Users can choose between single belt systems or magazine and stacking solutions with a large tray store for high autonomy times and cost-saving potential in plant operation. Additionally, intelligent product memory systems slash setup times after product changeovers.

Linear robots guarantee top productivity and accuracy and their precision can be boosted even more with direct measurement systems. This is the basis for gentle gripping and an attractive solution for placing products in custom trays with ridges, protrusions or other structures. Freely programmable placement patterns designed for high densities also ensure optimum furnace loading.

Variable gripper systems also contribute significantly to gentle component handling. Driven by motors, they allow flexible programming of the rotational, turning and tilting motions. Depending on the component, suction cups, balloons or gripper jaws are used for optimal handling.

Today's systems must, however, offer more than precise pick and place processes. Also crucial is component quality control and documentation of the inspection results to ensure traceability in the production process, especially in the automotive industry. A whole range of inline functions can be integrated in picking systems such as part weighing, optical geometry measurement and tactile height measurement.

To support a fast handling process, up to two precision scales can be integrated. This means that while one part is being weighed, the second scale can be loaded. Depending on the ambient conditions, precision levels of +/- 0.005 g or better can be achieved in the process.

Precision placement of components on trays

For optical geometry measurement, the user can flexibly define and save the relevant dimensions. The dimensions are simultaneously and automatically aligned. It is possible to define inner and outer circumferences, lengths and widths, angles, radii and shapes. During height measurement, various sensors determine the component height. An accuracy in the process of as close as 0.01 mm is possible.

Components that do not match the specified tolerance are immediately identified and sorted out by corresponding devices. In some PM processes, feedback to the press can trigger automatic correction. This interaction between the production and the automation system with programmable and saved movement sequences and process data boosts process stability.

Despite the many functions available for integration, in an environment where time is money automation systems must be easy and fast to program and operate. Roboworker stated, "All this makes it clear that today automation goes much further than just palleting and stacking operations. Not only the devices themselves, but also numerous additional functions contribute decisively to quality assurance of precision parts, increase process reliability and deliver documentation for traceability of parts. These quality benefits also optimise costs in a number of PM manufacturing processes".

www.roboworker.com

Device for geometry measurement

French research institute readies PIM for industrial roll out

Liten is a major European research institute based in Grenoble, France, which forms part of CEA Tech, the French Atomic Energy and Alternative Energy Commission's technology research unit. The unit is a driving force behind the development of the sustainable energy technologies of the future. Liten's 'Poudr'Innov' programme is demonstrating that Powder Injection Moulding is a technologically and economically efficient way to manufacture complex-shaped metal parts without machining. The organisation is looking to assist French manufacturers to access the technology and to offer support at all stages up to test manufacturing runs.

Offering high throughput and reproducibility, Liten states that PIM is an excellent technology for the manufacture of complex-shaped parts. Researchers working in Liten's Poudr'Innov programme have successfully used the process to make a demonstration part that featured as many challenging shapes as possible including hemispheres, flat areas, corners, forks and micro-sized features.

The researchers experimented with both feedstock blends and process parameters. They state that they successfully produced 600 parts per hour without the need for machining, achieving excellent reproducibility and a reject rate under 1%, all for a unit cost of less than €0.50. The materials used were not specified. This work, it was stated, positions Poudr'Innov to meet the needs of its industrial partners, from helping them to draw up initial product specifications through to sample part manufacturing and test manufacturing runs.

www-liten.cea.fr

MIM2017 Call for Presentations

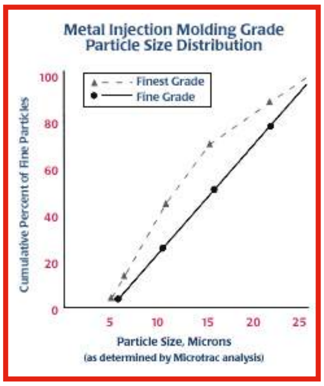
A Call for Presentations has been published for the MIM2017 International Conference on Injection Molding of Metals, Ceramics and Carbides. The event takes place from February 27 to March 1, 2017, at the Hilton Orlando Lake Buena Vista hotel in Orlando, Florida, USA. Authors have until September 30, 2016, to submit their presentation abstract. The event is organised by the Metal Injection Moulding Association (MIMA).

The organisers state that innovation is responsible for the rapid growth of Powder Injection Moulding, comprising Metal Injection Moulding, Ceramic Injection Moulding and Cemented Carbide Injection Moulding), a $2 billion advanced manufacturing industry. This conference, it was stated, provides a venue for the latest technology transfer.

www.mim2017.org

-45 Micron to -325 Mesh

Stainless Steel Fine Powders for MIM & Other Specialty Applications



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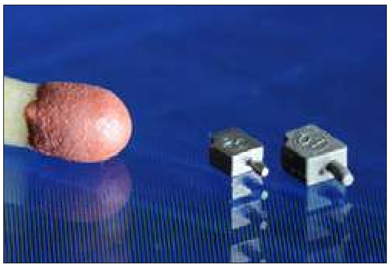
MIM producer OBE extends its reach into the Asian eyewear market

As of 1st April 2016, OBE GmbH & Co KG, Ispringen, Germany, has solely managed the eyewear component company Globe Precision, with its factory in Shenzhen, China, and offices in Hong Kong. OBE is a world leader in the production of components for eyewear frames, with particular expertise in the production of small, complex eyewear components via Metal Injection Moulding.

In mutual agreement, OBE and former Globe Precision shareholder Ching Lan made this strategic decision which, it was stated, guarantees a streamlined, clear positioning in the international optical market as well as assuring a smooth transitioning process via a consultancy agreement with Ching Lan.

In the future OBE will provide a full service to all customers as this second factory will be fully integrated into the OBE Group. In the Asian market, Globe will continue to offer a flexible portfolio of tailor-made hinges in addition to the current wide range of standard products.



An award winning MIM eyewear component manufactured by OBE (Photo PIM International)

By strengthening its sales force, OBE will support the expansion of Globe with its expertise and experience going back more than 100 years.

www.obe.de

APMA2015 papers available as free downloads

Contributed papers from the 3rd International Conference on Powder Metallurgy in Asia (APMA2015), November 8-10 2015, Kyoto, Japan, have been published in the *Journal of the Japan Society of Powder and Powder Metallurgy* Vol. 63 (2016) No. 7. Of the 52 papers published, a number of papers address the latest research in MIM. Short reviews of three papers are published on pages 42-47 of this issue of *PIM International*.

Further topic areas include Additive Manufacturing, compaction and sintering, PM production management, magnetic materials, hard materials and ceramics. The papers are available to download free of charge from the journal's website.

www.jstage.jst.go.jp/browse/jjspm/63/7/_contents

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D-96515 Sonneberg

Tel. +49 3675 / 7484-0
Fax +49 3675 / 7484-44

email: info@fct-anlagenbau.de
web: www.fct-anlagenbau.com

Management changes at UK's Metal Injection Moulding producer CMG

CMG Technologies Ltd, based in Rendlesham, Suffolk, is making changes to its management team which, it states, will ensure a secure future for the UK's leading Metal Injection Moulding specialist. Chris Conway, the outgoing Managing Director, is taking semi-retirement from his current role but will remain involved with the day-to-day running in his new position as Chairman.

Taking over as Managing Director will be Rachel Garrett, who is stepping up from her current post as Technical Sales and Marketing Director. Garrett's ambition is to maintain and build on the company's growing reputation and ensure the needs of both existing and new customers are fully met. She told *PIM International*, "I am delighted to have been appointed Managing Director and aim to continue and build on what Chris has achieved through his dedication to the company and his unwavering resilience to drive our business forward."

"It is an exciting time for our industry with the uptake of metal powder manufacturing techniques being actively pursued due to the buzz around 3D printing and I believe the cost savings possible with our Metal Injection Moulding technology will continue to attract more business, not least from reshoring."

Medical device parts manufactured by CMG Technologies

Conway stated, "I have thoroughly enjoyed my time as Managing Director and I am looking forward to having some more free time in the future as well as continuing to share my industry knowledge as company chairman. CMG is now firmly established as a market leader in MIM, a reputation I am sure will continue to grow when Rachel takes over at the helm."

CMG Technologies, which previously traded as Egide UK, is an internationally renowned specialist in Metal Injection Moulding, providing injection moulded components to the medical, aerospace, automotive and industrial sectors for over 14 years.

www.cmgtechnologies.co.uk

Left, Chris Conway (Chairman), centre, Rachel Garrett (Managing Director) and right, Dr Phil Marsh (Director)

MIM specialist AMT strengthens its position in the medical technology sector

Accuron Technologies Limited, a technology and engineering holding company wholly-owned by Temasek Holdings, has announced that it has acquired a majority stake in Malaysia-based Aurum Healthcare Sdn Bhd. This is the sixth medical technology related acquisition that Accuron Medtech Group, a division within Accuron Technologies, has made in the last two and a half years.

Accuron Medtech was set up to focus efforts on addressing opportunities in the global medical technology market. This, stated the company, is because the global medical technology market is projected to reach some US$537 billion by 2020, with the Asia Pacific being the fastest growing region at nearly 8% CAGR to become the second-largest market at US$133 billion by 2020.

"Accuron Medtech welcomes Aurum Healthcare into our family of medtech businesses, which include Advanced Materials Technologies, Dornier MedTech and Veredus Laboratories. Our operating businesses provide therapeutic, diagnostic and medical device solutions to customers internationally through our direct presence in the U.S., Europe, China, Japan and Singapore. By adding a commercial and manufacturing presence in Malaysia through Aurum, we believe this deal will be beneficial for our group operating companies. Accuron Medtech companies can leverage upon each other's capabilities, networks and expertise in order to maximise their market and technology reach," stated Abel Ang, Group Chief Executive Officer, Accuron Medtech.

Accuron Medtech will position Aurum under Advanced Materials Technologies (AMT), a Singapore-based contract manufacturer focusing on the medical technology sector. The acquisition will increase AMT's manufacturing footprint from its current 120,000 ft^2 facilities located in Tuas, Singapore and Dongguan City, China to include Aurum's 20,000 ft^2 facility at the Setia Business Park, Johor Bahru, Malaysia. Aurum's facility is able to provide sterilisation services for medical devices and instruments, as well as clean room manufacturing and assembly services.

With over 25 years of experience, AMT specialises in Metal Injection Moulding and metal Additive Manufacturing for high precision and complex metal parts used in the medical device sector. AMT's products include metal components found in endoscopes and robotic surgery instruments. Existing AMT medical technology customers include companies in the urology, endoscopy and robotic surgery fields. The addition of Aurum's capabilities means that AMT will expand its OEM expertise to include manufacturing of plastic medical consumables, such as those used in heart bypass, catheterisation or angiography procedures.

"This acquisition of Aurum into the Accuron Medtech group of companies will help AMT transform into an integrated, end-to-end medical device outsourcing specialist. We plan to scale up and diversify in the fast growing medtech outsourcing sector in Asia. The combination of Aurum's capabilities with AMT's extensive experience transforms us into one of a few contract manufacturers globally that is able to offer a comprehensive, fully-integrated suite of medical device outsourcing services. This means that we are able to handle increasingly sophisticated product designs as well as a wider scope of manufacturing and assembly projects in a cost-efficient and shorter time-frame," stated Albert Ngoh, Chief Executive Officer, Advanced Materials Technologies Pte Ltd.

www.accuron.com/accuron-medical.html

www.amt-mat.com

www.aurumhealthcare.com

Spain's 2017 national Powder Metallurgy conference heads to Ciudad Real

The organisers of Spain's 6th National Conference on Powder Metallurgy have announced that the bi-annual event will be held in Ciudad Real, Castilla La Mancha, from June 7-9, 2017. The conference will be open to presentations from both the PM and ceramic sectors and will for the first time include participation from Latin American countries by incorporating the first 'Congreso Iberoamericano de Pulvimetalurgia' within the event.

The conference will include plenary keynote presentations from leading researchers including Dr Frank Petzoldt, Fraunhofer Institute for Manufacturing and Advanced Materials IFAM, Germany; Professor Elena Gordo Odériz, University Carlos III of Madrid, Spain; Professor Sebastián Díaz de la Torre, National Polytechnic Institute (IPN), Mexico, and Professor Paolo Colombo, University of Padova, Italy.

A formal call for papers will be issued in the near future. Those interested in presenting should forward an abstract to the organisers (trabajos@vicnp.es) before January 20, 2017.

www.vicnp.es

Success for the Metal Injection Moulding industry in the MPIF's PM Design Excellence awards

Award winning parts in the Metal Powder Industry Federation's 2016 Powder Metallurgy Design Excellence Awards competition were announced at POWDERMET2016, Boston, USA, June 5-8. Metal Injection Moulded parts once again dominated the awards, accounting for more than half of the award winners and these parts are reviewed in the following report. To view the complete list of all 2016 award winning parts, including those produced by conventional Powder Metallurgy processes, download the Autumn/Fall 2016 issue of *Powder Metallurgy Review* magazine (www.pm-review.com).

Grand Prize Awards

Aerospace/Military: Advanced Forming Technology

The Grand Prize in the Aerospace/Military Category was won by Advanced Forming Technology, an ARC Group Worldwide Company, Longmont, Colorado, USA, for a Metal Injection Moulded front sight base used on the AR-15 rifle (Fig. 1).

The MIM-4605 low-alloy steel part is much larger than the typical Metal Injection Moulded part and has a complex geometry. The switch from a part machined from bar stock to the Metal Injection Moulded part yielded cost savings of more than 30%.

Medical/Dental: Parmatech Corporation

The Grand Prize in the Medical/Dental Category was won by Parmatech Corporation, Petaluma, California, USA,

Fig. 1 A MIM front sight base manufactured by Advanced Forming Technology used on the AR-15 rifle

for four stainless steel Metal Injection Moulded components used in an articulating endoscopic surgical device designed specifically for thoracic surgery (Fig. 2).

The parts, an articulation lock bar, articulation connector, articulation drive block and knife guide, feature complex geometry that would be extremely difficult to machine. The Metal Injection Moulding process saves an estimated 70% of cost over a traditional machining method. The ability of the Metal Injection Moulding process to produce parts of different alloys with tight tolerances enabled the design of a smaller endoscopic device, a critical benefit in thoracic surgery.

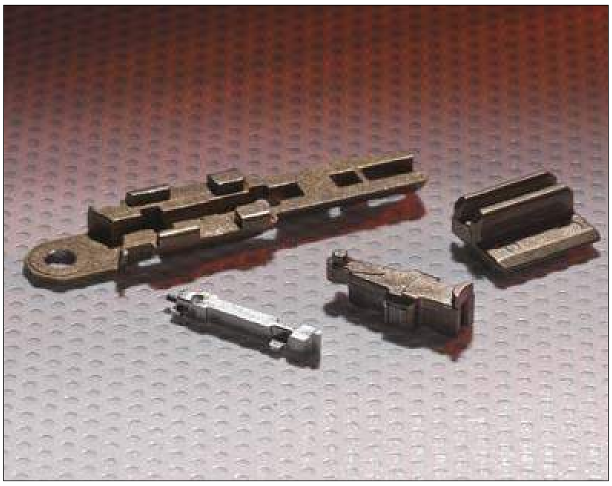

Fig. 2 Four stainless steel MIM components manufactured by Parmatech Corporation, used in an articulating endoscopic surgical device

Awards of Distinction

Lawn & Garden/Off-Highway: Indo-US MIM Tec Pvt. Ltd

The Award of Distinction in the Lawn & Garden/Off-Highway Category was given to Indo-US MIM Tec Pvt. Ltd, Bangalore, India, for a Metal Injection Moulded 17-4 PH stainless steel diesel leak-off union made for Lombardini (Fig. 3). The part goes into the fuel injection of a line of Kohler diesel engines that are assembled in JCB midi and mini excavators, compact wheeled loaders and Teletruk forklifts. A conversion from a previously used plastic part whose performance suffered in the tough working environment, the MIM part delivered cost savings of around 10% through improved quality.

Aerospace/Military: Advanced Forming Technology

The Award of Distinction in the Aerospace/Military Category was presented to Advanced Forming Technology for an aerospace engine ferrule made for Rolls Royce (Fig. 4). Made of MIM 17-4 PH stainless steel, the part provides a conductive path between the screen and the engine, while offering support to the single cable and preventing the placement of cable loading on the screen.

Fig. 3 A 17-4 PH stainless steel diesel leak-off union made for Lombardini by Indo-US MIM Tec Pvt. Ltd

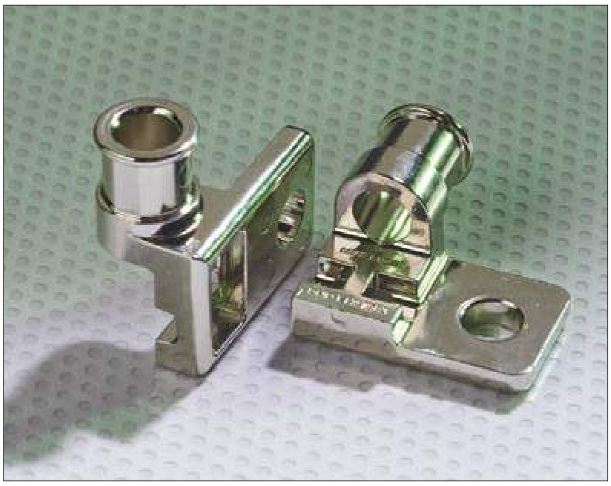

Fig. 4 A MIM aerospace engine ferrule made for Rolls Royce by Advanced Forming Technology

The complex component is sintered exactly to net shape, with no secondary operations needed to meet required dimensional specifications. Cost savings were the primary driver for the switch to a Metal Injection Moulded part from one machined from bar stock.

Hand Tools/Recreation: Parmatech Corporation
The Award of Distinction in the Hand Tools/Recreation Category was given to Parmatech Corporation for a Metal Injection Moulded 4605 low-alloy steel trigger used in an adjustable trigger system on a pump-action shotgun (Fig. 5) The extremely complex part geometry, which features multiple thickness changes and slots, required precise tooling to address sufficient machine stock for effective secondary operations. The Metal Injection Moulded trigger delivers cost savings of around 50% over the machined version it replaced.

Fig. 5 A MIM 4605 low-alloy steel pump-action shotgun trigger manufactured by Parmatech Corporation

Electronic/Electrical: Indo-US MIM Tec Pvt. Ltd

An Award of Distinction in the Electronic/Electrical Category was presented to Indo-US MIM Tec Pvt. Ltd for three parts, a mirror cover, a base and a middle, made for Optosense (Fig. 6). Moulded from MIM-316L stainless steel, the parts are assembled into an infrared gas sensor for methane and carbon dioxide detection that has extremely low power consumption. A new application designed specifically for the Metal Injection Moulding process, these are medium-complexity parts that have an aesthetic requirement on a few reflective surfaces.

Medical/Dental: Flomet, LLC

An Award of Distinction in the Medical/Dental Category was presented to Flomet, LLC, an ARC Group Worldwide Company, DeLand, Florida, USA for a Metal Injection Moulded tungsten electrode used in a surgical ablation device (Fig. 7). The device uses high temperature for the removal of tissue and the use of tungsten enables

Fig. 6 MIM-316L stainless steel parts for an infrared gas sensor for methane and carbon dioxide manufactured by Indo-US MIM Tec Pvt. Ltd

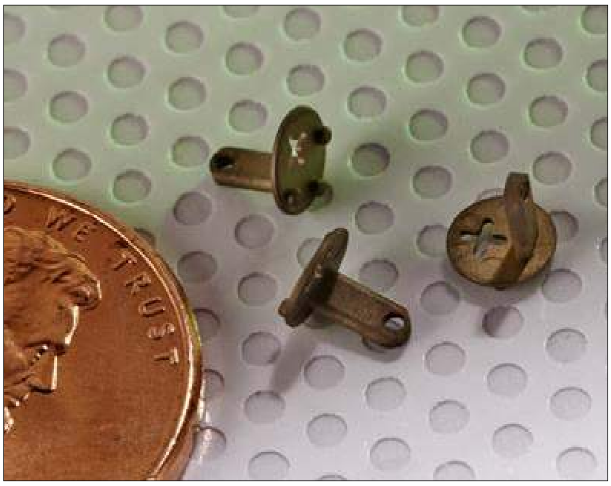

Fig. 7 Flomet LLC manufactured these MIM tungsten electrodes used in surgical ablation devices

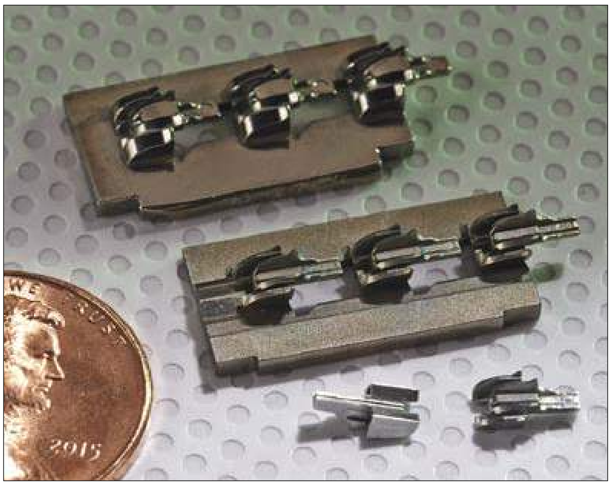

Fig. 8 Advanced Forming Technology produced these MIM wedge blanks used in an endoscopic staple gun

the electrode to reach its operating temperature more efficiently, maintaining it for a longer time than with other alloys.

Medical/Dental: Advanced Forming Technology

A further Award of Distinction in the Medical/Dental Category was given to Advanced Forming Technology for a MIM wedge blank used in an endoscopic staple gun (Fig. 8). Made from a MIM-440 stainless steel, the part has a complex and very small geometry that pushed the MIM process to the very limits of tolerance capabilities. The part's 5 mm diameter, less than half the previous low of 12 mm, enables new procedures to be created and enhances procedures in smaller patients, particularly in the area of paediatrics.

www.mpif.org

GMC appoints Arnd Thom to international sales role in expansion of MIM and CIM feedstock business

GMC Feedstocks GmbH, based in Rheinbach, Germany, has announced the appointment of Arnd Thom as Managing Director International Sales and Business Development. GMC stated that Thom is well-known in the Metal Injection Moulding industry from his previous position as Senior Sales Manager at BASF, concentrating on the Catamold business.

Thom will focus on distributing GMC's products worldwide. Dr Bodo Fink, GMC's Chief Financial Officer, stated, "It is a great honour that Arnd Thom will join our team. Arnd has an exceptional background in Process Engineering and Powder Injection Moulding, combined with an international sales background. While GMC is concentrating on penetrating European and South American markets, we believe that there are growth opportunities outside of those markets, particularly in Asia and USA."

Thom added, "I am very excited to join the GMC team. I believe that together we are able to create a strongly competitive platform in Powder Injection Moulding with a holistic approach on ceramic and metal technology. Moreover, our unique approach of combining different binder systems leads to an excellent long term strategy. This includes an intensive technical support of our customers concerning part design, mould making and computer tomography analysis of prototype parts. There is a big opportunity to take our feedstock products and technology to new international markets, which I am quite excited to get working on." Thom has had an extensive international sales and business management career with more than fifteen years in the PIM business.

GMC Feedstocks produces feedstocks for MIM and CIM based on a variety of binder systems. With more than twenty years of experience in the PIM industry, GMC offers binder systems that can be chosen on the basis of the powders to be used or the requirements of a customer's equipment. Options include wax-based binders for water and thermal debinding, polyamid based systems for alcohol and thermal debinding and POM based systems for catalytic debinding.

www.gmcfeedstocks.com

Submitting your news...

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

Ceramic Injection Moulding used to produce high performance gas turbine components

Stationary gas turbines are destined for local and independent energy conversion with combined heat and power generation. Recent research efforts have focused on how the efficiency of these gas turbines can be increased either through using a higher operating temperature or a lower amount of cooling. Both approaches result in significantly higher gas turbine component temperatures. Because metal alloys are already operating at their physical limits in terms of temperature, researchers are seeking to develop ceramic components capable of substituting metal alloys used at the very high temperatures required.

The recently published *Annual Report 2015/2016* of the Fraunhofer Institute for Ceramic Technology and Systems (IKTS), based in Dresden, Germany, contains a review of a research project undertaken by IKTS with four other Fraunhofer institutes where Ceramic Injection Moulding is used to produce radial gas turbine rotors from silicon nitride (Si_3N_4) powders (Fig. 1). Si_3N_4 was chosen for the rotors because of its suitability for operating under high thermomechanical loads from room temperature to 1400°C in a micro gas turbine with a capacity for producing 30 kW electricity.

CIM was used to produce the near-net shape rotors because of its suitability for the manufacture of high quantities of components with low loss of material. However, the large volume of the rotor (148 cm³) imposed numerous demands on the mould cavity and the CIM feedstock, with the greatest challenge proving to be the debinding process. This problem was solved by an innovative combination of the chemical and thermal treatment of parts to enable the sintering of defect-free CIM rotors. The properties of the micro gas turbine Si_3N_4 CIM material are shown in Table 1. Fraunhofer IKTS reported that following minor structural modifications the Si_3N_4 CIM rotors were being installed in the Capstone® C30 gas turbine located at Fraunhofer IFF. Fraunhofer IKTS also reported that it is producing sintered ceramic blades for the first stage of the Klimov GTD 350 helicopter engine that are machined in the green state.

www.ikts.fraunhofer.de

Fig. 1 Radial turbine rotor made by ceramic injection moulding of silicon nitride (Fraunhofer IKTS)

Operating temperature	1200°C
Fracture toughness	6.8 MPa $m^{1/2}$
Strength	~ 1000 MPa
Fatigue strength at 1200°C	~ 500 MPa

Table 1 Material data for CIM silicon nitride micro gas turbine rotor (Fraunhofer IKTS)

Lower cost titanium alloys studied for high strength MIM parts

A number of titanium alloys, such as Ti-6Al-4V, are already used to manufacture Metal Injection Moulded parts for various industrial and medical applications because of their low density, high strength, high corrosion resistance and good biocompatibility. Recent research in Japan has focused on developing lower cost Ti alloys for application in MIM by substituting vanadium with cheaper elements such as Fe, Cr and Mo. Yoshinori Itoh (Hamamatsu Technical Support Center Industrial Research Institute, Shizuoka Pref., Hamamatsu) and Hideshi Miura (Kyushu University, Fukuoka) presented the results of their work to find a lower cost alloying element to replace vanadium in a paper published in the *Journal of Japan Society of Powder & Powder Metallurgy* Vol. 63 No. 7, July 2016, pp 438-444).

The authors used elemental metals including gas atomised Ti powder (-45 μm), aluminium powder (5.4 μm), carbonyl iron (4.31 μm), chromium (2.97 μm) and molybdenum (1.59 μm), which were mixed with a binder containing polypropylene, polymethyl methacrylate, paraffin wax and stearic acid in a wt% ratio of 30:40:29:1 to produce the MIM feedstock. The injection moulded parts were first debound in n-hexane at 343K to partially remove the wax and polymethyl methacrylate and the compacts were then thermally debound at 703K at reduced pressure in argon. Sintering was performed in high vacuum from 1323K to 1573K.

The effect of the various sintering temperatures on final density of the MIM Ti alloys containing different amounts of Mo is shown in Fig. 1. The tensile strength of

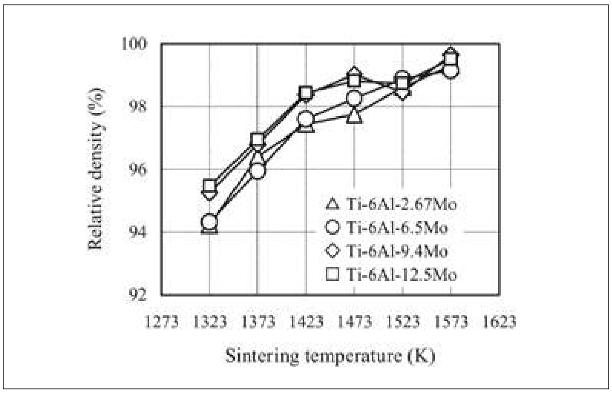

Fig. 1 Effect of sintering temperature and Mo content on relative density of Ti alloy compacts where Mo has replaced V (Y. Itoh and H. Miura. J., Jpn Soc. Powder & Powder Metallurgy Vol. 63, No. 7 July 2016, 438-444. Originally presented at APMA 2015, the 3rd International Conference on PM in Asia, Kyoto, November 8-10, 2015)

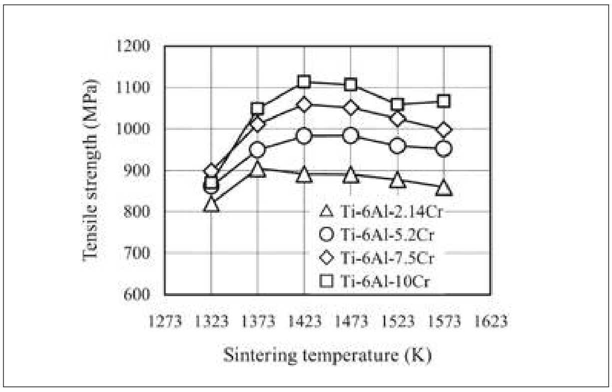

Fig. 2 Effect of sintering temperature and Cr content on tensile strength of Ti alloy where Cr has replaced V in Ti-6Al-4V(Y. Itoh and H. Miura. J., Jpn Soc. Powder & Powder Metallurgy Vol. 63, No. 7 July 2016, 438-444. Originally presented at APMA 2015, the 3rd International Conference on PM in Asia, Kyoto, November 8-10, 2015)

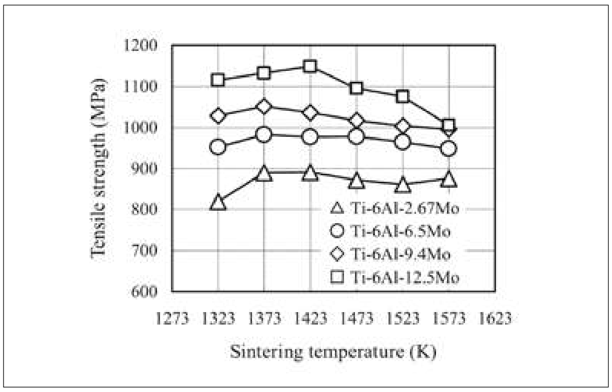

Fig. 3 Effect of sintering temperature and Mo content on tensile strength of Ti alloy where Mo has replaced V in Ti-6Al-4V (Y. Itoh and H. Miura. J., Jpn Soc. Powder & Powder Metallurgy Vol. 63, No. 7 July 2016, 438-444. Originally presented at APMA 2015, the 3rd International Conference on PM in Asia, Kyoto, November 8-10, 2015)

the sintered MIM Ti alloy where Fe replaced V was found to be improved, but elongation was reduced to around 5%, whereas, when using Cr and Mo, elongation values were above 10%. The tensile strength of the Ti alloy where Cr and Mo replaced V also improved to around 1000 MPa. To further improve tensile strength, the authors increased the contents of Cr and Mo in the Ti alloys, but it was found that these increases led to a reduction in elongation. They reported that the best tensile strength (greater than 1100 MPa) was achieved with the Ti-6Al-12.5Mo alloy, which had elongation of 8%. Figs. 2 and 3 give results of tensile tests on the Ti alloys where Cr and Mo replaced V.

www.jstage.jst.go.jp/browse/jjspm/

MIM TiAl alloy shows potential for turbine wheels for turbochargers

One solution to the demand for ever higher fuel efficiency and to meet increasingly stringent emission controls in the automotive industry is for the turbine wheels used in turbochargers to operate at higher temperatures. Ti-Al intermetallic alloys have excellent high temperature tensile properties, oxidation resistance and low specific gravity. However these alloys are difficult to produce as complex shapes because forging and casting can lead to inhomogeneous microstructures and poor machinability.

Toshiko Osada and co-authors from Kyushu University in Fukuoka, Japan, have reported in the *Journal of Japan Society of Powder and Powder Metallurgy* (Vol. 63, No. 7, July 2016, pp 457-461), on the use of Metal Injection Moulding to overcome the problems in cast and forged TiAl intermetallic alloys for producing complex shapes. The researchers used a TiAl powder, produced by gas atomisation and having a mean particle size of 21.3 μm and initial oxygen content of 0.13%. This was mixed with a binder material consisting of paraffin wax (69%), atactic polypropylene (10%), carnauba wax (10%), ethylene vinyl acetate polymer (10%) and 1% di-n-butyl. Powder loading was 69 vol%.

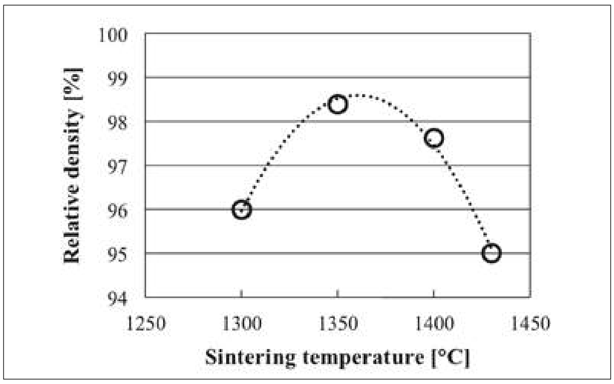

Fig. 1 Relative density of TiAl MIM compacts sintered at different temperatures (T. Osada, et al J. Jpn. Soc. Powder & Powder Metallurgy Vol. 63, No. 7 July 2016, 457-461. Originally presented at APMA 2015, the 3rd International Conference on PM in Asia, Kyoto, November 8-10, 2015)

After the injection moulding of flat bar tensile green compacts, debinding was first performed in heptane at 58°C for 3 h followed by thermal debinding in argon under pressure. Sintering was performed under vacuum or in Ar atmosphere (5 kPa) at 1300-1430°C for 8 h.

The researchers studied the density obtained in the sintered TiAl MIM compacts and tensile testing was performed at room temperature and at 700, 800 and 980°C. The highest density of 98.5% was obtained on sintering at

1350°C (Fig. 1). Different microstructures were obtained at the various sintering temperatures used. For example, duplex microstructures were found in TiAl sintered at both 1300 and 1350°C with near lamellar structures sintered at 1400°C and full lamellar structures when sintered at 1430°C. Oxygen content in the sintered TiAl MIM parts increased only slightly to 0.2%.

Elevated temperature tensile strengths obtained for MIM compacts sintered at various temperatures are shown in Fig. 2 and elongation values (also at elevated temperatures) are shown in Fig. 3. The highest elongation values, of 110%, were obtained with MIM TiAl compacts sintered at 1350°C and tested at 980°C. Although the tensile strength of the MIM sintered compacts was 10 to 15% lower at room and elevated temperatures respectively than the fully dense cast material, the researchers are confident that the same property levels can be achieved, or even surpassed, by further optimisation of the sintering conditions and Hot Isostatic Pressing to achieve full density.

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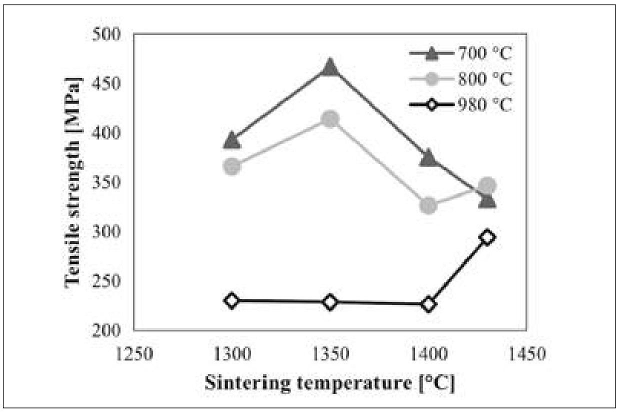

Fig. 2 Tensile strength of MIM TiAl alloys at elevated temperatures (T. Osada, et al J. Jpn. Soc. Powder & Powder Metallurgy Vol.63, No.7 July 2016, 457-461. Originally presented at APMA 2015, the 3rd International Conference on PM in Asia, Kyoto, November 8-10, 2015)

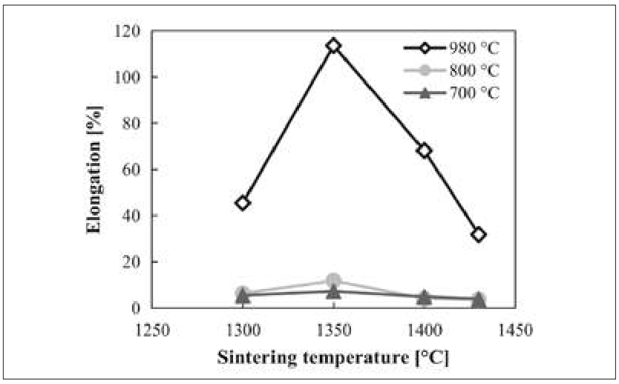

Fig. 3 Elongation values of MIM TiAl alloys at elevated temperatures . (T. Osada, et al J. Jpn. Soc. Powder & Powder Metallurgy Vol.63, No.7 July 2016, 457-461. Originally presented at APMA 2015, the 3rd International Conference on PM in Asia, Kyoto, November 8-10, 2015)

New *PIM International* website launched

PIM International's website has been re-launched with a number of significant visual and technical upgrades. The site is the largest on-line resource for the PIM industry. As well as featuring the latest industry news, an archive of back issues of *PIM International* offers anyone with an interest in the technology the chance to download past copies of the magazine in PDF format, free of charge.

Hugo Ribeiro, Production Manager at Inovar Communications, stated, "We have designed this new website to be much easier to read, with clearer, larger text and a more user-friendly interface. Importantly, the site now adapts to different screen sizes, so whether you are viewing it on a smartphone or a desktop computer, you will always be able to clearly read the contents."

The site also features significantly more flexible advertising banner spaces. Jon Craxford, Commercial Director at Inovar Communications, stated, "These new banner sizes allow companies to project their marketing message in a much clearer and more visual way, allowing more cohesive marketing campaigns to be developed across our digital/print magazine and the website".

www.pim-international.com

Addition of Si sees improvements in the properties of MIM aluminium

There has been relatively little research effort on the Metal Injection Moulding of pure aluminium powders due to the relatively low sintered density values that can be achieved as a result of the strong surface oxides on aluminium powder particles. Kiyotaka Katou and Akihiro Matsumoto of the Structural Materials Research Institute, National Institute of Advanced Science and Technology in Moriyama, Nagoya, Japan, have reported in the *Journal of Japan Society of Powder and Powder Metallurgy* (Vol. 63, No. 7, July 2016, pp 468-472) on their work to improve both the sintered density and strength of MIM pure aluminium using fine powders, along with the impact of the addition of Si to Al.

The authors first mixed pure Al powders having 20 µm, 10 µm and 3 µm particle sizes with organic binder based on paraffin wax and polymethacrylate and injection moulded the resulting feedstock to produce compacts having 50 mm (l) x 50 mm (w) x 2 mm (t). Debinding was performed in air at 325°C and at 380°C in argon with the latter resulting in lower oxygen content in the debound parts. All compacts were vacuum sintered at 650°C for 2 h. Density levels of 86%, 90% and 96% were achieved when average particle sizes were 20 µm, 10 µm and 3 µm respectively. Tensile properties of the sintered MIM pure Al compacts increased with decreasing particle size of Al powder and reached 120 MPa using 3 µm powder (Fig. 1). Elongation to fracture for this grade was 19% at room temperature.

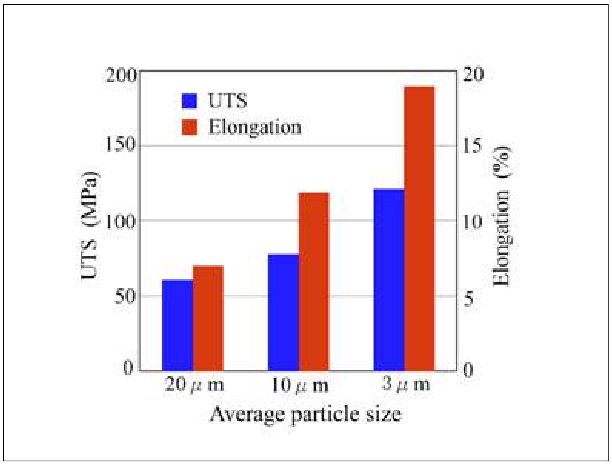

Fig. 1 Tensile properties of pure Al MIM compacts at room temperature (K. Katou, A. Matsumoto. Published in J. Jpn. Soc. Powder & Powder Metallurgy, Vol. 63, No. 7, July 2016, pp 468-472. Originally presented at APMA 2015, the 3rd International Conference on PM in Asia, Kyoto, November 8-10, 2015)

Composition	Particle size of Al powder (μm)	Sintering tempera-ture (°C)	Relative density (%)	Tensile properties		
				$\sigma_{0.2}$ (MPa)	UTS (MPa)	ε (%)
Pure-Al	11	650	83.3	41.7	74.6	5.2
Al-1Si	35	625	85.3	26.0	63.6	9.3
	35	635	87.7	25.8	69.7	10.2
	20	625	91.8	29.5	77.0	9.1
	20	635	93.0	31.7	79.2	8.5
	11	625	95.7	42.7	104.6	20.7
	11	635	96.9	41.7	107.8	24.6
1100[a]	-	-	-	35.0	90.0	35.0

Strain rate is 5×10^{-4} (/sec). a) Annealed wrought pure-Al

Table 1 Room Temperature tensile properties of sintered pure Al and Al1Si compacts produced by MIM (K. Katou, A. Matsumoto, Published in J. Jpn. Soc. Powder & Powder Metallurgy, Vol. 63, No. 7, July 2016, pp 468-472. Originally presented at APMA 2015, the 3rd International Conference on PM in Asia, Kyoto, November 8-10, 2015)

It is known that Si can enhance the densification of Al powder through the formation of a liquid phase during the eutectic reaction during sintering and the researchers carried out tests to establish the optimum addition needed to raise the sintered density of MIM AlSi compacts. They found that additions above 1 wt% Si did not provide a further contribution to raising sintered density. 1 wt.% Si was therefore selected for the production of the MIM Al-Si compacts. The five different grades, using 35 μm, 20 μm and 11 μm Al powder, were mixed with Si powder having 2 μm particle size and subsequently kneaded with an organic binder. Al-Si powder loading in the binder was 62%. The moulded compacts were debound in Ar at 380°C and sintered in vacuum at up to 640°C for 2 h. Linear shrinkage in the sintered Al-Si MIM parts was 14.2% compared with 6.8% in sintered pure MIM Al parts.

The researchers established that, regardless of Al powder size, the addition of Si powder widely enhanced the sintered density of Al-Si compacts especially for the finer Al powder grades (Table 1). The sintered MIM Al-1Si compacts had a tensile strength of more than 100 MPa and elongation of more than 20%, taking the MIM properties close to those of annealed wrought pure aluminium.

www.jstage.jst.go.jp/browse/jjspm/

Magnesium implant demonstrator parts successfully produced by MIM

Metal Injection Moulding appears to be an attractive process for the production of biodegradable orthopaedic implants using Mg alloys. A report by Martin Wolff and colleagues at the Institute for Materials Research at Helmholtz-Zentrum Geesthacht, Germany, published in *Metals* 6, 118, 2016, outlines the approach taken by researchers to adopt the MIM process to mass produce near net, complex shape implants. These are based on a new magnesium alloy material, which is stated to fully degrade into non-toxic elements and offer properties matching those of human bone.

The main focus of the research effort was to overcome the problem of the stable oxide layer on Mg powder particles, which acts as a diffusion barrier during sintering, along with the need, therefore, to prevent additional oxygen pick up and reactions between the Mg and polymer binder or debinding products during processing. The addition of a small amount of Ca was found to be beneficial in forming a liquid phase during sintering and weakening the oxide layer on the Mg particles. An addition of 0.9 wt% Ca proved to be optimal in terms of mechanical properties.

The researchers used a gas atomised Mg powder as the base material and mixed this with a gas atomised Mg-10Ca master alloy to achieve the desired Mg-0.9Ca composition. Paraffin wax, stearic acid and several organic polymer binder components were used to prepare the feedstock for the injection moulding process. The polymer content was varied between 5 and 35 mass% of the binder system. Use of PPcoPE copolymer in the feedstock binder system was found to provide defect-free green injection moulded parts without any jetting, blistering or cavity formation and satisfactory thermal debinding performance without impacting on the sintering of the Mg parts. The powder loading was 64 vol% for all feedstock batches. Injection moulding was successfully carried out to produce complex shaped demonstrator parts, as shown in Fig. 1, including a biodegradable Mg bone screw to replace polymer-based screws. The Mg-0.9Ca screws were moulded in the same moulds used for the polymer screws.

Debinding of the paraffin wax and the stearic acid components was carried out in a hexane bath at 45°C for 10 to 15 h using automatic solvent debinding equipment. Thermal debinding and sintering were performed in a combined debinding and sintering hot wall tube furnace

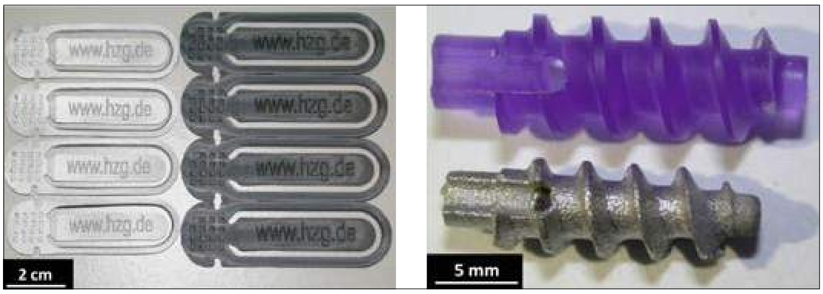

Fig. 1 Left: MIM demonstrator parts made from Mg-0.9%Ca at HZG. Green parts are on the right and the as sintered parts are on the left. Right: suture anchor screws produced by injection moulding. The lower screw is produced using MIM Mg-0.9Ca feedstock and the upper screw made from PLDLA using the same mould (Courtesy Conmed Linvatec., M. Wolff, et al. Metals, 6, 118)

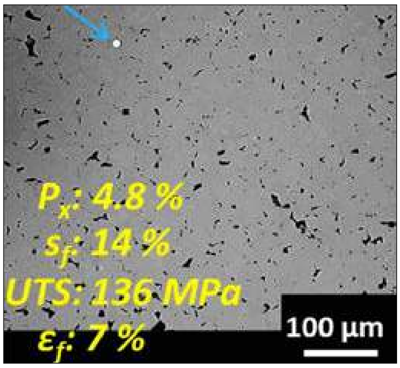

Fig. 2 SEM micrograph of sintered MIM Mg-0.9Ca (Courtesy M. Wolff, et al. Metals, 6, 118)

with integrated binder precipitation zone. The thermal debinding phase was carried out under vacuum and the atmosphere was switched to argon for the sintering cycle at 635°C for 64 h. The long sintering cycle is needed to destabilise the oxide layer on the Mg particles and to achieve high sintered density. The shortening of the sintering time down to 32, 16 and 8 hours is currently under development.

Fig. 2 shows an SEM micrograph of sintered MIM specimens after 64 h sintering time. The figure shows residual porosity P_x, shrinkage s_f, ultimate tensile strength (UTS) and elongation values at fracture ε_f as a function of the used backbone polymer.

Satisfactory mechanical properties were achieved at a porosity level of 4.8%, with a tensile strength of 136 MPa and 7% elongation at fracture. This could be increased to 142 MPa UTS and elongation of 8% ±1% and yield strength of 67 ±1 MPa by reducing the PPcoPE backbone polymer amount to 25 wt.% in the binder system.

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BASF interview: The global leader in MIM feedstock on the Asian market, growth opportunities and a new binder system

The MIM industry's success over the last two decades, in particular the spectacular recent growth in Asia, can be attributed in large part to the availability of continuous production systems. The introduction of BASF's Catamold® feedstock was the driver behind the development of these systems and BASF remains the industry's leading feedstock supplier. *PIM International's* Nick Williams interviewed the Metal Systems Global Unit management team on topics including the Asian market, growth opportunities and the development of a new catalytic binder system.

BASF SE, headquartered in Ludwigshafen, Germany, is the world's largest chemical company with 2015 revenues in excess of €70 billion. Nearly thirty years ago this giant of a company fundamentally transformed the fortunes of the Metal Injection Moulding industry with the introduction of its Catamold® feedstock system. This feedstock, based on a new catalytic debinding process, enabled for the first time the development of continuous MIM production lines, allowing MIM to deliver fast and stable high volume production and opening up new markets for the technology. In addition, the availability of a commercial feedstock system from such a recognised global company attracted new entrants into the industry, triggering rapid growth.

To this day, BASF remains the dominant global supplier of MIM feedstock. Whilst there is now a wide selection of feedstock and binder vendors, BASF's position as market leader has been strengthened in recent years thanks to the growing use of MIM components by global brand leaders in the computer, communications and consumer electronics (3C) industries. Such industry growth necessitated an expansion of BASF's Catamold operation and, in 2012, the company announced plans for a new MIM feedstock production facility at its Kuanyin site in Taiwan. The plant has a production capacity in excess of 5,000 tons per year.

Reflecting the rapid growth of MIM in China, the company also opened a new technical service laboratory for its MIM feedstock business in Shanghai. The new technical service laboratory for Catamold is located within BASF's Innovation Campus Asia Pacific in Pudong and provides technical support as well as customer training. As a result of MIM's success

Fig. 1 BASF's catamold feedstock system

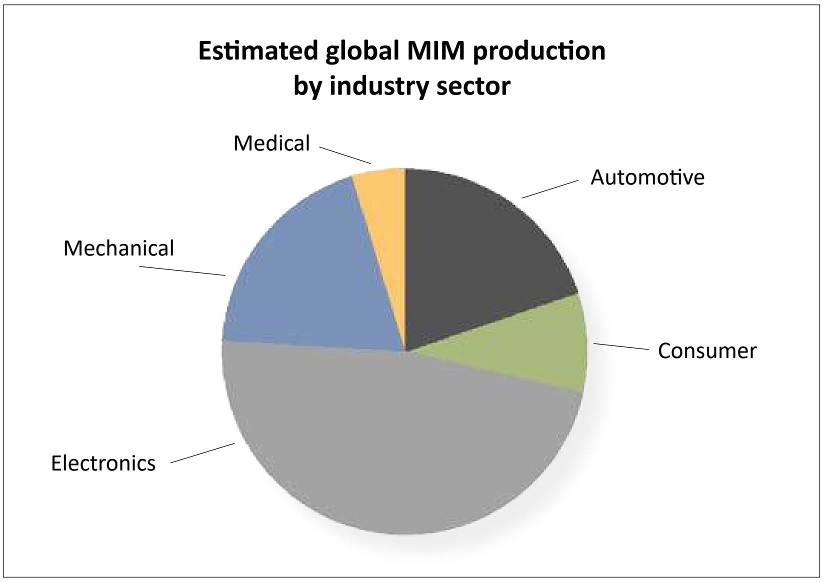

Fig. 2 Estimated global MIM production by industry sector

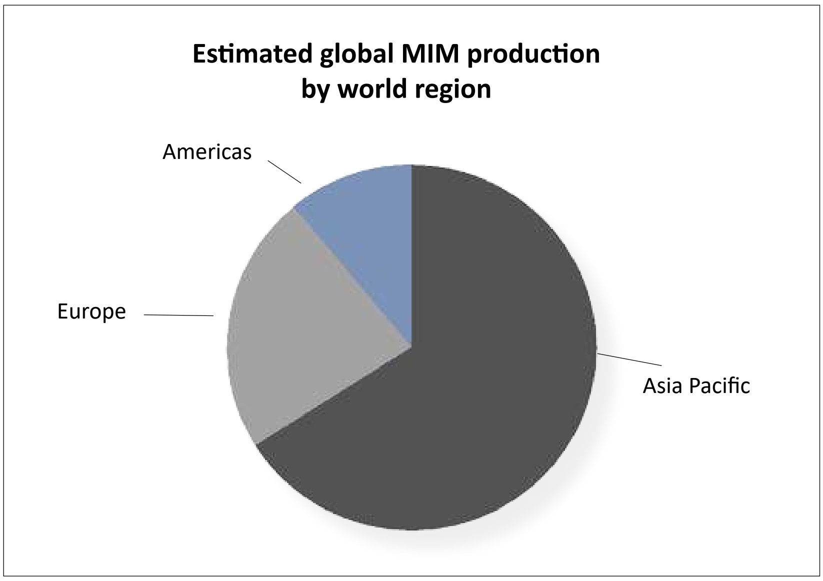

Fig. 3 Estimated global MIM production by world region

in the 3C sector, Asia's share of global MIM production has increased from an estimated 50% in 2012 to around 70% in 2016.

With the spectacular growth of MIM in Asia, it is, of course, all too easy to overlook the significant progress that MIM has made in other global markets. Whilst BASF has not offered its own estimate of the total current value of global MIM part sales, suggested by industry commentators to be in the region of $2 billion, the company has provided a breakdown of the production of MIM parts (by volume) by industry sector (Fig. 2) and by world region (Fig. 3).

PIM International recently interviewed BASF's Dr Stefan Koser (Vice President Metal Systems), Dr Oliver Koch (Global Business Manager Metal Systems), Dr Sven Fleischmann (Product Manager Catamold) and Matthew Lee (Regional Business Manager Metal System Asia Pacific). Over the following pages we share the management team's insight into the current status of MIM and the challenges and opportunities that lie ahead.

The 3C market in Asia

Asia has become the leading region for the production of MIM components and the most important market for Catamold feedstock, a dramatic change to the early days of Catamold when European MIM producers were the largest consumers. Commenting on how the 3C sector has transformed the MIM industry in Asia in recent years, Fleischmann explained, "The breakthrough for MIM parts production was clearly the industrial-scale use of the technology in consumer electronic parts production. The 3C sector was a catalyst for the whole MIM industry in Asia, as well as for the industrialisation of MIM technology globally. The industry was able to demonstrate that it could be relied upon to deliver part volumes running into the multi-millions. In Asia, this growth enabled established players to invest further in MIM and create new opportunities. What is clear is that the big 3C industry brands recognised the benefits of MIM technology for their component divisions, paving the way for the massive growth of the last few years."

Koser commented, "The Asian MIM market's spectacular growth over the last four years was, of course, initiated with the launch of a new generation of smartphone connectors. We are very confident that this tremendous growth will continue, driven primarily by the engagement of large consumer electronics brand owners." Other major applications for MIM are SIM card trays, buttons and bezels. However, there are numerous other MIM components to be found in today's smartphones.

BASF responded to the growth of the Asian market with major investments in both production capacity and customer support capabilities. Koser stated, "BASF has today gone truly global with its Catamold business. We launched a world-scale production plant in Taiwan in 2015 producing 17-4PH and 316L grades dedicated to the Asian market, in particular the Chinese and Taiwanese MIM industries. We opened and further expanded an application laboratory in

Fig. 4 An aerial view of BASF Ludwigshafen, the company's headquarters and one of the two manufacturing sites for the Catamold feedstock system. Some 39,000 employees work on this site

Shanghai with a dedicated Catamold team to boost innovation in the region and support customers on site with field application engineers. Our Catamold team in Asia expanded significantly in 2015 and this regional expansion will continue with the addition of further R&D, sales and technical support staff. We trust in the future growth of the MIM market in Asia, with growth opportunities in both the 3C sector and automotive applications."

The industry's success in the 3C sector has not been without challenges. Koser explained, "The 3C industry certainly challenged both the MIM production houses and feedstock suppliers in two ways. Firstly, it demanded the batch-to-batch consistency that was necessary in order to be able to deliver consistently high quality parts in volumes that had never been attempted before. Secondly, it demanded extremely cost effective feedstock combined with low cost MIM part production. These challenges forced the MIM industry to operate as a truly industrialised business. As a consequence, MIM has today developed from a niche to an extremely capable and competitive industrial-scale part production technology."

Fleischmann added, "The Asian market is extremely dynamic and is driven by innovation in the consumer electronics sector, with smartphones and more recently wearables being just two examples. We all know from our own lives that mobile device designs change every year. New sophisticated design features and steep production ramp-up phases require the rapid response of the whole value chain. In some cases we only have a few months to develop a new product and prepare for the production ramp-up before market launch. This business is ultimately project driven, which requires excellent teamwork and very close cooperation with our partners across the world. Our whole team is always very proud when we see parts made from Catamold in the latest 3C devices."

"We trust in the future growth of the MIM market in Asia, with growth opportunities in both the 3C sector and automotive applications"

BASF believes that despite the tremendous levels of growth in recent years there are many more

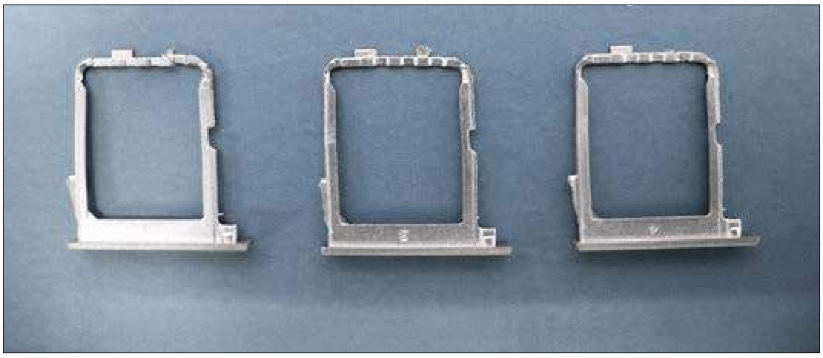

Fig. 5 SIM card trays in the BASF application laboratory for testing and development purposes. A typical grade for this application is 17-4PH

Fig. 6 Prototypes of a smartphone frame and back cover produced by BASF and Arburg GmbH + Co KG in a joint initiative using 17-4PH Plus grade Catamold feedstock. These parts are in an unpolished and unfinished state

Fig. 7 Prototype USB-C connector components developed at BASF's Shanghai laboratory as an alternative to conventional production processes. BASF states that the advantages of the 17-4PH Plus shell are in the good surface quality and very high strength, as well as the possibility to produce high volumes in a short period of time

opportunities for MIM if awareness among design engineers can be improved. Lee stated, "MIM is a very poorly known technology compared to other metal forming processes. One of our tasks is therefore to educate the market about this technology and help train newcomers. For us at BASF, in order to reach into new territories and markets for MIM technology, we always have to be the first to break through the barriers. Barriers that we have had to overcome - and continue to push through - include those relating to production volumes, the size of parts, material properties and performance and price, to name just a few. This is why BASF has been putting more resources into scouting new industries and seeking new applications where MIM has so far failed to penetrate."

Looking to the future, BASF anticipates that there are a number of new applications in the pipeline for MIM. Fleischmann stated, "We believe that besides buttons, SIM card trays [Fig. 5] and bezels, completely new part groups will be produced using MIM technology. In the short term, the next part groups will be the cases and enclosures of wearable devices. Smartphone frames [Fig. 6] and logos will be the new parts in the mid-term. The viability of new connectors, for example, is also being continuously evaluated as an alternative to stamping and forging production technologies [Fig. 7]."

In a number of sectors, including 3C, MIM parts have become commodity items. Fleischmann stated, "Indeed, the industrialisation of MIM has already taken place to a considerable degree. In certain markets, you can already call many high volume components commodity items. BASF, of course, welcomes and supports the high volume production of MIM parts as it clearly demonstrates the technology's viability. We are well prepared with innovative products and industrial-scale feedstock production processes to support the industrialisation process of MIM production."

Fig. 8 BASF's Ludwigshafen application laboratory team

Lee believes that the success that the technology has enjoyed in Asia in recent years will have positive knock-on effects for the global industry. "The Asian MIM market has, for the last three years, accounted for approximately 70% of global MIM production, with the main growth drivers being the big global consumer electronics brands. The global Catamold specialists within BASF run a large number of projects for multinational brand owners as one team. However, most of the manufacturing sites are located in Asia. As Sven mentioned, Catamold's Asian teams have expanded to support the dynamic market situation in Asia and we believe that these teams not only contribute to industry growth and development in Asia, but also in the global market."

Growth in automotive MIM

The automotive industry is becoming an increasingly important global market for MIM. Many of the earliest MIM automotive applications were developed in Europe, where some of the early adopters of MIM technology were Powder Metallurgy component producers with close connections to the automotive industry. As a result, the automotive industry is still the largest consumer of MIM parts in Europe.

With the globalisation of the automotive industry, MIM applications developed in Europe are now being adopted globally. In addition, the new automotive powerhouses such as China and Korea are taking an increasing interest in the potential of MIM. Koser told *PIM International*, "The roots of our MIM business are in Europe. We have enjoyed excellent relationships with customers in the region for more than two decades and these customers are very often the innovators and big players in the automotive, mechanical and consumer part sectors. The European market was key for us to penetrate the automotive industry with our Catamold products and expand the production of MIM automotive powertrain and interior parts. The EU market is still, and will remain, a strong pillar in our strategic goal to increase the number of applications in the automotive sector."

Fleischmann added, "The next growth step in MIM technology will be the further penetration of automotive parts production with a number of low alloy grades such as 8740 or 42CrMo4." Looking ahead, Koser stated, "Automotive customers will further challenge MIM technology with very high volume production, long part durability and very high quality standards. These customers will require us to improve our products and streamline our processes to meet all the needs of the automotive value chain."

There are, of course, major differences between the automotive industry and the 3C industry. Whilst both are extremely cost competitive, the pressures from purchasers in the 3C industry are different to those in the automotive sector. Koser stated,

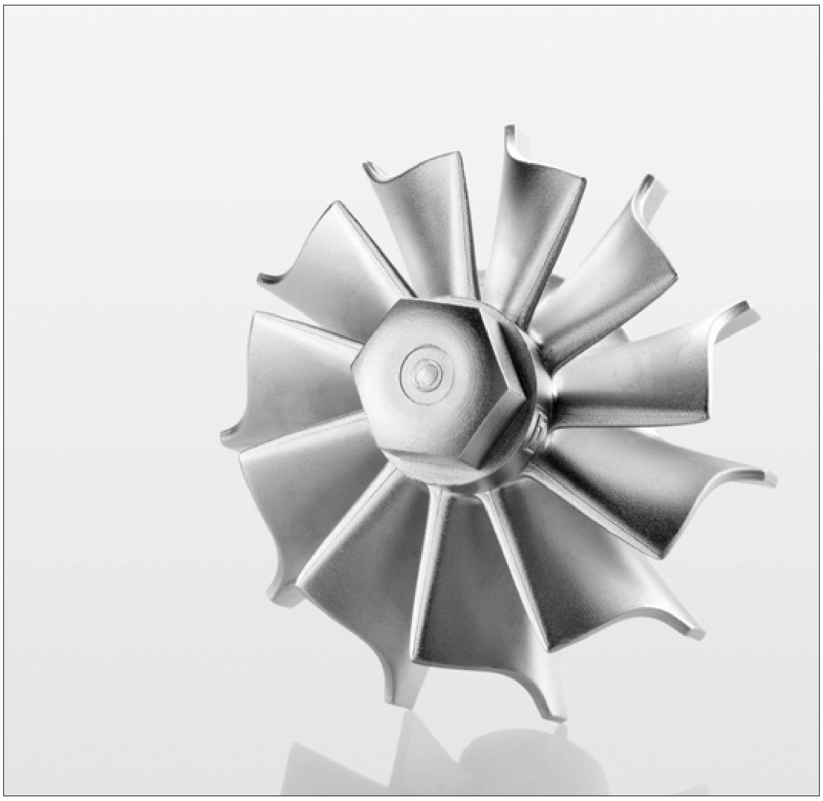

Fig. 9 The turbocharger wheel has been a target application for the MIM industry for a number of years. MIM technology has a strong track record in the production of turbocharger components from high temperature materials

"Projects for the 3C industry usually have a very tight schedule and need to be commercialised within a year, so time is of the essence. The product may then have a lifetime of between one and two years. 3C projects are very demanding with respect to fast ramp up and short project cycles. Automotive projects, on the other hand, follow a three to four year schedule prior to commercialisation and the life cycle of a product is then usually five to seven years. The qualification process follows a strict plan and there is a demand for very high standards of quality and consistency. Quality, consistency and cost are always of the essence."

Commenting on how BASF sees growth of automotive applications in the Asian MIM industry, Koser stated, "The 3C industry will continue to consume the major share of Asian MIM production in the future. However, we will see automotive projects reaching commercialisation in Asia and driving further market growth. As mentioned earlier, automotive applications require different materials, mainly low alloy steels. There is also the requirement for high quality, consistent feedstock. High quality MIM feedstock is a prerequisite in order to achieve stable, high quality parts production. While Europe is a crystallisation point for advanced automotive projects, with a wide range of exciting developments underway, the US and Asia follow suit, thereby adding to strong market growth."

Opportunities in the aerospace industry

The aerospace industry is becoming an ever more important user of MIM parts. Commenting on the primary drivers behind the adoption of MIM and the specific challenges associated with the sector, Koser stated, "The aerospace industry represents a potential future market for Metal Injection Moulding. As a competitive technology to investment casting, many turbine parts are potential target parts for MIM production. The major market entry barrier is the very high qualification requirements of aerospace engine parts. MIM parts used in the aerospace sector have to be scrutinised by a multi-year qualification regime. Liability questions in the case of part failures also need to be addressed before MIM can become a standard manufacturing technology for aerospace parts. For this reason, it can be anticipated that the majority of early MIM parts for the aerospace sector will be non-moving engine components."

The aerospace industry is also a major driving force behind the growth of metal Additive Manufacturing, a technology that, in some cases, uses alloy powders that are very similar, if not identical, to those used in MIM. In this regard, some see the use of metal powder based technologies such as AM as opening up opportunities for MIM in the case of a move to higher volume production. Koser stated, "Additive Manufacturing is a very interesting technology for the production of complex parts in low volumes. Where there is a steep ramp-up of parts production, MIM would be the ideal technology to enable this. It would therefore be very interesting to use AM materials that can be also be processed by MIM. This would also shorten the development cycle to convert an AM part to a MIM part."

Sustaining MIM's growth: winning business from competing technologies

It is widely accepted that in order to sustain current levels of growth the MIM industry not only has to develop new components that are specifically designed for the process, but also to convert parts from the more established competing production processes. "The major driver for MIM industry growth will be the qualification of existing parts that are currently produced using CNC or investment casting technologies. With each new part qualified for MIM production, the market will leapfrog. There are

Fig. 10 BASF's Shanghai application laboratory team, taken during a visit by Martin Bloemacher (middle, bottom row), Head of Application Service Catamold. Bloemacher is one of the driving forces behind BASF's feedstock system

already examples of new automotive engine and gearbox parts. However, in order to replace established technologies, MIM has to consistently demonstrate its superior costs of ownership versus CNC and investment casting technologies," stated Koser.

New applications or conversions to MIM are, of course, limited by part size. Whilst some relatively large MIM parts have successfully reached commercial production, Fleischmann explained that part size is just one factor that needs to be considered. "With very large parts, especially those with rather simple geometries, there are clear boundaries. There are, of course, highly complex MIM parts that go beyond 100 g and we have customers who make such parts. Typically, however, high volume MIM parts will range from 0.5 g to 50 g. MIM has the advantage of offering very attractive and high quality surface finishes as well as surface features. This can be a decisive factor in the cost analysis in comparison to investment casting, for instance. Purely on size and geometry, investment casting might be beneficial, but these parts then need extensive surface treatments that, in most cases, make MIM the winner. In my mind, understanding the total cost of ownership is essential. Here, as a rule of thumb, MIM has proven in a billion cases the advantages in the above scenario."

Next-generation binder systems on the horizon

BASF's Catamold technology was transformative for the MIM industry and since the launch of the system the range of alloys available has been tailored to meet market demand. The company now states that its focus is not only on developing new alloys but also on developing the next generation of Catamold binder system that will address some of the shortcomings of the original.

Fleischmann told *PIM International*, "We have invested substantial resources into R&D in recent years. Whereas in the past the emphasis was on new alloy development, we have put a lot of effort into the development and formulation of new binder systems. As a chemical company, we are striving to expand the boundaries of MIM with superior new binder chemistry. This new chemistry should overcome the disadvantages of comparatively low flowability whilst still preserving the benefits of the Catamold system such as fast debinding, high dimensional control, high green part strength and green part machining capabilities."

Fleischmann added, "We are highly committed to our POM [polyoxymethylene/polyacetal] binder based feedstock. POM is an excellent material with a level of stiffness that provides very good green strength and it is the core element for the catalytic debinding process. Our POM-based feedstock has convinced numerous customers over the years and many companies producing copies of the system follow in our footsteps. The feedstock is simple to use and usually quite forgiving."

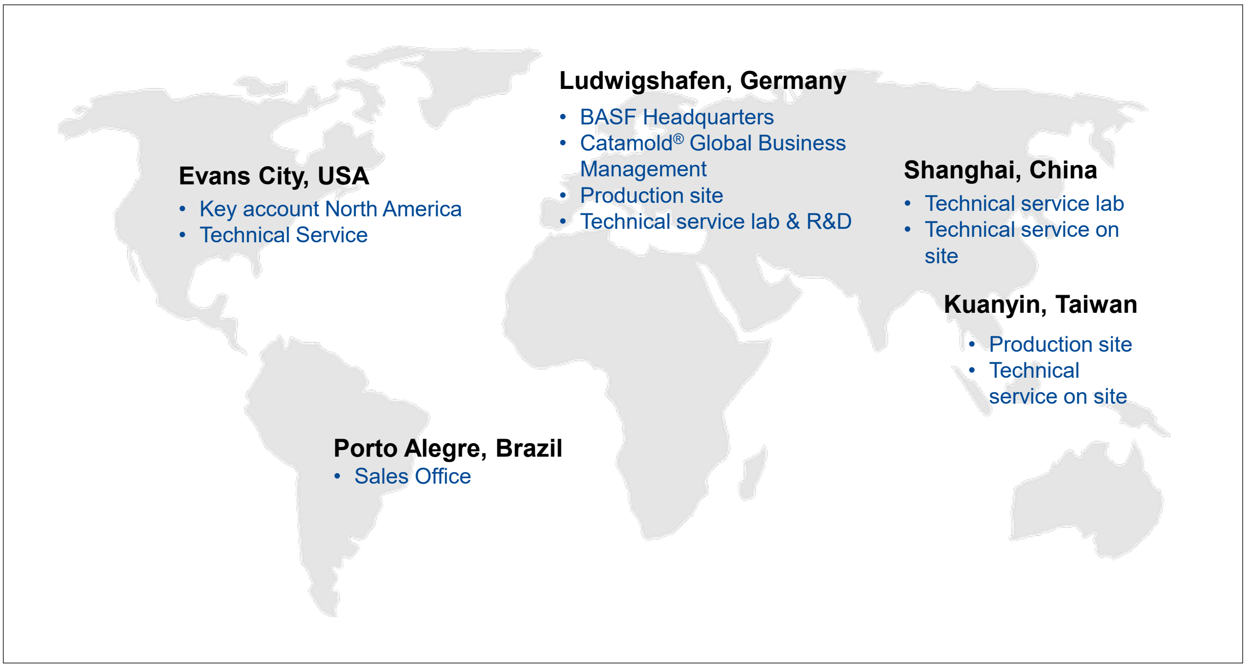

Fig. 11 Locations for BASF's Metal Systems Global Unit. The unit, led by Vice President Dr Stefan Koser, produces, supplies and develops on Carbonyl Iron Powder (CIP) and Catamold feedstock

"We would like to further improve the performance of our Catamold feedstock so that it will be as simple to use for skilled as well as less experienced users. This will enable a robust production process to penetrate into even more complex shapes and geometries as well as heavier parts. Again, innovation is an important tool here as well as operational excellence. Transfer of R&D products to production must follow stringent quality control processes so that all users in the dynamic and ever changing project landscape can enjoy, and trust in, the same quality of product."

"We would like to further improve the performance of our Catamold feedstock so that it will be as simple to use for skilled as well as less experienced users"

Since the expiration of the original Catamold patent, almost all other feedstock producers have started to offer a catalytic feedstock system. BASF is confident, however, that it can maintain its market leading position. Fleischmann stated, "The whole process requires more fundamental know-how than might appear at a first glance. We have often been told that competitors who energetically enter the market for catalytic feedstock can't keep their promises. The experience of the market leader over many decades brings with it the required knowledge to act with confidence in the market. It is also, of course, essential for a company to have a lot of stamina when it comes to large projects in this dynamic environment. It is of the essence to optimise each step of the value chain through operational excellence in order to launch a competitive and sustainable product. We at BASF have the critical mass to pursue these tasks. Innovation is the second pillar to defend our market position and, as stated before, new alloys will be important in the future, but we are also pressing ahead with our R&D activities on new, enhanced binder formulations."

Supporting industry growth

The PIM industry is made up of a diverse range of producers, from companies with just one injection moulding machine to giants with more than 250. Commenting on the challenges of supporting such a diverse market, Fleischmann stated, "We value the start-up company and the giant alike. In 2015, we consolidated our portfolio and took a considerable number of grades off the market. This was a big hurdle for our customers, regardless of whether they were start-ups or giants. We are, however, convinced that, with the ongoing industrialisation of MIM technology, a balanced product mix of a few real high volume grades, speciality products and the development of new applications will boost the technology further. We will constantly work on improving our product portfolio."

One of the first decisions that a new entrant has to make when considering moving into MIM is whether to develop feedstock in-house or purchase ready to mould feedstock. "Smaller companies will, at first, take the opportunity and go for a ready to mould feedstock. The decision might be driven by the investment costs for feedstock production equipment and skilled personnel or a lack of knowledge concerning binder formulations and processing," stated Fleischmann. "Only if they can't find a supplier, or they are dissatisfied with feedstock quality, will such a newcomer go in-house. Very often, however, the decision is influenced by the final customer who will inevitably consider the security of raw material supply and will very often insist on an independent feedstock supplier."

Fig. 12 Sensor housings in the green (left) and sintered (right) state manufactured by Denmark's Sintex a/s using the Catamold feedstock system

Outlook

There is no doubt that the Catamold team at BASF sees a bright future for MIM technology. The company's industrial-scale feedstock production plant in Taiwan has, to a large extent. enabled the dramatic growth of MIM that we have seen in Asia in the last five years. With the development of its next generation binder system for MIM the company can be seen to be putting its faith in the continuing expansion of the industry.

Fleischmann stated, "The catalytic debinding system has been proven to be superior to wax based systems. When it comes to high volume manufacturing and stringent quality requirements, such as tight tolerances and minimum distortion, industrialised production using the POM system clearly offers the best advantage. We therefore believe that the POM based system will play the major role in the coming years for high volume projects."

Concluding, Koser told *PIM International*, "MIM will capture increasing production volumes from CNC and investment casting technologies. Manufacturing and design engineers in the 3C and automotive industries are increasingly recognising MIM as a very reliable, proven large volume production technology for small, complex parts that fulfil demanding mechanical and design requirements. Our dream is that MIM technology will have a chapter devoted to it in standard engineering university textbooks. Once MIM has made it into the standard textbooks for metal forming technologies, then the technology has made it and the future market will be multiples of today's market size"

Fig. 13 A BASF employee at the Catamold applications laboratory in Shanghai inserting a sample tray into a sintering furnace

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Silcon Plastic: Metal Injection Moulding drives innovation in the luxury eyewear sector

The world market for luxury eyewear is dominated by Italian manufacturers and northern Italy is a centre for the design and development of this type of consumer product. Silcon Plastic s.r.l., in Forno di Zoldo, Italy, is an important manufacturer of eyewear components and frames. Dr Georg Schlieper recently visited the company on behalf of *PIM International* and reports on the ongoing development of its MIM activities.

Forno di Zoldo is a small village in a remote valley in the Italian region of Veneto. At an elevation of 900 m above sea level, it is situated below the majestic peaks of the Dolomite Alps and not far from the alpine ski resorts of Cortina d'Ampezzo, venue of the 1956 Olympic Winter Games. Silcon Plastic s.r.l. is the only industrial company in a valley that otherwise has a modest prosperity based mainly on tourism.

Arcangelo Costantin, one of the founders of Silcon Plastic , grew up in the Zoldo valley. He went through an apprenticeship for toolmaking and worked for several years in Milan, manufacturing tools for plastic injection moulding. In 1986 he returned to his home town and established a plastic injection moulding company together with his partner, Pietro Battistin. The young company specialised in overmoulding metallic parts with plastic and car keys were among the initial products. Eyewear parts, namely pads made from silicone, were however soon added to the company's portfolio. Nose pads, which are typically manufactured from silicone by injection moulding, were the inspiration for the company's name.

Today, Silcon Plastic specialises in aesthetic components for the eyewear and consumer products sectors. The company initially started in a private house with limited space. As the company grew, however, a second and then a third building were rented until the factory was split over five locations. In 2001 a new building with 4,500 m² of floor space was erected in the industrial zone of Forno di Zoldo that was large enough to accommodate all the company's operations under one roof (Fig. 1). This modern building provides a friendly, comfortable and state-of-the-art working environment.

Fig. 1 Silcon Plastic's factory building in Forno di Zoldo, Italy

Fig. 2 A section of the main injection moulding hall at Silcon Plastic

Fig. 3 Further view of the main injection moulding hall at Silcon Plastic

The Costantin and Battistin families are the sole owners of Silcon Plastic and the second generation is now in the process of taking over management responsibilities. Pietro Battistin's son, Andrea Basilio, manages the planning department and oversees the Material Requirements Planning (MRP) system. Virgilio Costantin, son of Arcangelo Costantin, manages the MIM business unit at Silcon Plastic and explained that staff turnover at the company is low because the roughly 130 employees of Silcon Plastic, most of whom live in the Zoldo valley, have a strong affinity for the region. "Recruiting qualified personnel in this area is, however, not so easy," stated Virgilio Costantin. "It is difficult to encourage people from outside the area to move into our valley. Life can be hard here, particularly in winter when heavy snowfall leads to poor traffic conditions. We therefore encourage school leavers from the valley to go on to higher education, gain their degree and then return to work with us as process engineers or tool designers, for example."

Silcon Plastic, on an ongoing basis, offers ten to fifteen apprenticeships in technical and commercial jobs. Technical professions are trained in the factory for toolmaking, operating injection moulding machines, learning surface finishing processes, undertaking quality inspection and trimming parts.

All parts of the eyewear frame, including the frame holding the lenses, the nose pads, temples, temple tips and hinges, are produced by Silcon Plastic. Most of these parts are manufactured by plastic injection moulding or by the pressure die casting of Zamac alloys. Approximately one hundred injection moulding machines are in service and Silcon Plastic stated that it has a total daily production of around 200,000 parts, including both Metal Injection Moulded and plastic components. Figs. 2 and 3 show the company's main injection moulding hall.

Some of the world's most prestigious eyewear brands such as Emporio Armani, Bulgari, Chanel, Dolce & Gabbana, Prada and Ray-Ban, just to name a few, use Silcon Plastic's products. In order to help these design houses to create striking and fashionable glasses, the company has developed specialist skills in mould design, overmoulding and surface finishing. These skills contribute to the successful production of parts that can achieve the highest aesthetic requirements.

A high priority is also given to protecting the environment. As examples, the water used in surface finishing processes is fully recycled and solar cells installed on the roof of the factory provide 12.5% of the electricity used in the plant.

Silcon Plastic's approach to Metal Injection Moulding

Small and complex components for eyewear frames have been an important application for the Metal Injection Moulding industry for a number of decades. As interest in the technology increased it was a natural step for the company to adopt the technology in order to supply its eyewear customers with a complete portfolio of products.

Fig. 4 Furnaces for vacuum sintering (left) and thermal debinding (right)

The company started the development of its in-house MIM operation in 2007 and today it is managed by Virgilio Costantin. A materials engineer, Virgilio studied metallurgy at the University of Trento and was additionally educated in MIM technology at the European Powder Metallurgy Association's specialist short courses and Powder Metallurgy Summer School. With this background knowledge the company selected MIM feedstocks based on a water soluble binder system which is available from a commercial feedstock supplier. "This was the most environmentally friendly solution and only a moderate investment was required for our debinding and sintering systems. Moreover, the injectability of these feedstocks was excellent for small parts with thin walls," stated Costantin.

Silcon Plastic's MIM operations are based on batch type production facilities (Fig. 4). The debinding process is performed in two steps, with the parts first immersed in hot water to extract the polyethylene glycol binder, the water soluble constituent, to create an open pore network in the parts. The remaining backbone binder is then removed thermally and initial sintering is achieved in a second step at temperatures up to 600°C. Two high temperature vacuum furnaces, one with molybdenum and one with graphite heating elements, are used for sintering. The graphite furnace is used for carbon steels and the molybdenum furnace for carbon-free stainless steels and titanium alloys.

Silcon Plastic has a relatively straightforward approach towards minimising distortions during sintering. Aesthetic MIM components have to be sintered to high densities in order to be able to achieve the necessary surface finish after polishing. This requires high sintering temperatures at which alloys can soften and, as a consequence, undesired distortion can occur.

"Aesthetic MIM components have to be sintered to high densities in order to be able to achieve the necessary surface finish after polishing."

Sintering supports are therefore used as necessary to counteract this effect. Sizing after sintering is also used where necessary to improve the dimensional accuracy of sintered parts, but, in general, the company believes that MIM parts should be ready for surface finishing operations immediately after sintering wherever possible. "Each part requires

Fig. 5 The final polishing of an injection moulding tool at Silcon Plastic

careful engineering of the process to reach the best possible results," commented Virgilio Costantin.

High-end eyewear products are an important part of the global fashion industry and Italy's fashion houses are included amongst the leading players in this market. By definition, fashion oriented products are subject to frequent design changes and the life cycles of fashion products are relatively short. Suppliers are therefore forced to react quickly on model changes.

For injection moulding based technologies, with their requirement for relatively costly tooling, this is a particular challenge. Silcon Plastic has learned to operate profitably in this market, where production volumes can be as low as one to two thousand parts per year. Only a few products are required in volumes of hundreds of thousands or millions. With an in-house department for part and tool design, along with a large tool shop, the company is in a position to react quickly to customer demands and it is able reduce the time from the drawing board to market to a minimum.

The tool design department is equipped with workstations for CAD/CAM and mould fill simulation software and the tool shop is equipped with modern EDM and CNC machines. A staff of ten toolmakers produces approximately 200 moulds per year. Some parts of the tooling can be standard, but the main parts, such as the cavities and the sliders, are manufactured specifically for each component. The final manual polishing of the tooling requires skill and experience (Fig. 5).

The first MIM parts produced by Silcon Plastic were hinges for eyewear frames however in the last two years the company has expanded into the wider fashion industry, as well as the industrial automation and domestic appliance markets. Part weights range from 1 to 50 g and most parts are manufactured from 316L or 17-4PH stainless steels. A part for an automotive application is made from the low alloy steel 42CrMo4.

When Silcon Plastic started its MIM activities nearly ten years ago the factory was organised solely for the production of plastics. The owners therefore decided to start MIM production in a new area that was entirely dedicated to MIM. There was also some concern that contamination might arise between the MIM feedstocks and plastic raw materials. In order to avoid this, the decision was taken to separate the MIM production from the plastics plant in another building.

The challenges of producing aesthetic MIM parts

Eyewear components demand the highest aesthetic standards and marks from gates, ejector pins and mould parting lines must therefore be avoided or removed. In order to achieve this, manual trimming is often required. This is the most labour intensive part of the production and on MIM parts trimming is usually done in the green state. A wide variety of post-sintering operations is installed at Silcon Plastic, including polishing, tumbling with stones or wood chips and electroplating in order to achieve the necessary surface finish.

Crucial for the quality of aesthetic MIM parts is a homogeneous mould fill. Powder-binder separation has to be avoided as this can lead to irregular surfaces. Mould fill studies are undertaken for each new MIM part and, during production runs, all parameters of the injection moulding machine are recorded so that, in the case of defective parts, it is possible to trace the cause.

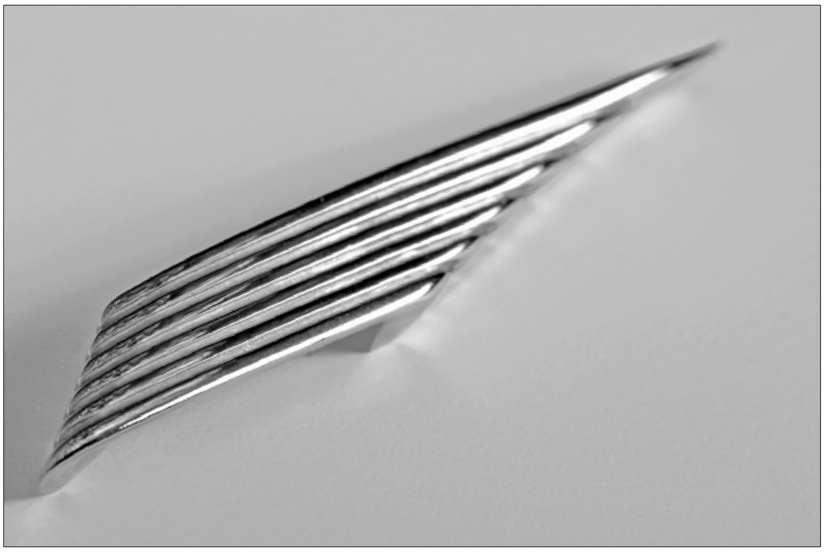

Fig. 6 An example of a MIM eyewear component with a polished surface

Collaborating on award-winning MIM design

The market for fashion-oriented eyewear is steadily growing and specialist designers strive to come up with striking designs and original solutions. An extremely innovative design for a MIM eyewear hinge was created in close cooperation with Silcon Plastic by the Danish eyewear design studio ProDesign and its partner Visottica Industrie S.p.a., the company that assembles the MIM hinge. The patented hinge consists of three MIM parts of complex geometry, one connected to the temple, one holding the frame and an intermediate component that forms a stable and attractive, yet flexible, connection between the eyeglass frame and the temple. The hinge won the highly respected "Eyewear of the Year 2016 Award" at the International Optical Fair in Tokyo, Asia's leading eyewear show.

Fig. 7 An eyewear frame with an award-winning MIM hinge, showing the movement of the temple

"The main concerns in the design phase were given by the fact that, for aesthetic reasons, the intermediate component is subjected to a PVD treatment, which coats the component with a black ceramic layer in order to make it wear and scratch-resistant," Virgilio Costantin told *PIM International*. "The outer two parts are light grey. The most at-risk areas, in fact, are the small faces of the temple and of the front component that are continuously sliding on the intermediate component."

In contrast to most eyewear frames, the temple movement of this design is radically different (Fig. 7). The temple doesn't horizontally fold towards the frame, but instead is turned in the vertical direction at an angle of 90° until it reaches the desired position in parallel with the frame.

In the assembled condition, the award-winning hinge does not look particularly complex (Fig. 8), however the complexity of the three interlocking MIM parts can be fully appreciated when the hinge is disassembled (Fig. 9). A particular challenge for Metal Injection Moulding was the low wall thickness

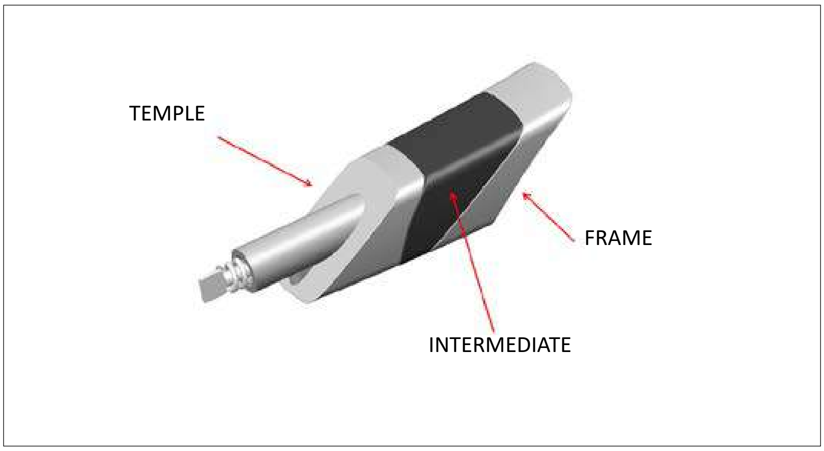

Fig. 8 The three MIM parts used in the award-winning hinge

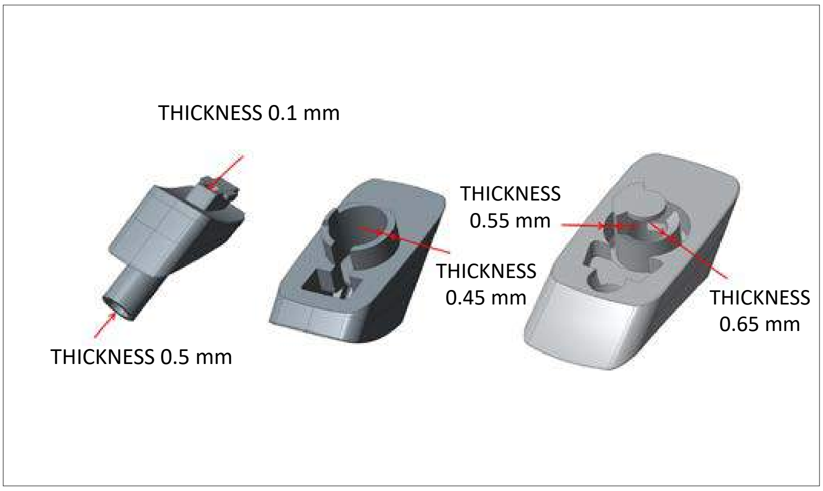

Fig. 9 Wall thickness below 0.5 mm on the three complex MIM components of the eyewear hinge

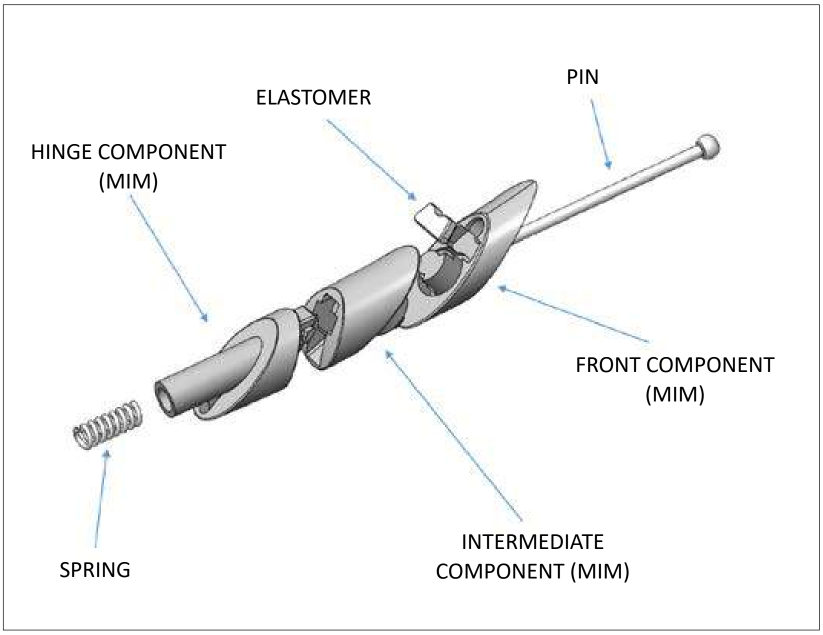

Fig. 10 Exploded view of the eyewear hinge

of less than 0.5 mm at several points. MIM is the only viable technology that can deliver the required shape and dimensional accuracy without any machining operations.

Fig. 10 shows an exploded view of the eyewear hinge in which its function can be understood. The outer shape of the parts is non-functional and this can therefore be round or rectangular depending on the temple design and a third shape will be released soon. The turning movement for closing the temples occurs between the front component and the intermediate component. The intermediate component and the hinge component are separated so that the temples have some flexibility when overstretching occurs.

Intensive fatigue testing was performed on the hinge in order to prove its strength and durability. The movements relating to overstretching, turning and closing the temples were tested over 50,000 times and the MIM 17-4PH parts passed all tests without any failures.

Other MIM parts

Other examples of MIM products made by Silcon Plastic are compo-nents for automatic doors, hinges for a whiteboard and parts for a wristwatch. Fig. 11 shows a selection of eyewear hinges and a home automation part that are produced by the company. These parts are made by MIM because of the high volumes required and because no additional process steps are necessary other than surface finishing. In particular the components in the first line belong to two famous fashion brands. The part in the bottom corner on the right is a component for a home automation application that was originally produced in Zamac, but then switched to MIM stainless steel because of the insufficient strength of the Zamac material. "Because many of the parts that we produce are very small, we have capacity for relatively high volume production with just two sintering furnaces," stated Virgilio Costantin. Besides the eyewear sector, where Silcon Plastic

Fig. 11 A selection of MIM eyewear hinges and a home automation part (lower right) produced by Silcon Plastic

has a strong position in the market, the search for other MIM applications continues.

A number of MIM parts are overmoulded with plastic, a process in which Silcon Plastic has much experience. An example of a MIM part for a temple which is overmoulded with red plastic is shown in Fig. 12. Overmoulding requires the metal inserts to be produced to extremely high tolerances. Without the necessary precision, plastic can squeeze into the gap between the mould cavity and the insert, significantly impacting on the quality of the product.

Titanium MIM parts

The interest in titanium MIM has been steadily growing in recent years. Titanium has the strength of steel, yet just under half the weight, is corrosion resistant and is compatible with human tissue. Consumer products can be produced with an attractive colourful appearance by hard anodising the surface. Applications

Fig. 12 A MIM part for a temple overmoulded with red plastic

Fig. 13 MIM titanium parts used in the joint of a knee rehabilitation device

Fig. 14 Quality control at Silcon Plastic

Fig. 15 MIM parts for the luxury market in the green state

range from aerospace to biomedical as well as consumer goods such as watches.

In recent years, Silcon Plastic has worked with the University of Trento to qualify its MIM process for the titanium alloy Ti6Al4V. The material properties were studied by tensile testing and fatigue testing. Light and scanning electron microscopy were also applied, along with chemical analysis. The limit values for the interstitial elements C, N and O of ASTM Standard B348-02 were successfully undercut and the required mechanical properties were met. Some of Silcon Plastic's first MIM titanium parts are used in the joint of a knee rehabilitation device as shown in Fig. 13.

Other R&D partnerships

In addition to collaboration with the University of Trento, research is also undertaken in cooperation with Padova University. Technical problems based on actual parts in production or under development are given to students in the form of research projects, allowing the students to gain an insight into the reality of an industrial production plant.

Marketing activities

Securing the future of the company requires continuous marketing activities. In the eyewear sector, Silcon Plastic is widely known and the company has a well-established customer base. Orders from existing customers therefore ensure a baseline utilisation of the MIM facility without the need for marketing activities. Nevertheless, as a leading supplier of eyewear components, Silcon Plastic is committed to strengthening its customer relations by exhibiting at the main trade exhibitions for this sector. The company is also marketing its MIM expertise via an exhibition stand at the Powder Metallurgy World Congress in Hamburg, Germany (October 9-13 2016).

The company is exploring additional exhibitions in other end-user sectors with a view to diversifying its product range and expanding into new markets. Finding new applications outside the eyewear sector is top of the agenda. "Diversification is an important issue for us," Virgilio Costantin told *PIM International*, "and we have great expectations that the Metal Injection Moulding of steel and titanium alloys will help us to develop new applications and new markets where we can build on our expertise for the further growth of our business."

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The evolution of continuous furnaces for MIM: Delivering enhanced quality, energy efficiency and capacity

The introduction of continuous debinding and sintering furnaces has significantly improved Metal Injection Moulding's ability to challenge machining and investment casting for the production of high volume precision components. Early systems, however, had a number of restrictions that hampered both production flexibility and the drive towards increased energy efficiency. In the following article Eisenmann SE's Sven Heuer explores the impact of continuous furnace technology on MIM and explains how the technology has advanced to meet the demands of the industry.

While MIM stands for Metal Injection Moulding, its uniqueness actually lies in the debinding and sintering processes. In the first debinding step most of the binder is removed, creating open pores in the component. In the second step, the rest of the binder is removed by thermal degradation. As this usually takes place during the sintering cycle, it is essential to ensure that no binder remains before sintering closes the pores. At the moulding stage, components with defects can be recycled, but faults that occur during sintering lead to total loss of material. Sintering defects are therefore a major cost factor in MIM and the effective management of the debinding and sintering steps is critical.

The current state of the art in the sintering of MIM parts is a combined process comprising secondary debinding and high-temperature sintering. Core requirements include the meticulous removal of all residual binder, carbon control, oxygen reduction, precisely controlled shrinkage and optimal diffusion. The processes involved are complex. Injecting the feedstock into the mould produces a green part consisting of approximately 60% metal powder and 40% binder. During first stage debinding, generally by thermal treatment and a catalytic reaction or the use of a solvent, binder content falls to 5%. The resulting brown part has a porosity of 35%. Secondary

Fig. 1 The Eisenmann Thermal Solutions headquarters in Bovenden, Germany, is at the heart of the company's development of MIM and PM sintering furnaces

debinding at temperatures between 200 and 600°C and sintering at 1,200 to 1,360°C in various atmospheres (vacuum, nitrogen, hydrogen and/or argon) converts what are known as 'brown' parts into the finished component. Porosity has been reduced to less than 2% and the parts meet basic strength and surface-quality requirements (Fig. 2).

The growth of MIM in relation to continuous furnace developments

Although MIM has existed for around four decades, it only became a viable and successful field of manufacturing with the development of dedicated debinding and sintering equipment. Binder formulations were the primary focus in the early 1980s. The market leaders, primarily US-based, sold corresponding licences to companies worldwide. Debinding and sintering systems usually consisted of modified laboratory-scale equipment and high vacuum sintering furnaces, similar to those used in vacuum brazing. It was BASF SE's development and commercialisation of the Catamold catalytic debinding system in the late 1980s and early 1990s that led to the first continuous debinding and sintering process. In the early 1990s, Cremer Thermoprozessanlagen GmbH launched its first fully continuous MIM Master system onto the European market, heralding a new era for the technology.

In Europe, the deployment of continuous furnaces to produce automotive and wristwatch components enabled Metal Injection Moulding to grow rapidly. Swiss, German and Spanish companies demonstrated the method's suitability for continuous production on a large scale. The European MIM industry, which focused on automotive applications, looked set to dominate worldwide.

At the start of the 21st century few could have predicted MIM's phenomenal growth in Asia as very few producers in the region had adopted continuous sintering systems. Leading players in Japan, Taiwan and Singapore concentrated on 3C applications and, as the corresponding parts were relatively small and the applications life cycles short, batch processes were initially regarded as more appropriate.

At the same time the European MIM industry began to explore potential process improvements. The main goal was to raise the capacity of debinding furnaces without driving up consumption of substances such as nitrogen and nitric acid. The most recent continuous furnaces are now able to halve the quantities of nitrogen and nitric acid required while doubling throughput [1-3].

In addition, a new type of continuous debinding and sintering furnace was introduced by Elino Industrie-Ofenbau GmbH. Based on a conventional pusher furnace, this modified unit featured fully segregated atmospheres in the secondary debinding and sintering zones (Figs. 3 and 4) [4].

"In Europe, the deployment of continuous furnaces to produce automotive and wristwatch components enabled Metal Injection Moulding to grow rapidly."

While European MIM specialists sought to diversify their applications, Asian players began focusing on the mobile-phone industry, where the technology proved very successful. Apple's extremely high demand for MIM components became common knowledge following a special-interest seminar on Powder Injection

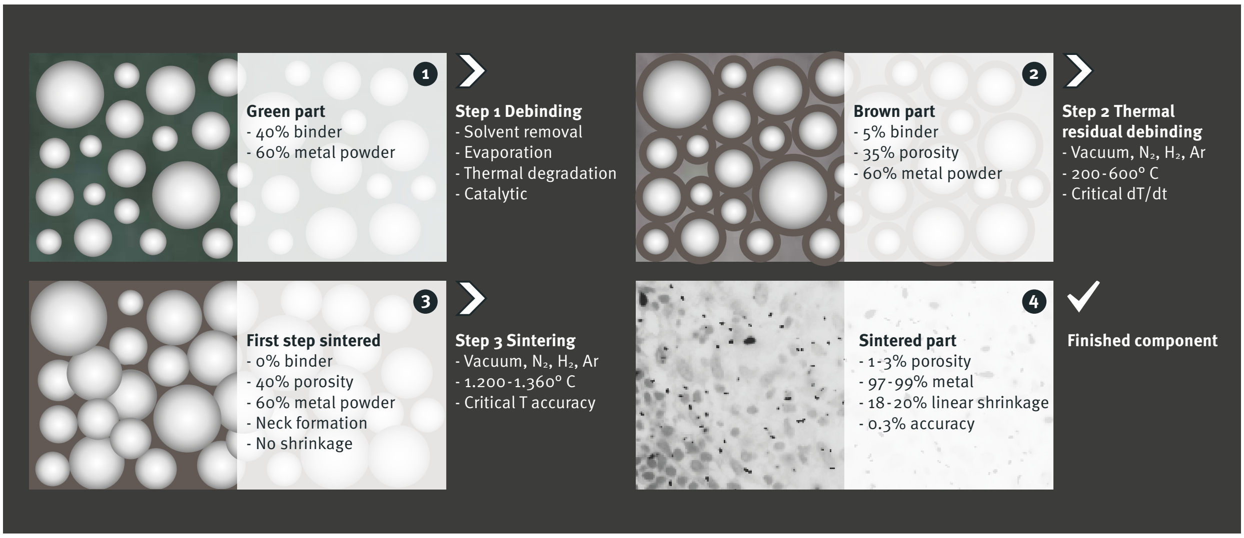

Fig. 2 The steps from a green part to a sintered part in MIM

Fig. 3 Continuous MIM processing system including debinding, secondary debinding and sintering (Courtesy ITB Precisietechniek, The Netherlands) [4]

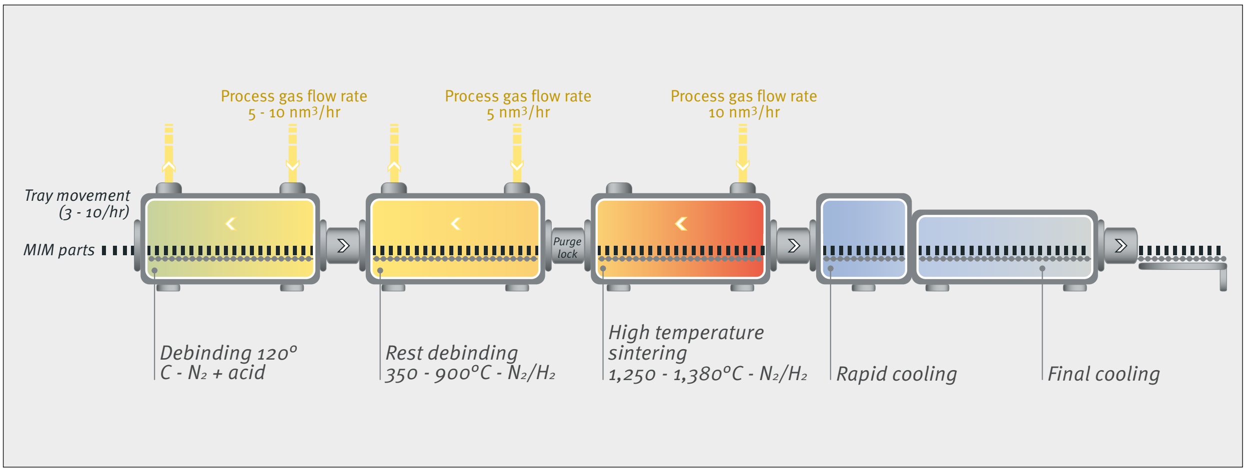

Fig. 4 Continuous MIM debinding, secondary debinding and sintering layout

Moulding held at the 2012 Powder Metallurgy World Congress in Yokohama, Japan. In conjunction with the development of smart watches and fitness trackers, this has helped Asia to become the world's largest producer of Metal Injection Moulded parts.

The 2016 PM China Exhibition, held in Shanghai from April 27-29, once again highlighted the meteoric rise of MIM in Asia. There are now more than thirty continuous MIM lines in operation in Greater China and India, underscoring the widespread uptake of continuous debinding and sintering systems.

Chinese equipment suppliers have responded accordingly. For example, Ningbo Hiper Vacuum Technology recently introduced its first continuous debinding and sintering furnace, consisting of a catalytic debinding furnace and a walking-beam secondary debinding and sintering furnace, similar to the MIM Master systems.

These trends point to strong competition among furnace makers and, as demand grows, users' expectations of this state-of-the-art technology are also rising.

Batch or continuous operation?

Manufacturers of typical Metal Injection Moulded products, for example for medical devices, electrical goods, telecommunications or the automotive industry, often have to decide whether to invest in batch or continuous furnaces. Relevant process parameters include product type, dimensions, composition and output, plus temperature profile, sintering temperature, composition of the atmosphere (N_2, H_2, argon, endothermic gas, mixtures) and pressure (vacuum, atmospheric, high

Criteria	Small batch furnace (30l max)	Large batch furnace (> 30l)	Pusher furnace	Walking beam furnace	Roller hearth furnace
Capacity	Low	Medium	High	Very high	Very high
Flexibility	Very high	Medium	Low	Low	High
Investment	Low	Medium	High	High	High
Sintering cost per part	High	Medium	Low	Low	Low
Energy required per part	High	Medium	Low	Low	Very low
Floor space required	Little	Little	Large	Large	Large
Fast cooling / quenching	Good	Good	Fair	Fair (Loss of capacity)	Excellent
Temperature uniformity	Excellent	Fair	Excellent	Fair	Excellent
Vacuum sintering	Possible	Possible	Impossible	Impractical	Technically feasible
Atmosphere control	Excellent	Good	Good	Fair	Good
Vibrations on parts	No	No	Yes	Yes	Yes

Table 1 The properties of all major furnace types used in the Metal Injection Moulding industry

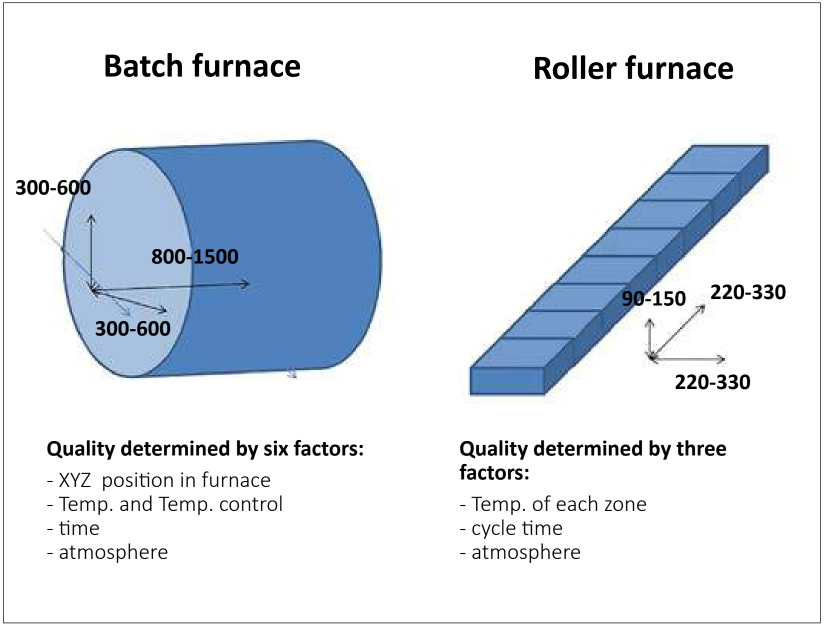

Fig. 5 Determining quality variables in the batch versus continuous sintering of Metal Injection Moulded parts [5]

pressure). Table 1 shows the properties of the major furnace types used in the MIM industry.

Meeting customers' expectations is always a high priority and manufacturers agree on the challenges. Rising energy prices and the growing need for companies to reduce their environmental footprint mean that energy efficiency is the key issue. Production systems must also be cost-effective whilst offering maximum flexibility. Against this background, ease of operation, ease of maintenance and support for automation are further key criteria. Last but not least, production plants must fulfil both throughput and quality requirements. "Customers' choices are often shaped by outdated thinking," stated Peter Vervoort, Vice-President Product Development & Technology at Eisenmann Thermal Solutions. "In many cases, continuous roller hearth furnaces with state-of-the-art double doors and continuous heating are the best option today and in the future."

Metal Injection Moulding processes are largely performed in conventional batch furnaces. These are usually cold-wall vacuum furnaces with capacities of between 50 and 500 litres. Heating elements, radiation shielding and fixtures are made from graphite or molybdenum and cycle times are generally 14 to 24 hours. Continuous roller hearth furnaces are much faster, have higher throughput, consume less energy at suitable workloads and are more cost-efficient to operate. Continuous furnaces also offer advantages, stated Vervoort, in terms of production quality. "In the cylindrical combustion chamber of a batch furnace, reproducible product quality is dependent on six factors: atmosphere, cycle time, temperature control and X, Y and Z positions within the furnace. The position of components in a roller furnace, by contrast, has no significant impact on quality, as the material passes through the furnace along a single axis. As a result, all finished parts are of consistent quality" (Fig. 5).

While batch furnaces with closed chambers have to be cooled and reheated after every sintering cycle, the smaller trays employed in continuous furnaces (three to ten per hour) are conveyed steadily through the open system at a constantly high temperature. As a result, the parts themselves are heated uniformly. This is key to high product quality as even slight temperature fluctuations can lead to non-uniform shrinkage. Systems with multiple temperature-control zones and very high-precision sintering temperatures (+/- 3°C) are favourable in this regard. In short, batch furnaces are advantageous in terms of capital expenditure, flexibility, floor space, atmosphere control and minimising the vibration of fragile brown parts, whereas continuous furnaces with pusher or elevator hearths offer tangible benefits with respect to capacity, sintering costs and energy consumption per part.

From the above it could be easily concluded that continuous production is always the best solution. The overall production scenario is decisive. As Vervoort explained, "A continuous system would be inappropriate for the production of titanium endoscopy components with an annual output of 1,000 units. Similarly, continuous furnaces are unsuitable for titanium dental implants, both in terms of application and output quantities. Sintering of titanium requires a very clean atmosphere and continuous systems operating under an argon atmosphere have oxygen concentrations that would oxidise titanium."

"On the other hand, an automotive components supplier looking to produce a million hydraulic connectors made from 316L stainless steel (Fig. 6) is likely to opt for a continuous furnace. Critical factors, in addition to temperature control, will be large batch sizes and high throughputs. A small continuous furnace can process three trays per hour, or some 65,000 parts per day, whereas a batch furnace with similar energy consumption per day can only handle 10,000 parts [Fig. 7]. The bottom line is that continuous sintering would cut production costs by up to 30%," stated Vervoort.

Fig. 6 Hydraulic connectors are produced in high volumes for the automotive using continuous furnaces (Image courtesy Eisenmann)

Fig. 7 Charge carriers loaded with MIM parts (Courtesy ITB Precisietechniek, the Netherlands)

Even for large scale applications, many MIM producers are still reluctant to use continuous operation. Vervoort added, "In the early days of MIM it was stated that continuous debinding and sintering only paid off with a utilisation of 80% or more. With the second generation continuous MIM furnaces delivered from 2006, this statement was proven wrong."

Modern continuous furnaces for Metal Injection Moulding offer several enhancements that allow for much lower operating cost at low utilisation. These are:

- Reduced energy consumption through improved insulation
- A reduction in the use of process gas when the furnace is empty by 80% in combination with a quick purge of the furnace when switching between process gases
- The possibility to operate with one shift only, without loss of quality (earlier furnaces needed to be continuously full with a stable loading to be able to guarantee constant part quality)

Fig. 8 Eisenmann's roller furnaces for Powder Metallurgy defined new standards for the sintering and heat-treatment of sintered parts

- Improved visualisation systems with 100% tracing of the lots facilitating fast change over production.

"Depending on the local cost of energy, process gas and labour, continuous debinding and sintering already pays off at a utilisation of 40%," stated Vervoort.

Developing the next generation of MIM furnaces

The continuous systems available today certainly perform well, but Vervoort believes that there have been no new developments for a decade or more and the technology has by no means reached its peak. "We at Eisenmann are determined to change this situation and are partnering closely with customers to design, build and test continuous furnaces. It's time to discover and exploit their full potential."

Eisenmann is a leading global provider of industrial solutions for surface finishing, thermal process technology, environmental engineering and material flow automation. By merging with furnace specialist Ruhstrat in 2015, Eisenmann Thermal Solutions now enjoys an extensive skillset. In its technical centre, based in Bovenden, engineers develop heat treatment furnaces for many sectors of industry. Its roller furnaces for Powder Metallurgy, which were introduced in the late 1990s, defined new standards (Fig. 8). The development of temperature-resistant double-door systems, in conjunction with flexible roller drives, allows the segregation of all furnace zones, even the hottest. In combination with a modular design, the solution enables sintered parts to be carburised in a separate zone. Furthermore, the roller drive's flexibility has made it possible to begin rapid cooling of sintered components at a defined temperature while sealing off the sintering zone from the turbulence of the rapid cooling process. This is achieved by means of completely gas-tight double doors.

Atmosphere control

The latest continuous roller furnaces bring extremely high performance to the sintering industry and they effectively separate strong oxidising atmospheres from reducing and carburising atmospheres. New pusher furnaces offer some interesting solutions, but due to the pushing principle and slow movement there is a lack of flexibility and efficiency. "In the future, roller hearth furnaces with double door lock technology will allow active carbon control. Thus, it becomes possible to carefully manage the carbon content of the MIM parts. Several roll drives with different, freely selectable velocities will help to ensure that every process step, from secondary debinding to sintering and, where appropriate, carburisation, only takes as long as the component requires," stated Vervoort.

Cooling

Modern roller hearth sintering furnaces feature efficient gas quench units that allow cooling rates over 4 K/s, sufficient for the integrated hardening of PM steel parts. In the late 1990s the MIM industry also considered using this technique in its continuous furnaces [7].

However, due to the lack of proper charge carriers and a significant reduction of throughput (instead of three layers only one single layer was possible), the idea was rejected. In the last decade, in conjunction with a number of major sintering companies, Eisenmann developed a new range of charge carriers that can withstand high quench rates. As to the lack of throughput, a modern roller hearth furnace allows much wider charge carriers while maintaining a very high temperature homogeneity of +/- 3°C over a width of 800 mm. Continuous production of Ni free stainless steel, which requires a cooling rate of 200 K/min, could now easily be realised (Fig. 9) [8].

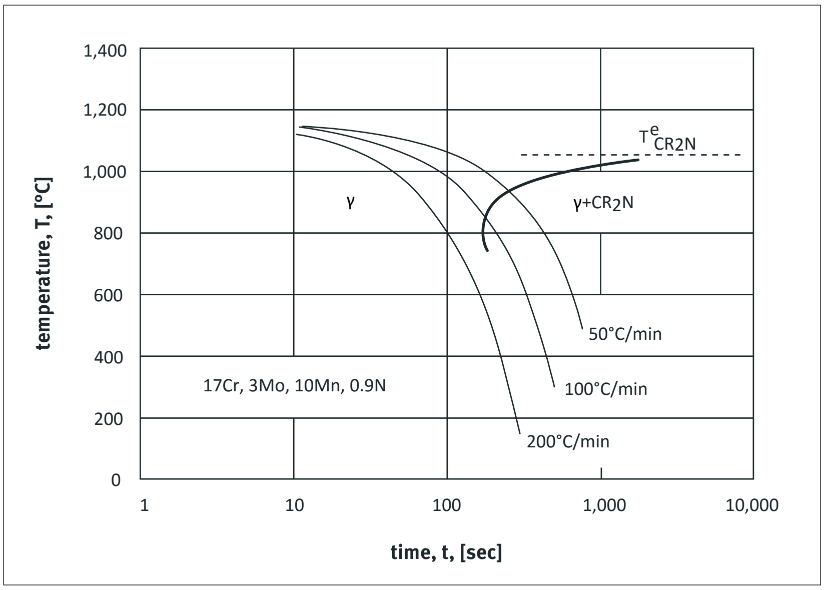

Fig. 9 Example of a cooling diagram for a nickel-free high nitrogen austenitic stainless steel that could easily be achieved in modern roller hearth furnaces [8]

Improving flexibility and increasing efficiency

High-temperature processes are major consumers of energy. For this reason the industry is committed to increasing energy efficiency. The latest generation of continuous sintering furnaces shows a 40% reduction in energy loss compared to furnaces from 2004. The outside wall temperature range is now significantly below 60°C, compared to 80 to 110°C on older systems. The myth that a continuous furnace requires hot outside walls to dry the thermal bricks while commissioning is also completely out of date. Smart isolation concepts reduce initial drying times by 50% or more. "With these new figures it will be interesting to see how the breakeven point, currently around 40%, may fall," stated Vervoort.

"Continuous furnaces will create even more value in the future. Advances are always driven by customer demands, such as further reductions in production costs in conjunction with improved energy efficiency, lower gas flow rates, maximum availability and minimum changeover times. Other compelling benefits include low downtime, maintenance and capital expenditure, small plant footprints and long service."

Active process gas control

Vervoort is confident that effective solutions are now on the horizon for the challenges that lie ahead, challenges that he listed as achieving more precise and application-specific control of gas atmospheres, time and temperature profiles and improved carbon control. "Very promising approaches are emerging through the deployment of nitrogen atmospheres with low hydrogen content and low dew points, in combination with high temperatures, uniform temperature distributions and proactive control of the CO/H_2 ratio. Eisenmann is exploring these possibilities at its technology centre and reference plants."

Automation and flexibility

Continuous roller furnaces also offer significant potential for automation, leading to more stable processes and lower production costs. As Vervoort explained, "Traditional furnace systems are inflexible: debinding, secondary debinding and sintering are performed in a single cycle or, with simultaneous secondary debinding and sintering, in just two cycles. We will make it possible to define a different cycle for each of the three steps. The rewards will be substantial: improved process steps, higher workloads, unbeatable quality. This way, users will be able to configure their equipment according to what they are manufacturing. Furnaces should be tailored to the needs of the product, not the other way around."

It was also stated that more effective control of the extremely rapid cooling process will lead to marked improvements in product quality. "New ways to produce alloys will bring further benefits. In addition, methods are being devised for sintering even harder metals at temperatures as high as 1,600°C, with atmospheres containing detectable quantities of hydrogen and with graphite insulation. Gas analysis and gas-composition monitoring are central to the control of atmospheres in line with the requirements of materials and end-products," commented Vervoort.

Outlook

As the MIM industry continues to grow in all world regions, Eisenmann is committed to developing the next-generation of roller furnaces

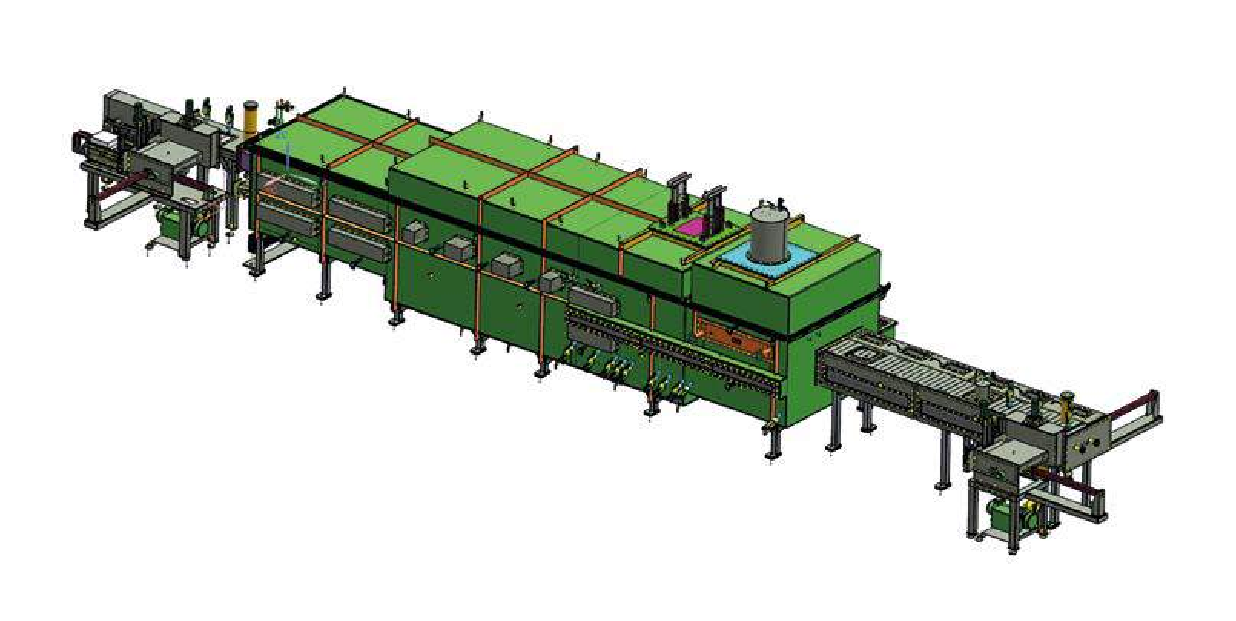

Fig. 10 Eisenmann's next generation furnace design combines debinding, sintering and rapid cooling and features the latest development in furnace technology such as quench rates of >6K/s, active debinding and sintering atmosphere control

for Metal Injection Moulding that will contribute to making the industry even more competitive compared to other manufacturing technologies. "Excellent reproducibility and strictly controlled atmospheric conditions and temperatures will be essential," Peter Vervoort concluded. "We're making good progress. This next generation of furnaces will set new benchmarks across the board – in energy efficiency, flexibility, product quality and cost savings."

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Expanding the role for MIM and CIM feedstock: Evolving PIM binder systems for extrusion and compression moulding

Binder systems lie at the heart of the Powder Injection Moulding process, enabling metal and ceramic powders to be injected into a die as if they were plastics. Binders have, of course, evolved significantly since the earliest days of PIM and their ongoing advancement enables part producers to continue to push the boundaries of what can be achieved. In the following article Dr Christian Mueller and colleagues review the types of binders used in PIM and present an established binder system from Emery Oleochemicals GmbH that is being adapted to find applications in the related processes of extrusion and compression moulding.

Metal and ceramic parts for numerous industrial and consumer applications can be manufactured from the respective powders by using an organic, polymeric binder. When compounded with such a binder, these inorganic powders can be processed in a way that is comparable to a thermoplastic material. The most common example of this is Powder Injection Moulding, however extrusion and compression moulding are also widely used. Different binder types are usually used for these different processes, accompanied by various challenges such as low green or brown part strength, high shrinkage and the usage or emission of hazardous chemical substances.

An organic binder system for metal and ceramic powders that was developed by Emery Oleochemicals GmbH has now evolved to suit all processes that have an analogy with plastic processing. These include not only metal and ceramic injection moulding, but the extrusion of sheets, films, profiles and pipes as well as compression moulding.

Foaming green parts in order to produce porous sintered products is also possible using this system. As a leading supplier of additives to adjust rheology, flow and release properties of polymer melts, Emery Oleochemicals has the expertise to provide tailored solutions for a binder system to address all specific applications.

Thermoplastics in PIM

Plastics are probably one of the most important classes of materials in our modern world. From a chemical perspective, plastics are polymers, namely macromolecules built up from smaller repetitive units. Thermoplastics are just one sub-category

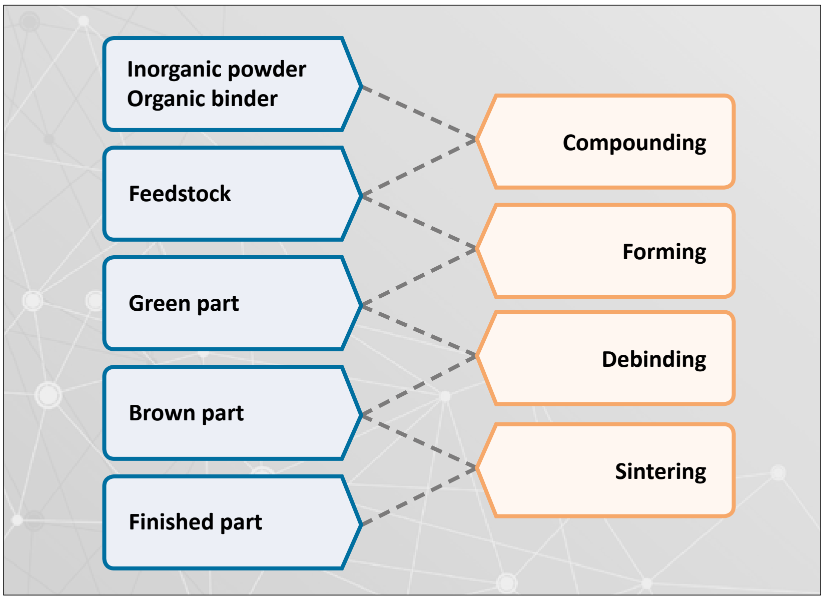

Fig. 1 Flow chart of products (left) and processes (right) in PIM related processes

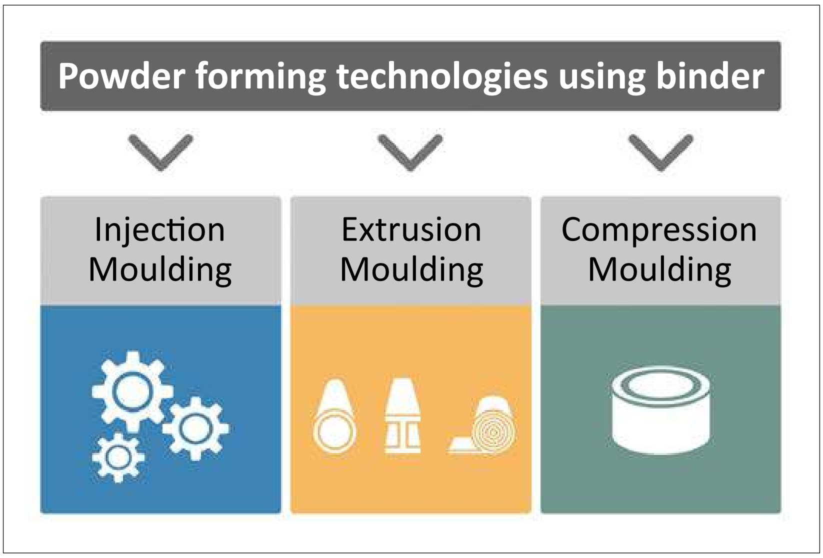

Fig. 2 The most common forming technologies for metal or ceramic feedstocks

of plastics. In thermoplastics, the polymer macromolecules are not chemically crosslinked, so they are able to move against each other when the temperature is elevated. Hence, parts made from thermoplastics are solid materials at the temperature of use, but soften when heated to or above the so-called glass transition temperature. In this state they can be transformed by various shaping processes.

All moulding processes for thermoplastics have in common the fact that they subject the material to both thermal and shear strain. In order to protect the material from decomposition, which would lead to discolouration or deterioration of mechanical properties, it is state-of-the-art to use lubricants to improve processability. Emery Oleochemicals, a leading global manufacturer of polymer lubricants and plasticisers, has used its expertise in these products to enable the accurate adjustment of rheological properties to match a specific process. This includes internal and external lubrication, flow enhancement and release effect.

In many cases however, thermoplastics are not processed as a pure lubricated polymer, but in combination with inorganic components, such as pigments, flame retardants, fillers and reinforcing fibres. Manufacturers of polymer lubricants and plasticisers are fully aware of the consequences that these additions can have on the process, which include:

- Increased internal friction, due to higher stiffness; decreased flow
- Increased external friction, higher abrasion depending on the type of inorganic material; challenges to maintain surface quality
- Change of heat capacity
- Need to finely disperse the inorganic material in the polymer matrix

The topics mentioned above have led to a deep understanding and expertise in the design of lubricants and plasticisers tailored to the requirements of processing various blends of polymers and powders. The inorganic additives that are commonly used during plastics processing naturally serve as part of the polymer matrix during the usage of finished plastic products.

Although in Powder Injection Moulding or related processes the polymer is nothing more and nothing less than a carrier or binder for the inorganic powder, with the polymer being removed after the forming step, this forming step is crucial and sensitive. A PIM feedstock is in many aspects the ultimate combination of a thermoplastic and an inorganic material in respect to the ratio of the inorganic in the total composition and the requirements on the process. As a consequence, the experience of an additive supplier in relation to rheology modifiers is highly valuable. Whilst one could state that a feedstock should be considered as an inorganic powder with a rather small proportion of organic binder, Emery Oleochemicals views a feedstock as a highly filled thermoplastic material.

Binder types

A number of different thermoplastic compounds are used as binder systems for Powder Injection Moulding. The binder types offered mainly differ in the following aspects:

- The powder type they are suitable for: Powders differ in chemical composition, particle shape, average particle size and particle size distribution.
- The targeted forming process: The feedstock rheology for injection and compression moulding, for instance, must be significantly different.
- The debinding process: Debinding can be done thermally, by dissolving the binder or by its catalytic decomposition.

The production sequence of a metal or ceramic part from the respective powder is shown in Fig. 1.

Compounding a PIM feedstock

An inorganic powder and a polymeric binder cannot simply be compounded by powder blending. The binder needs to be in its thermoplastic state in order to coat every single particle of the powder and several methods are available for this process.

Kneaders

The most universal device to produce a feedstock is a kneader, with or without a discharge screw, as even small batches for development can be produced. For upscaling, it is possible then to use the same technology. A low abrasion level is a key advantage and the ingredients do not have to be premixed.

Compounding extruders
Another option is a compounding extruder. This is especially useful for higher volume throughput and continuous production. The product of the extrusion is a ready-to-use, dust-free feedstock in granules. In order to feed the extruder, a powdery premix of all the ingredients is necessary.

Shear roll extruders
The shear roll is the most popular device in the ceramic feedstock industry. It is very easy to clean and allows for a continuous production process. It provides the lowest possible abrasion. As with the extruder, the shear roll requires a premixing of the ingredients.

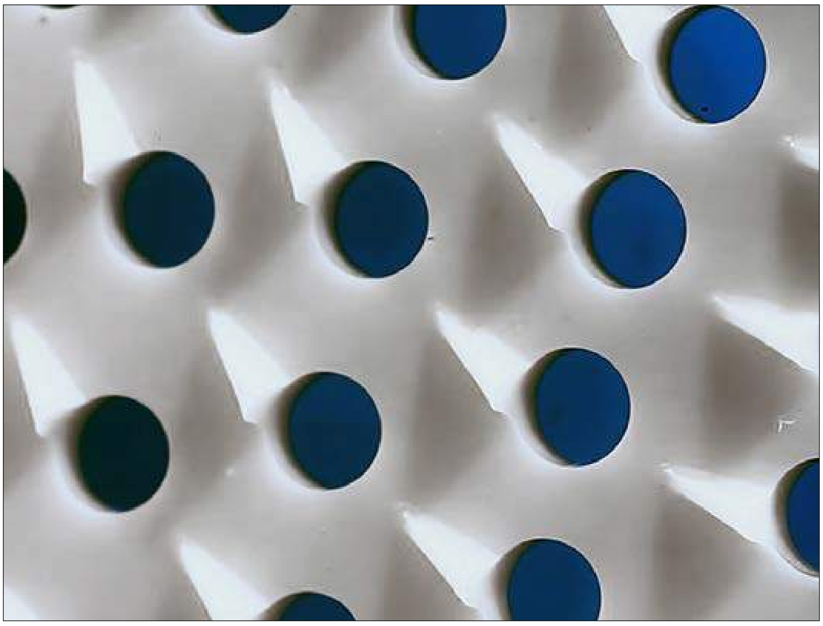

Fig. 3 Detail of an aluminium oxide disc formed by Powder Injection Moulding

Forming the green part

The goal of the forming process is the conversion of the feedstock to the green part. Among the many possible forming technologies for a metal or ceramic thermoplastic feedstock, Powder Injection Moulding is the most important (Fig. 3). In the ceramics industry, however, the extrusion process is at least as important as Ceramic Injection Moulding. In the extrusion of ceramic feedstocks it is state-of-the-art to use an aqueous system. For special applications, however, a water-free, thermoplastic system provides significant advantages including fast debinding and excellent green part strength [1]. The thermoplastic binder system developed by Emery Oleochemicals can be tailored to cover the demands of both injection and extrusion.

In powder compression moulding, cold uniaxial and isostatic pressing represent the state-of-the-art. Emery Oleochemicals' thermoplastic binder system can be modified to be a semi-thermoplastic binder for compression moulding at elevated temperatures. After the powdery feedstock has been pressed at room temperature, there are two possible further procedures. The first option is to temper the compressed parts at typically 160°C for one hour without pressure being applied. This leads to increased green part strength, sufficient for post-machining processes. The second option is to compress the parts a second time, but at elevated temperature (80-160°C), resulting in both an even higher green part strength and density, low shrinkage and high density after sintering. The binder content in the green state is about 15-25% in volume and debinding is done thermally [2]. The different forming processes discussed are presented schematically in Fig. 2.

Debinding processes

During debinding, the binder must be partially removed from the green part. Some binder has to remain in the resulting brown part to give the necessary part strength prior to sintering. For this reason, a binder must be a mixture of two primary classes of components. One binder component must be capable of being removed in the initial stage of the debinding process whilst the second binder component remains in the part. It is important that, after debinding, the brown part is porous. This allows the residual binder, or its decomposition products, to diffuse through fine channels prior to the sintering phase, enabling the effective removal of residual organic carbon without cracking the parts.

Thermal
The simplest process for debinding is the thermal process. Green parts are heated to vapourise the binder, either with or without its decomposition. The vapourised binder is removed by a flow of carrier gas. The heating rate should be chosen very carefully and is usually low as the vapour pressure of the binder, or the binder's decomposition products, in the core of the part might rise too fast and crack the part. The main advantage is that sintering can be done directly after debinding in one continuous step. This method is mainly used for pressed parts as the binder ratio in the feedstock is much lower than in injection moulding, for instance.

Catalytic
Catalytic debinding is usually done with a binder based on polyoxymethylene (POM). A catalyst decomposes POM at a relatively low temperature of around 120°C, starting at the surface of the green part, with the reaction site gradually moving to the core. As the evaporating binder

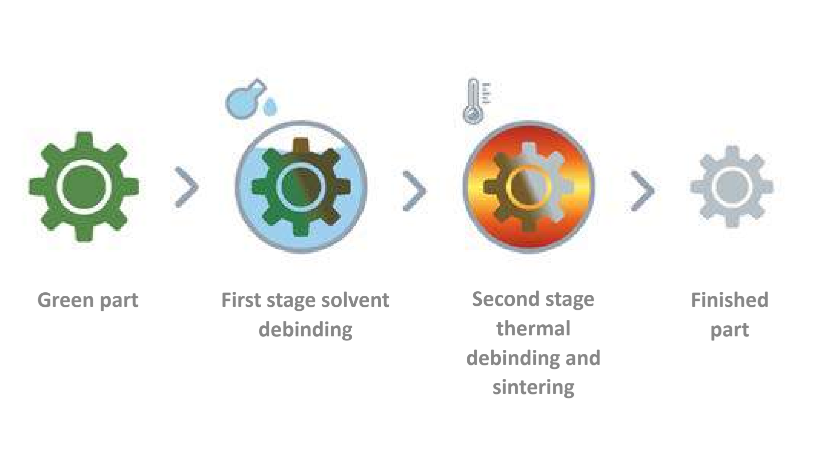

Fig. 4 Schematic route from green to sintered parts using solvent debinding

leaves pores and channels behind, cracks are minimised compared to thermal debinding. The most common catalyst is pure nitric acid in its gaseous state. This makes precautionary measures essential. During the process, the nitric acid decomposes to form nitrogen oxide. Furthermore, the decomposition product of POM is formaldehyde. Both products are toxic substances, making post-treatment of the exhaust gases mandatory. The backbone of the binder, which is not susceptible to the catalyst, is removed thermally prior to sintering.

Solvent

Solvent debinding, as with catalytic debinding, starts at the surface of the green part and thus opens pores and channels for the subsequent thermal removal of non-dissolvable binder components. The term "solvent" not only includes organic solvents such as alcohols, acetone, hexane or trichloroethylene but also water. Supercritical fluids can also be used but relatively rarely. Solvent debinding is done at even lower temperatures than catalytic debinding, usually at 40-60°C. The low temperature applied causes minimum distortions and warping, leading to maximum accuracy (Fig. 4). The binder system developed by Emery Oleochemicals belongs to this third group of binders, with the solvent being acetone at 34-45°C [3].

The advantages of the binder system

The binder system from Emery Oleochemicals can be used in all of the previously highlighted part forming processes by tailoring the feedstock composition. By adjusting the melt flow rate of the binder, dosing rheology modifiers or release agents or by adapting the binder-powder-ratio, the binder can also be tailored to nearly any sinterable powder. Powders successfully processed, in addition to widely used ferrous alloys, include tungsten alloys, oxide ceramics, silicon carbides, silicon nitrides and cemented carbides.

Whilst originally developed for Powder Injection Moulding, the system has been modified also to enable production of extruded goods. It has been demonstrated that using this binder system one can produce extruded sheets and films in a flat die down to 0.5 mm thickness in the green state, as well as fine pipes and profiles. Special compression moulding applications complete the application portfolio.

The binder system also allows for high levels of powder loading, enabling the production of parts to extremely high tolerances. Linear shrinkage of 15% is realistic for water and gas atomised steel powders (5-24 µm), whereas linear shrinkage for finer average particle sizes (0.1-3.0 µm) is 17-20%. In order to re-use existing tooling when changing from binders that have different levels of powder loading and shrinkage, the loading can be adapted to meet the shrinkage of the originally used system.

High green part strength, despite high levels of powder loading that are possible, enables mechanical processing of the green part such as turning, milling, drilling or cutting. This is an attractive proposition for prototyping. The binder system also offers excellent brown strength thanks to a highly rigid backbone material, resulting in a low scrap rate.

Both green and brown part scrap can be recycled. For brown part scrap the binder share that has been removed by solvent has, of course, to be added again. As the solvent can be recycled by distillation, the solid residue of the distillation process is the binder share that has been dissolved by the acetone. This raw material can be re-used and topped up with new backbone binder, taking into consideration the backbone binder that remains in the brown part. Such a process is not possible for thermal or catalytic debinding systems as all of the binder is decomposed to exhaust gas in the process. Taking the low debinding temperature into account, Emery Oleochemicals believes that this system can be considered the most sustainable for processes such as Powder Injection Moulding.

With the use of blowing agents, which are well-known in the plastics industry, porous sintered parts can also be produced [4, 5].

Application opportunities

This binder system presents opportunities to a number of different branches of the PIM industry. Companies currently offering metal or ceramic powder but wishing to forward integrate into feedstock supply, or even into part production, can consider this system, particularly with the advantage of its being able to be used in feedstock extrusion (Fig. 5) and compression (Fig. 6) processes. The binder is also available to

Fig. 5 Pipes made from extruded sheets of silicon nitride feedstock

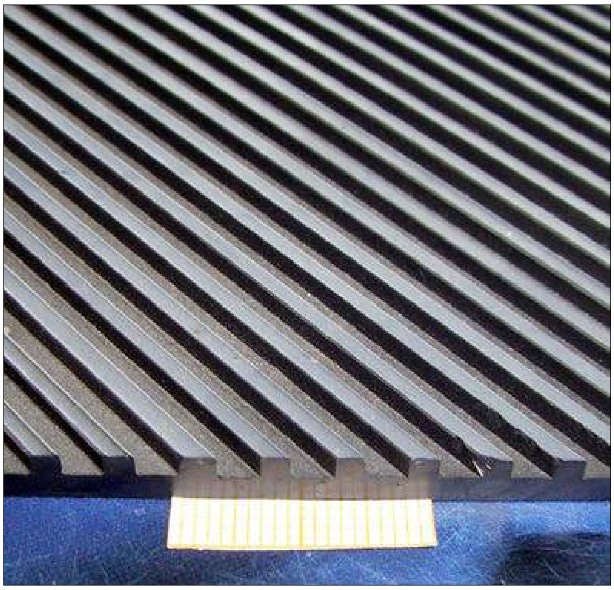

Fig. 6 A plate made from a compressed flat sheet of silicon carbide feedstock, grooved in the green state

companies already offering feedstock systems to the market, presenting the possibility to sell feedstocks based on multiple binder systems. Existing MIM and CIM part producers who currently purchase feedstock may also consider the binder as a solution to bring feedstock production in-house or simply reduce their dependency on a feedstock supplier.

Changing the binder for feedstock production is, of course, an ambitious step. Apart from different debinding methods and sintering processes, one first has to consider the influence of the binder on the forming process, for example in the change in rheology of the feedstock. This includes both the viscosity of the melt, affecting its flowability, and the friction of the melt in the processing machine, as well as the dispersibility of the powder in the binder. Furthermore, volume shrinkage by debinding and sintering needs to be considered, specifically for the ratio of green part volume to sintered part volume. The size of the sintered part is always fixed and it is usually the goal to also to keep the size of the green part fixed in order to avoid investing in new moulds. Emery Oleochemicals is aware of the need to provide the necessary technical services to assist in regard to all these concerns.

Conclusion

It is possible to use tailored versions of the same binder system for semi-thermoplastic compression and thermoplastic injection and extrusion moulding. These different methods can then be compared directly, without the need to consider differences in the binder chemistry and effects on debinding and sintering as subsequent processes. Although the detailed results achieved with partners and customers are confidential, our expertise is open to any institution willing to investigate the alternative technologies and production methods outlined.

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[4] Jörg Färber, Manfred Jaeckel: Method for producing porous sintered bodies, EP 1587772, priority date 2001-01-30.

[5] Manfred Jaeckel, Karl-Christian Danz: Method for producing a cellular sinter mould, EP 2679564, priority date 2009-09-04.


POWDERMET2017
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POWDERMET 2016: Advances in PIM processing highlighted in Boston

The POWDERMET2016 Conference and Exhibition took place in Boston, Massachusetts, USA, from June 5-8, 2016. North America's leading Powder Metallurgy event continues to encourage PIM producers, industry suppliers and researchers from around the world to share their latest research and developments. In our first report from the conference, Dr David Whittaker reviews three papers that addressed issues surrounding debinding, post-sintering Hot Isostatic Pressing (HIP) and the processing of translucent ceramics.

POWDERMET2016
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Notwithstanding their offering of a stand-alone annual conference dedicated solely to Powder Injection Moulding (PIM), the Metal Powder Industries Federation (MPIF) still included a significant PIM thread through the programme for POWDERMET2016. The programme included five technical sessions specifically dedicated to PIM, as well as PIM-related papers in other sessions. The following report reviews three papers that addressed the processing issues surrounding debinding, post-sintering Hot Isostatic Pressing (HIP) and the Powder Injection Moulding of translucent ceramics.

Controlling debinding damage in PIM

In an insightful contribution on debinding in Powder Injection Moulding, Prof. Randall German (San Diego State University, USA) outlined the importance of controlling debinding damage, described a suite of experimental methods for measuring relevant debinding parameters and provided examples of the use of these methods [1].

Corrections to final size or shape by post-sintering grinding, machining or coining often account for 40% of the total manufacturing cost and this burden is seen as an economic barrier to the penetration of many new applications. With a view to improving this situation, German's paper summarised studies on damage during debinding using unique experimental tools.

During debinding, PIM compacts pass through a state of low strength while changing size. Indeed the lowest strength, in the interval

Fig. 1 Delegates at POWDERMET2016 (Photo courtesy Glenn Kulbako Photography)

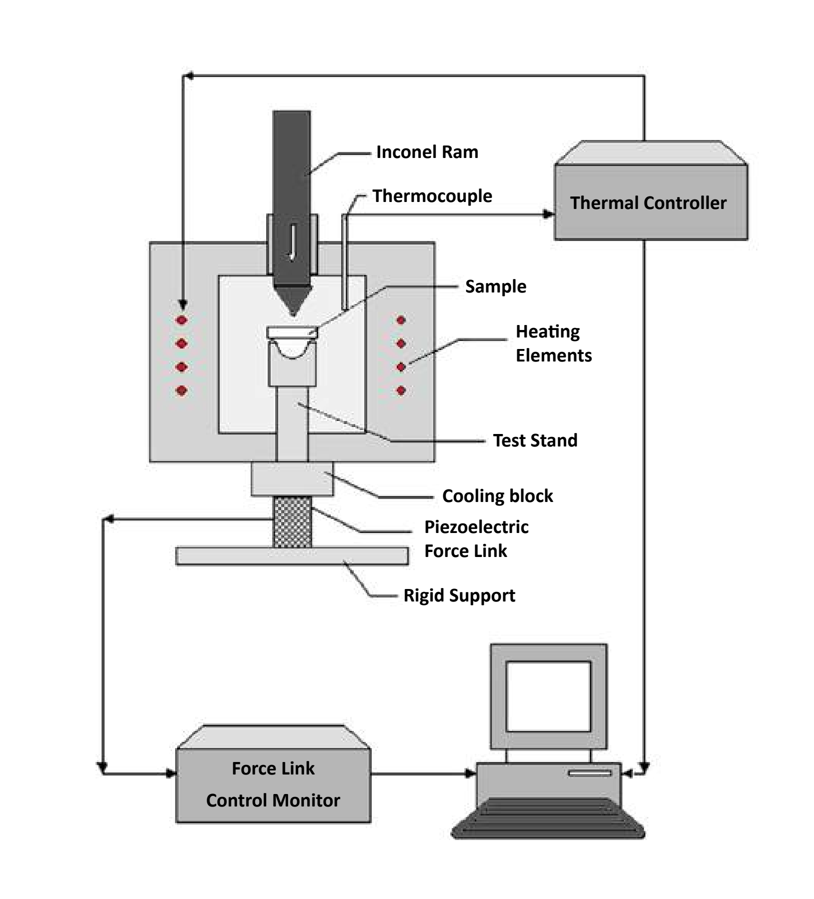

Fig. 2 A schematic of the in-situ strength testing during both thermal and solvent debinding [1]

between final binder removal and the onset of sinter bonding, is around 100 Pa, which is of the same order as the force of gravity acting on the compact. This provides an explanation for the propensity for cracking during debinding. Concurrent dimensional change during debinding is from 1 to 5% strain. This strain, combined with component softening, leads to a susceptibility for distortion, cracking, slumping, or blistering.

To avoid long debinding cycles, there is a need to understand the debinding phenomena that cause damage and the in-situ techniques, discussed in the paper, were aimed at providing relevant information. These in-situ techniques were aimed at measuring strength, mass loss, dimensional changes and distortions in a PIM component in solvent or thermal debinding. Although a range of powders and binders were tested, the main focus of the reported work was on two powders (5 µm carbonyl iron and 15 µm spherical stainless steel) and a wax-polymer binder (comprising paraffin wax, polypropylene and polyethylene with a range of formulations). Both the polypropylene and the polyethylene had added ethylene vinyl acetate.

In-situ strength

During debinding, in-situ strength is measured using a device that performs rupture during processing. The configuration allows testing in air, solvent bath, or during controlled atmosphere heating up to temperatures of 1100°C and is shown schematically in Fig. 2. Injection moulded samples, nominally 30 mm long, 12 mm wide and 6 mm thick, are placed on horizontal support rods within the sealed retort. Temperature is recorded using a K-type thermocouple contacting the sample. For solvent debinding, the test is performed in warm (40 to 60°C) heptane. An Inconel ram coupled to a piezo-quartz force sensor and linear variable differential transformer is used to induce fracture while measuring displacement and load. After fracture, two other samples are extracted and tested for strength at room temperature.

An example of debinding strength results was cited for 15 µm stainless steel powder in a binder of 60% paraffin wax, 32% polypropylene and 8% polyethylene. Strength was seen to fall during solvent debinding, as follows:

- Green strength = 19 MPa
- Strength minimum measured during 40°C immersion = 4 MPa
- Strength after 40°C immersion and cooling = 5 MPa
- Strength minimum measured during 50°C immersion = 2 MPa
- Strength after 50°C immersion and cooling = 5 MPa
- Strength minimum measured during 60°C immersion = 1 MPa
- Strength after 60°C immersion and cooling = 5 MPa

These results indicate that weakness and susceptibility to damage is largest during the latter stages of solvent immersion debinding when the backbone polymer is soft.

The in-situ strength during thermal debinding degrades from the green strength due to binder softening and binder evaporation. The strength after all binder is removed is difficult to measure, but drops to 0.2 MPa in some tests. Room temperature tests after thermal debinding reach strength levels above 4 to 5 MPa, probably due to incipient sinter bonding. During debinding, the strength falls in proportion to polymer softening and evaporation.

In-situ mass change

In-situ mass change measurements rely on thermogravimetric analysis or laboratory balances with samples suspended in furnaces or solvent tanks. Thermal balances suffer from sensitivity to convection currents, leading to reading oscillations. On the other hand, thermogravimetric

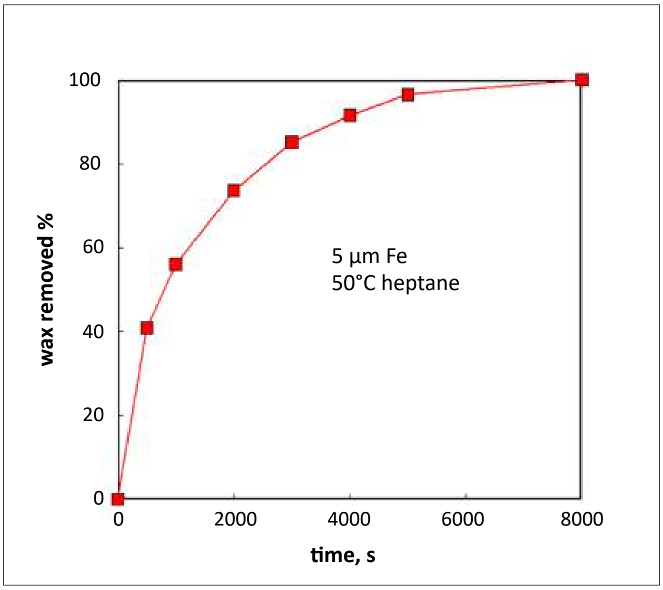

Fig. 3 Wax removal versus immersion time for 5 µm PIM carbonyl iron in heptane at 50°C [1]

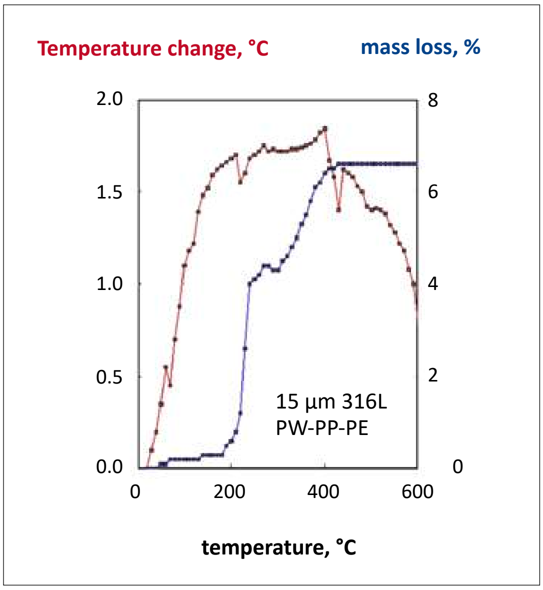

Fig. 4 Simultaneous differential thermal analysis and thermogravimetric analysis for 15 µm 316L stainless steel powder during thermal debinding with no prior solvent immersion [1]

analysis suffers from a small sample mass that is not reflective of typical injection moulded components. To circumvent this problem, solvent debinding mass change measurements were performed using samples processed in parallel with strength and dimensional tests. At a predetermined time, a sample was extracted, cooled, dried (if required) and weighed. The time interval was typically every 10 to 30 minutes, depending on the debinding rate. With this approach, some samples exhibited extra mass loss from particles dislodged by handling.

An example of the application of mass change measurements was provided for a feedstock, comprising 60 vol.% 5 µm carbonyl iron with the wax-polymer binder of 60% paraffin wax, 32% polypropylene and 8% polyethylene. Transverse rupture bars were immersed in heptane to remove the wax phase. After solvent treatment the samples were allowed to dry and measured for mass. Simultaneous data were collected for dimensional change and mass change. At 50°C immersion, the paraffin wax in a 3 mm thickness required less than 120 min for full extraction (about 1 to 2 mm/h penetration rate). Fig. 3 plots the wax removal versus time. At 40°C, the time for debinding was 50% longer, while at 60°C the time for debinding was 33% shorter than at 50°C. The debinding rate follows the German-Lin model where ln $(1/F) \approx t$, with F being the fraction of paraffin wax remaining and t being the immersion time. However, defect rates also depend on temperature, increasing from 8% at 40°C, 16% at 50°C, to 32% at 60°C.

In-situ differential analysis

In-situ differential analysis employs a simultaneous differential thermal analysis and thermogravimetric mass loss determination (DTA/TGA) in a nitrogen atmosphere. The sample size is small compared to the typical PIM component mass. The cycle employs a platinum standard in parallel with the test material. Comparative temperature readings indicate exothermic or endothermic events, as represented by a relative temperature rise or temperature lag. Both samples are perched on balance arms, enabling simultaneous mass change tracking. The platinum sample is inert, so all shifts in temperature or mass are attributed to the injection moulding feedstock. Heating rates of 5 to 10°C/min are typical.

The example of the application of this technique was for binder pyrolysis for a 15 µm 316L stainless steel powder and a binder of 60% paraffin wax, 32% polypropylene, and 8% polyethylene. Fig. 4 plots the temperature difference and mass loss versus temperature. As the binder began to burn out, there was a progressive temperature difference, peaking near 450°C. At higher temperatures, the completion of pyrolysis allowed temperature recovery. Mass loss correlated with heat flow events. Significant mass loss occurred near 220°C when paraffin wax started to break down into volatile species. The peak at 220°C was linked to paraffin wax by evaluating another sample, which had already been solvent debound, where that rapid mass loss peak was absent. Secondary burnout of the backbone binder occurred from about 300 to 420°C. No conventional PIM binder is able to survive to 550°C, so, as shown in the plot, the binder was fully extracted by that temperature.

In-situ dimensional change

This is monitored using a non-contact laser dilatometer in view of the very low strength measured during

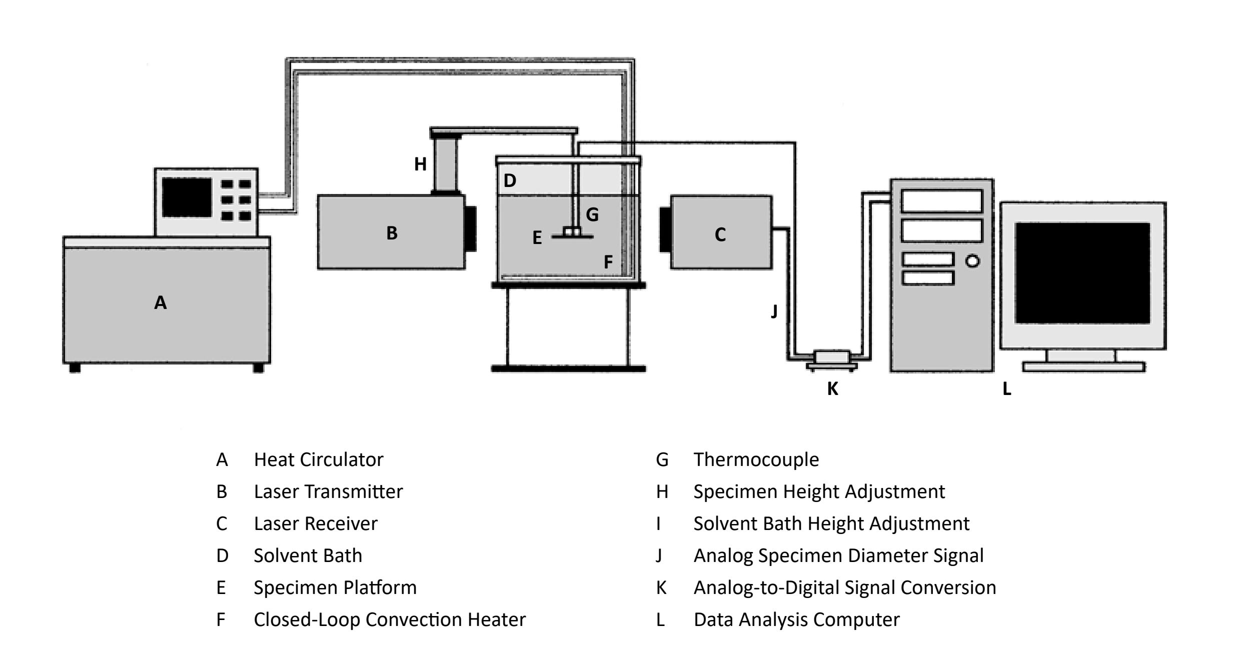

Fig. 5 A schematic layout of the non-contact laser dilatometer in the configuration for solvent debinding. In thermal debinding, a furnace was substituted for the solvent bath [1]

debinding. The device is shown schematically in Fig. 5. Two layout options were used, one for solvent immersion and the other for thermal debinding. This provides a means of measuring the in-situ dimensional changes during either thermal or solvent debinding. Sample temperature measurements were taken using a J-type thermocouple, with solvent temperature controlled within ± 0.5°C using a water bath and thermal debinding temperature controlled through atmosphere heating. Dimensions during debinding were measured using a laser micrometer with a wide laser beam.

The behaviour during solvent debinding was illustrated for 60 vol.% carbonyl iron immersed in heptane at temperatures of 40, 50, or 60°C for hold times up to 20,000 seconds. Length change versus immersion time for the three temperatures are shown in Fig. 6. Substantial swelling, when the compact was first immersed in the debinding solvent, can be noted. The largest size was observed after about 1 minute of immersion.

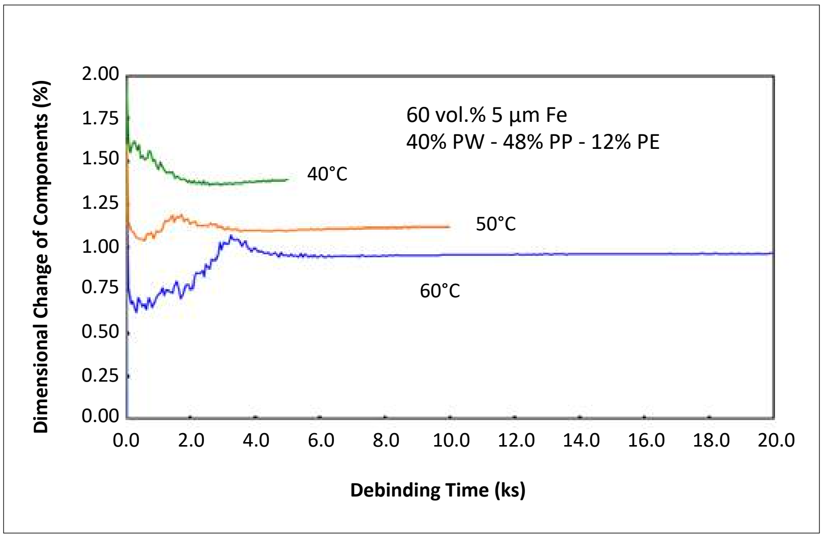

Fig. 6 Non-contact laser dilatometer dimensional change data for three solvent immersion temperatures using carbonyl iron powder in a wax-polymer binder. Large swelling of 1 to 2% occurs in the first 40 to 90 seconds of immersion [1]

The behaviour during thermal debinding was different. For these tests, the laser micrometer was mounted to observe inside a furnace. The tests used a 15 µm 316L stainless steel injection moulded compact, with 60 wt.% paraffin wax having been first debound in heptane at 55°C for 240 minutes, leaving the residual polypropylene and polyethylene binder ingredients. Fig. 7 plots dimensional change versus temperature during burnout. Binder burnout was completed by 450°C. There was a significant change in size as the backbone polymer softened, starting just prior to 100°C and reaching a maximum shrinkage at about 150°C. From that point, there was thermal expansion swelling, with a repeated pattern of sticking and slipping superimposed on gradual swelling.

Since the component was already solvent debound, the behaviour from about 200°C to 450°C appears to be a combination of thermal expansion, binder pyrolysis, capillary induced particle rearrangement and residual polymer liquid coalescence. As temperature increases, the high thermal expansion polymer expanded to create a dimensional increase, but the amount of polymer was decreasing, giving shrinkage. The residual polymer also flowed and clustered, pulling the particles together, again giving shrinkage. In turn, coalescence of the pools lowered the capillary stress, resulting in a relaxation. The result of these events was a dimensional oscillation superimposed on the softening, burnout and expansion events.

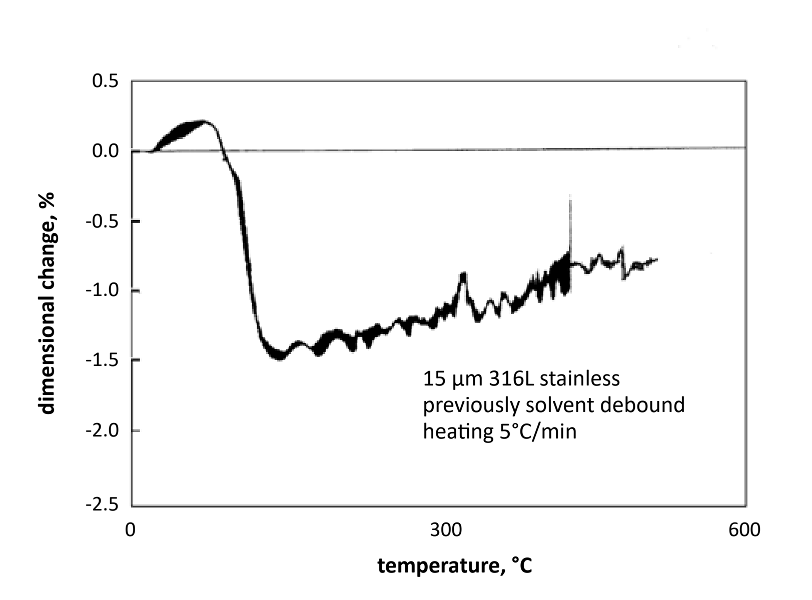

Fig. 7 Dimensional change for a solvent debound stainless steel component during thermal pyrolysis of the backbone polymer, showing thermal expansion and polymer coalescence during heating at 5°C/minute [1]

In-situ distortion

During thermal debinding and sintering in-situ distortion was observed using a synchronous video imaging system. The device records inside the process environment up to temperatures of 1500°C, using a coordinated strobe overflash and video capture. The experimental arrangement is shown schematically in Fig. 8; the system consisting of a camera with high speed shuttering, xenon flash lamp, optical lens and controller. The furnace was fitted with a quartz window for observation, allowing observations in vacuum, air, hydrogen, or other atmospheres. The image was collected by the camera through a 45° half-silvered mirror. The recorded images were digitised using an image analysis package.

Distortion during thermal debinding was observed using the video imaging system, especially after the clearing of polymer burnout smoke. Strength data in-situ demonstrated minimum strength at the end of thermal debinding prior to sintering. Shape loss and the generation of defects depends on the binder formulation, with damage typically occurring as the binder pyrolysis nears completion at intermediate temperatures.

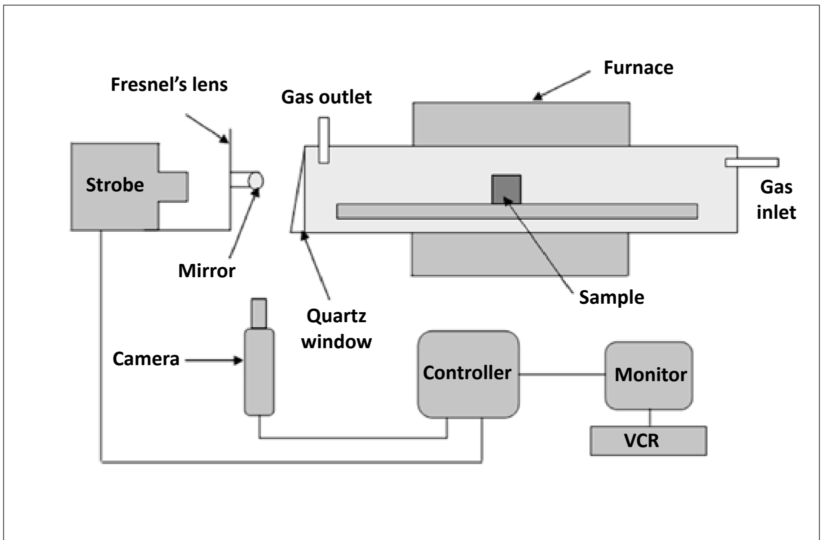

Fig. 8 A schematic outline of the experimental layout for the observation of shape change using video imaging inside a furnace [1]

Results

The results of the various in-situ characterisation methods provide insights into the events that occur during debinding and the paper went on to briefly discuss applications arising from the characterisations.

It is possible to select backbone polymers to minimise defects during thermal debinding. The in-situ strength and distortion observations assist in this task. For example, ethylene vinyl acetate increases strength during burnout because it forms double bonded polyethylene copolyacetylene and its addition can be used effectively in PIM binders.

Mass changes during both thermal and solvent debinding show that penetration rates are in the region of 1 to 2 mm/hour for all binder systems, possibly reflecting that, when debinding is optimised, this rate is about the best possible without

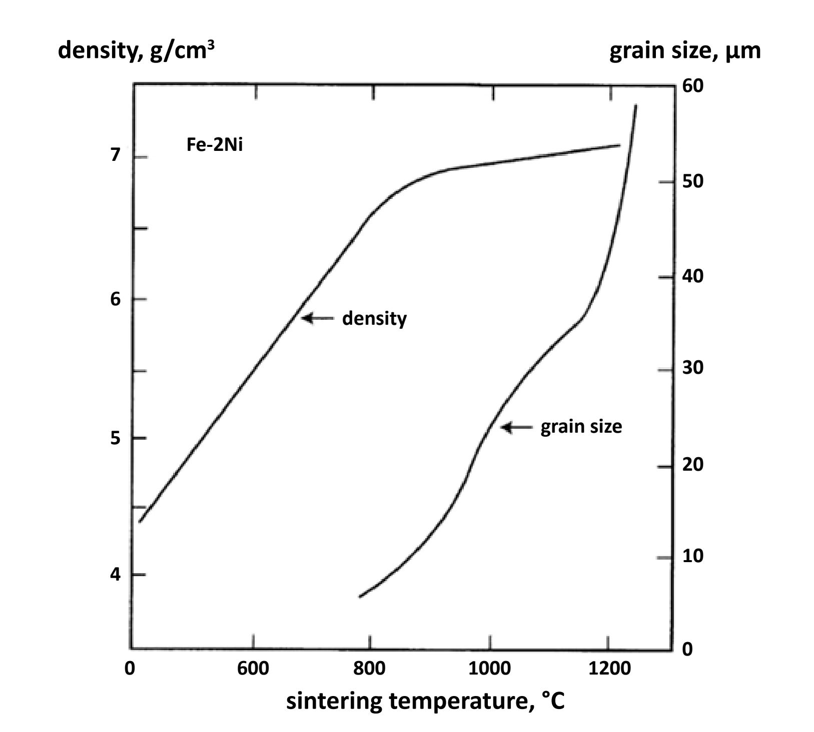

Fig. 9 Sintering temperature vs density and grain size [2]

damage, independent of the binder formulation.

The testing has shown that both thermal and solvent debinding induce large strains in the component. A means to reduce rapid size change in solvent debinding is to immerse the compact in room temperature solvent and heat after immersion.

Generally, uniform wall thickness designs allow for uniform heat exchange during moulding, binder removal and sintering. The differing responses from thick and thin sections induce damage and, therefore, it can be concluded that uniform wall thickness is paramount in ensuring quality.

Debinding cycles with minimised damage result from the in-situ characterisation. The powder compact is most susceptible to deformation at the end of binder removal, prior to sintering. Slower heating rates are appropriate at the end of pyrolysis. In this context, a continuous furnace for debinding and sintering minimises handling damage. The in-situ distortion observations shows that shape loss during thermal debinding occurs at the onset of polymer softening.

Post-sintering HIP operations for MIM parts

The contribution on post-sintering HIP came from Robert Conaway and Hugh Davis II (Isostatic Forging International Ltd, USA) [2]. This paper offered proposals for the tailoring of process protocols and HIP equipment, to deliver benefits, in terms of performance, costs and production lead-times, in the processing of MIM products.

One tenet of the authors' proposal was that, when the benefits of HIP for the removal of porosity become clear, extraordinary efforts in the primary forming process, aimed at achieving high density (low porosity) can be relaxed. Such changes can enable better results (e.g. less grain growth) and better economics, through sintering for less time or at lower temperatures or the use of less costly feedstock. Their key suggestion, in this context, was therefore to change the aim of the primary forming steps (MIM) to the attainment of closed porosity. This would result in a product in the 92 to 95% density range. As indicated in Fig. 9, lowering sintering temperature could deliver a finer grain size, while achieving the objective of closed porosity. Subsequent HIP would then bring the

Sample	Process	Density g/cm³ (%)	Ultimate Tensile MPa (psi x10³)		Reduction Area (%)		Hardness (HBR)	
			Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
H1300		7.59 (96.4)	406 (58.88)	72 (10.44)	18.2	3.4	58.5	0.9
V1300		7.57 (96.2)	498 (72.23)	84 (12.18)	5.4	2.6	85.1	0.8
V1200		7.30 (92.6)	261 (37.85)	7 (1.02)	2.4	2.3	48.5	1.6
STD HIP(a)		7.78 (98.9)	385 (55.84)	17 (2.47)	39.0	3.9	90.2 (top)	0.3 (top)
STD HIP(b)		7.78 (98.9)	385 (55.84)	17 (2.47)	39.0	3.9	56.1 (bot)	3.8 (bot)
QUICK HIP		7.83 (99.5)	732	7	23.4	0.9	91.8	1.1

Table 1 Properties of MIM carbonyl iron specimens processed by various methods [2]

component to a pore-free state, with the expected gains in properties.

At the present time, virtually all HIP processing of MIM/PIM parts is carried out using sub-contract toll HIP facilities, employing legacy process protocols that have been long ago developed for historical applications and characterised by cycles that are many hours long. In contrast to this approach, Isostatic Forging International (IFI), has focused on tailoring the HIP process and the HIP equipment for a specific application, generally through integration with part production within, or very near to, the primary manufacturing facility.

Some of the earliest data for the HIP of MIM parts were generated by Lin and German in the late 1980s. Table 1 is a summary of a comparison of properties of carbonyl iron parts subjected to various densification methods (sintering and post-sintering HIP. Standard HIP did not seem to offer better tensile strength compared to sinter-only. However, ductility increased quite dramatically. Remarkable were the impressive results of Quick HIP (a process developed jointly by IFI and Michigan Technological University), carried out very quickly at very high pressure. It is now believed that these results may have been delivered through pressure-enhanced quenching.

Overall HIP cycle time is a sum of:

- Load and unload
- Pressurisation and heating to bring the load chamber to a proper pressure and temperature
- Soak time for the entire load mass to reach the desired temperature
- Hold time required
- Cooling of the load to a temperature level to enable unloading
- Depressurisation and unloading.

All of these steps can be accomplished more effectively the smaller the processing unit.

In a HIP unit, occasionally the dominating time factor is the transient heat transfer within the component during heating and cooling. Since MIM parts are generally small, they can be heated and cooled quickly in a HIP. The heat transfer coefficient of the high pressure gas can be considered to be of the same order of magnitude as an oil quench bath, but for both heating and cooling.

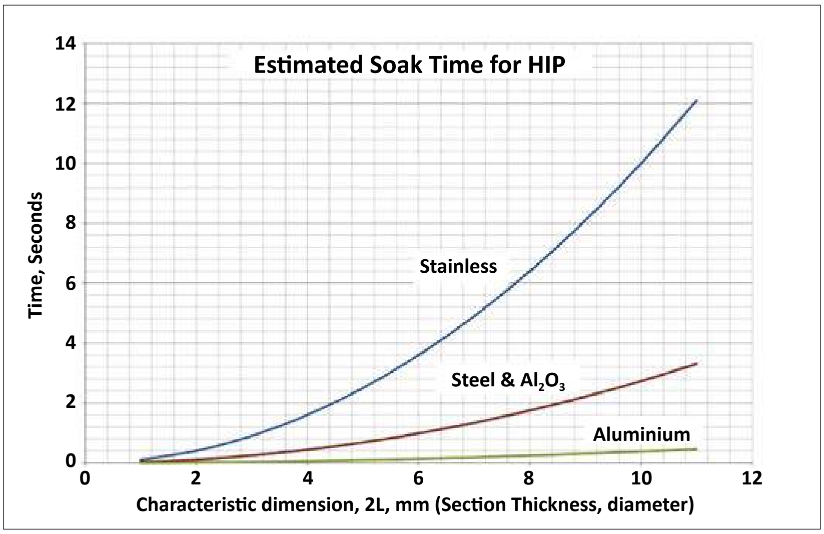

Fig. 10 Estimated Soak Time for a temperature uniformity of 2% [2]

IFI's methodology for estimating soak time is to assume that the surface of the part is at the desired temperature. A simple model can then be used, assuming:

- A long rod or two sided infinite slab
- Constant properties,
- A temperature uniformity of 2% (about +/- 12°C).

Fig. 10 indicates the estimated time to reach that uniformity, based on section thickness and thermal diffusivity. Three thermal diffusivities (mm/sec) are shown for the range of typical materials. Clearly, soak time is a minor issue with typical MIM/PIM products in a HIP unit.

The authors then discussed a case study, based on one of the early applications of HIP i.e. the post-processing of aluminium castings. In a partnership with a major producer of cast aluminium compressor wheels for automotive turbochargers, IFI were able to optimise the HIP process to just (but reliably) deliver the required results (design fatigue life) and then designed equipment to do so rapidly in a HIP that was suitable to be placed on the foundry floor. The actual time-pressure protocols that were suitable for the casting alloys typically used are proprietary. However, it can be stated that what was previously done in a sub-contract toll HIP facility, taking up to two weeks, was replaced by a less than 90 minute addition to the casting production line, using the same baskets that were used for subsequent heat treatment.

IFI now plan to carry out a similar development for the MIM industry, tailoring a HIP process and associated equipment to enable HIP to be placed in line on the MIM production floor.

The authors concluded that they have now demonstrated the promise, if not the feasibility, of rapid HIP for MIM. HIP cycles have been accomplished in a few minutes, obtaining virtually pore-free structures. While improvements in properties, consistent with zero porosity, are anticipated, definitive studies have not yet been completed.

It has been demonstrated that simulated production cycles are an order of magnitude faster that current practice for the HIP of MIM parts.

The success of IFI's tailored HIP approach has been demonstrated in high volume production as an in line process in a casting foundry. Well over 100,000 cycles have been accomplished in this context and the facility continues to run strongly.

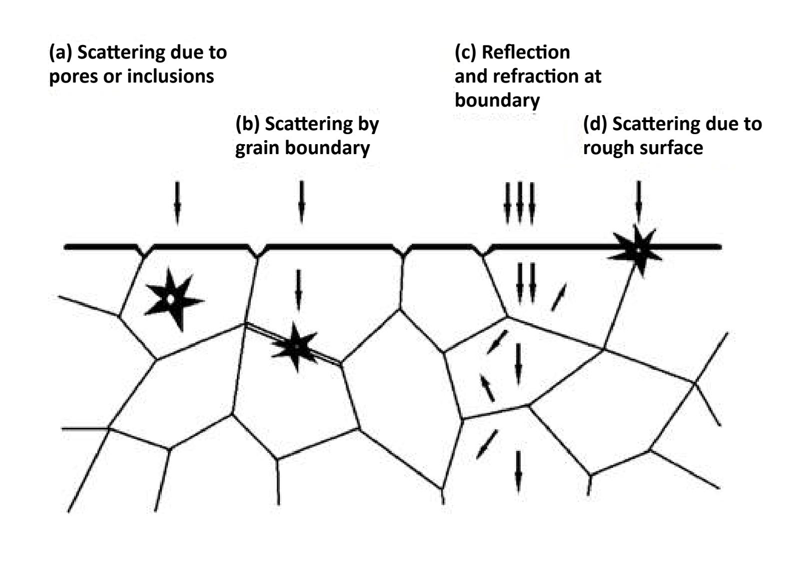

Fig. 11 Transmission of light in polycrystalline ceramic [3]

	Density (g/cm³)	Porosity (%)	Grain size (μm)	Hardness (Hv)	Total forward transmittance (%, at 550 nm)
DYTT-1000	3.977	0.201	8.13 (3.2×10^{-4} in.)	1855	41.6
DYTT-1000I	3.984	0.025	8.54 (3.36×10^{-4} in.)	1894	47.7
DYTT-1000D	3.983	0.050	14.81 (5.83×10^{-4} in.)	1808	51.1
DYTT-1000R	3.980	0.125	13.03 (5.13×10^{-4} in.)	1871	50.0

Table 2 Measured properties of the translucent ceramics [3]

The company is now in the process of finding a tailored solution for the MIM production floor and expects to confirm/refine its production cost projections for HIP, tailored to a MIM application, by the end of 2016.

The injection moulding and characterisation of translucent ceramics

The final paper in this review switches attention from Metal Injection Moulding to Ceramic Injection Moulding. Shengjie Ying (Dou Yee Technologies Pte. Ltd., Singapore) reported on the injection moulding and characterisation of translucent ceramics [3].

Ceramics possess excellent mechanical, thermal and electrical properties and superior resistances to wear, corrosion and oxidation. However, conventional ceramics are opaque. Translucent ceramics, otherwise known as semi-transparent ceramics, add unique optical properties and are of increasing application in several industry sectors, including jewellery, watches, dental, medical, optics and lighting industries.

Fig. 11 demonstrates the transmission of light in polycrystalline ceramics. The key factors which impair light transmittance are (a) scattering due to pores or inclusions, (b) scattering by grain boundaries (c) reflection and refraction at grain boundaries and (d) scattering due to a rough surface finish. Of these factors, light scattering at rough surfaces can be readily avoided by proper preparation or by polishing the surfaces.

Conventional ceramics are commonly opaque because they contain many defects such as pores, inclusions and impurities which cause the scattering loss of light transmission, as well as second- or multi-phase boundaries where severe light reflection and refraction occur in the internal structure. It is therefore necessary to exercise stringent control over the introduction of contamination and impurities in the whole PIM process, from raw material selection to final sintering and to minimise residual porosity in the body of the ceramic in order to achieve the required translucency. This process control includes:

- Use of a raw material powder of fine particle size and high purity,
- Critical control over the amount of sintering additives used, so that the additives have not completely evaporated until the end of the sintering process, but that the minimum level of additives remain at this stage,
- The use of high vacuum sintering rather than conventional pressureless sintering.

In the reported study, an alumina powder with a high purity of >99.99% and an average particle size of 0.18 μm was used. A proprietary polymer-based binder system was developed to facilitate a homogeneous feedstock, a uniform microstructure of the moulded green parts, no contamination of the work piece and complete binder-removal during debinding. The alumina powder was doped with one or several additives from the group CaO, MgO, ZrO_2, CeO_2, La_2O_3, Yb_2O_3, Y_2O_3 and Cr_2O_3 and mixed with the binder system in designed powder loadings. Disc specimens were moulded and then the binder was removed by a two-stage debinding process, solvent debinding followed by thermal debinding. After debinding, the specimens were sintered at 1700°C - 2000°C in a high vacuum of 10^{-5} – 10^{-6} torr. Specimens of four translucency grades, DYTT-1000, DYTT-1000I, DYTT-1000D and DYTT-1000R, were fabricated. Precise details of the selected additives and sintering temperatures for these various grades were not revealed in the paper. The specimens were lapped/polished to the standard sample thickness of 1.62 mm ± 0.025 mm and a surface roughness Ra ≤ 0.025 μm for the measurement of optical properties.

Total forward and in-line transmittances are used to measure the optical properties of translucent ceramics. The total forward transmittance is the measurement of all the light passing through the sample discs and equals the diffuse transmittance and the direct transmittance, while the in-line transmittance represents the direct transmittance. The total forward transmittance provides the quantitative characterisation of translucency, while the in-line transmittance provides the quantitative characterisation of transparency. A UV-Vis-NIR spectrophotometer was used to measure the total forward and in-line transmittances.

Table 2 shows the measured properties of the translucent ceramics DYTT-1000, DYTT-1000I, DYTT-1000D and DYTT-1000R. The total forward transmittances at a light wavelength of 550 nm of DYTT-1000, DYTT-1000I and DYTT-1000D were 41.6%, 47.7% and 51.1% respectively.

By comparing DYTT-1000 with DYTT-1000I, it can be seen that a decrease of porosity leads to an increase in total forward transmittance. On comparing DYTT-1000I and DYTT-1000D, it is understood that the effect of total grain boundary surfaces, which decreases with an increase in grain size, is dominant, although the porosity increases with the increase of grain size. Thus, the total forward transmittance of DYTT-1000D is higher than that of DYTT-1000I.

The hardnesses of DYTT-1000, DYTT-1000I and DYTT-1000D are in the range 1800 Hv to 1900 Hv. DYTT-1000I is the hardest of these materials because it has the lowest porosity and a relatively fine grain size. The average grain sizes of the translucent ceramics are in the range 8 μm to 15 μm and are finer than the reported average grain size, 30 - 50 μm, of translucent ceramic fabricated by PIM via conventional pressureless sintering.

Fig. 12 shows the total forward transmittances of the translucent ceramics DYTT-1000, DYTT-1000I and DYTT-1000D in the visible light wavelength 400 nm to 700 nm.

Fig. 13 shows the in-line

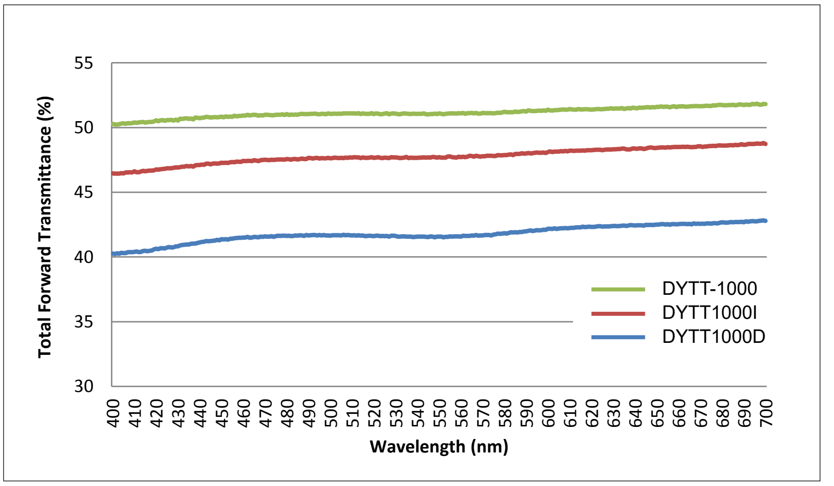

Fig. 12 Total forward transmittances of the translucent ceramics [3]

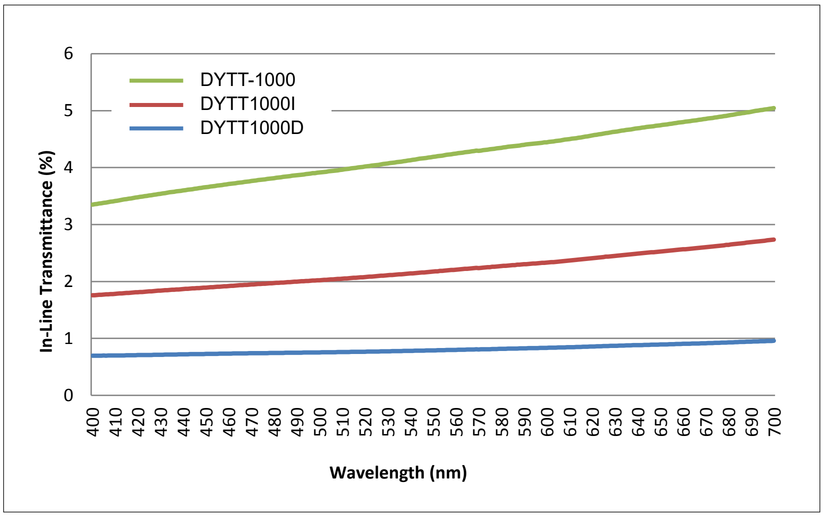

Fig. 13 In-line transmittances of the translucent ceramics [3]

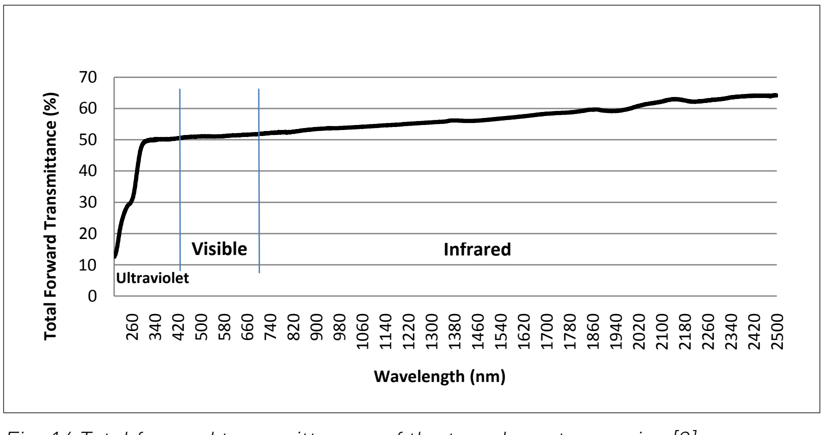

Fig. 14 Total forward transmittances of the translucent ceramics [3]

transmittances of the translucent ceramics DYTT-1000, DYTT-1000I and DYTT-1000D in the visible light wavelength range 400 nm to 700 nm. The in-line transmittances of the translucent ceramics are low, this being caused by the relatively large grain sizes arising from processing by the vacuum sintering process. They have a relatively high diffuse transmission but only a relatively low direct transmission, so that they are translucent rather than transparent. To improve the in-line transmittance, Hot Isostatic Pressing (HIP) is an effective process because it can significantly decrease the grain size of translucent ceramics to improve their transparency and can even lead to transparent ceramics, which have extremely fine grain sizes of the order of the light wavelength range.

Fig. 14 shows the total forward transmittance of translucent ceramic DYTT-1000D in the entire wavelength range from 200 nm to 2500 nm. In the ultraviolet wavelength range, the total forward transmittance of the translucent ceramic decreases rapidly with a decrease in wavelength and the material is almost opaque in the low ultraviolet wavelength range. In the light wavelength from the visible to infrared ranges, the total forward transmittance of the translucent ceramic increases with an increase in wavelength.

The paper was concluded with a discussion of two important markets for translucent ceramics – dental brackets and colour conversion in the lighting industry.

Dental brackets are of complex geometrical shape and in small sizes and therefore are very suitable for PIM processing. Utilising a total PIM manufacturing process means no cutting and, therefore, no micro-fissures to weaken the brackets. The PIM process also allows for smooth, rounded edges, maximising patient comfort. Opting for translucent ceramic brackets also tends to create a more pleasing, less conspicuous look for the patient's appliances, especially from a distance, as they blend in with the colour of the teeth.

Colour conversion is the foundation of all white LED light sources, which are actually blue LEDs coated by a luminescent material. This material is usually bonded inside silicone and is therefore not nearly as heat resistant as a fluorescent ceramic manufactured at temperatures in excess of 1600°C. In combination with high-intensity LEDs or laser diodes, the

POWDERMET2016

In addition to offering a comprehensive technical programme, POWDERMET2016 featured a trade exhibition and a social events that included a dinner at the John F. Kennedy Presidential Library and Museum (*Photos courtesy Glenn Kulbako Photography*)

outstanding temperature stability and thermal conductivity of translucent ceramic converters allow new light sources to be developed.

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Proceedings

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POWDERMET 2016: Super-high strength steels, maraging steels and advances in nickel powder production

In the second of our reports from the POWDERMET2016 Conference and Exhibition, Dr David Whittaker reviews two papers that report on research into the Metal Injection Moulding of two high performance steels. These materials promise to further expand the range of application for MIM technology into areas that demand either superior fatigue resistance or hardness. A third paper is reviewed that reports on the recent commissioning of the world's fourth carbonyl nickel refinery in Jinchuan, China, and compares the powder production routes with other carbonyl nickel plants.

Super-high strengthened Fe-Ni steels

A number of PIM related papers at the MPIF International Conference POWDERMET2016, held in Boston, Massachusetts, June 5-8, 2016, discussed material and property issues. The first of these papers came from Hideshi Miura, Toshiko Osada, Ziqi Song, Kenta Yasui and Kentaro Kudo (Kyushu University, Japan) and addressed super-high strengthened Fe-Ni steels [1].

In Metal Injection Moulding Fe-Ni alloy steels, Ni micro-segregation can be created by careful control of sintering temperature and time. Because of this segregation, a heterogeneous microstructure can be formed, consisting of a Ni-rich phase surrounded by a network of tempered martensite, as shown schematically in Fig. 2. Previous studies by this research group had shown that such a heterogeneous microstructure in Metal Injection Moulded Fe-Ni steels can provide superior static mechanical properties with a good balance of strength and ductility. Since dynamic mechanical properties are of great significance in practical applications, this reported research was aimed at creating superior Fe-Ni sintered steel with heterogeneous microstructure and evaluating the resultant fatigue properties.

In the study, powder mixes with three different Ni contents were prepared: Fe-4Ni-0.4C, Fe-6Ni-

Fig. 1 Delegates enjoy the view of the Boston skyline from the John F. Kennedy Presidential Library and Museum, venue for the event's main social event (Photo courtesy Glenn Kulbako Photography)

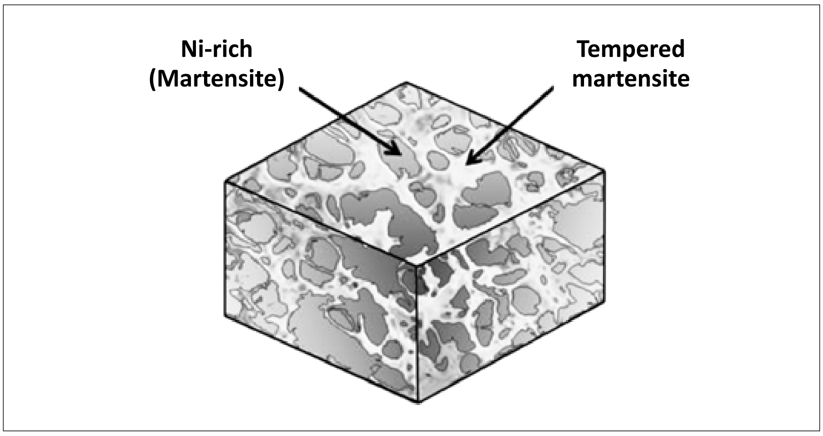


Fig. 2 Schematic diagram of 3D heterogeneous microstructure of Fe-Ni steel [1]

	Density	Melting point	Compounding ratio
	[g/cm^3]	[K]	[mass%]
Atactic polypropylene (APP)	0.860	383~403	20
Paraffin wax (PW)	0.895	329~331	69
Carnauba wax (CW)	0.995	341~347	10
Stearic acid (SA)	0.941	346	1

Table 1 Characteristics and compounding ratio of binder [1]

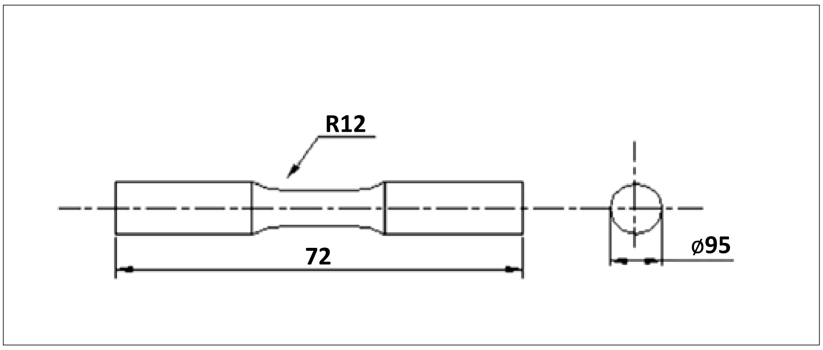


Fig. 3 Dimensions of green compact for rotating bend fatigue test-piece (mm) [1]

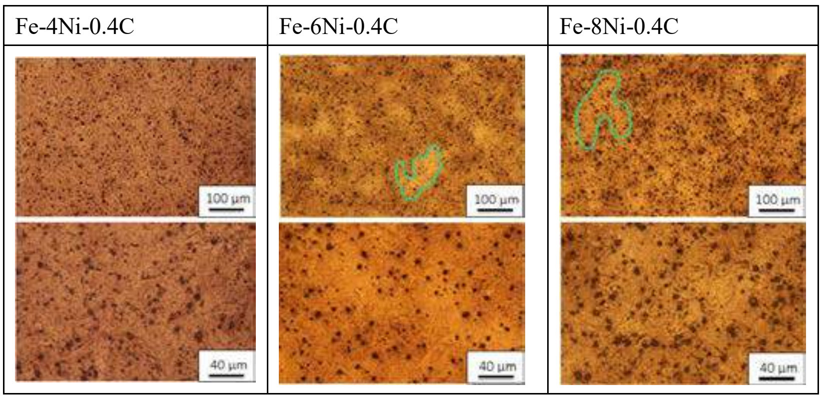


Fig. 4 Microstructures of heat-treated MIM Fe-Ni steels [1]

0.4C and Fe-8Ni-0.4C. In order to obtain the required heterogeneous microstructure, a carbonyl Fe powder, with mean particle size of 3.65 µm, was used as the matrix powder and a water-atomised fine Ni powder, with mean particle size of 6.43 µm, was used as the alloy powder. Both of these superfine powders had a spherical shape, which promotes sintering activity and leads to high sintered density.

A binder, comprising four constituent materials (Table 1), was used in preparing the feedstocks. The feedstocks were then injection moulded into rotating bend fatigue green compacts (as shown in Fig. 3). 50 to 60% of the binder was then extracted from the green compacts by solvent debinding in heptane at 60°C for 4 hours, followed by thermal debinding in an argon atmosphere at 600°C for 1 hour. The debound compacts were pre-sintered at 900°C for 0.5 hour prior to full sintering at 1250°C for 1 hour in vacuum. After machining, the sintered compacts were austenitised in an argon gas flow at 900°C for 0.5 hour and then oil-quenched to room temperature and tempered in an argon gas flow for 2 hours at 200°C, before conducting the rotating bend fatigue tests.

All of the Fe-4Ni-0.4C, Fe-6Ni-0.4C and Fe-8Ni-0.4C compacts showed high relative density, of around 95% of the theoretical density.

Optical metallography of the heat treated compacts confirmed the presence of the desired heterogeneous microstructures (Fig. 4). In the micrographs in this figure, the bright zones circled with green lines were the Ni-rich phase and the dark zones were tempered martensite.

Electron Probe Microanalysis (EPMA) was also used to study the Ni distribution in the heterogeneous microstructures and the results are shown in Fig. 5. Each of the Fe-Ni steels showed the heterogeneous Ni distribution. Moreover, when the Ni content increased, the Ni concentration of Ni-rich phase also increased, indicating that the Ni distribution tends to be more heterogeneous as the Ni content increases.

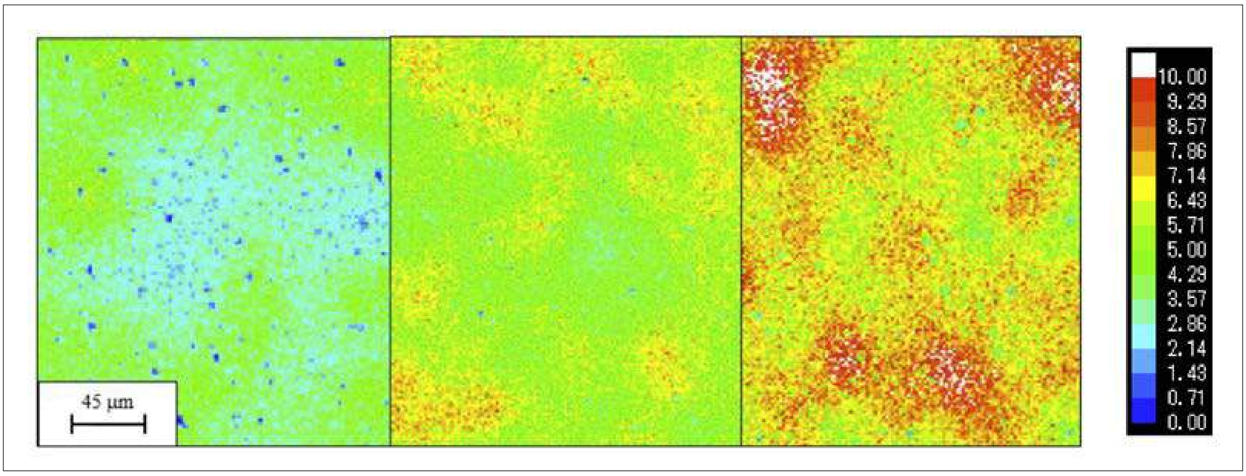


Fig. 5 Comparison of Ni distribution in various MIM Fe-Ni steels. Left, Fe-4Ni-0.4C Centre, Fe-6Ni-0.4C and right, Fe-8Ni-0.4C [1]

The fatigue properties of the MIM Fe-Ni steels were evaluated by rotating bend fatigue testing and the resultant S-N curves are shown in Fig. 6. Fe-4Ni-0.4C, Fe-6Ni-0.4C and Fe-8Ni-0.4C showed fatigue endurance limits of 520 MPa, 650 MPa and 611 MPa respectively. On the basis of these results, Fe-6Ni-0.4C steel showed the best fatigue properties, as was also the case for the static mechanical properties reported previously. Compared with die pressed 4600 steel, MIM 4600 steel and Powder Forged 4600 steel, the MIM Fe-6Ni steel with heterogeneous microstructure showed superior fatigue properties.

Fig. 7 shows the measured Vickers microhardnesses of the various MIM Fe-Ni steels. The hardnesses were investigated before and after fatigue testing. For all of the Ni contents (4, 6 and 8%), the tempered martensite showed a higher hardness (of around HV 600) than that of the Ni-rich phase. This seems to be due to the existence of retained austenite in the Ni-rich phase.

It has been reported that the excellent static mechanical properties could also be attributed to the martensitic transformation-induced plasticity (TRIP) effect in the retained austenite phases. As can be seen in Fig. 7, all compacts showed a slight increase in hardness after fatigue testing. On the other hand, the hardness of the Ni-rich phase increased dramatically after tensile testing,

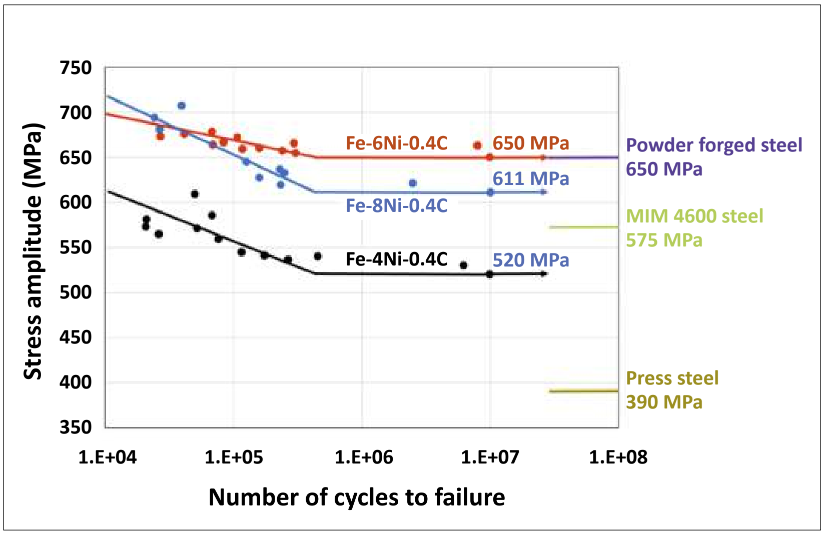


Fig. 6 S-N curves of various MIM Fe-Ni steels [1]

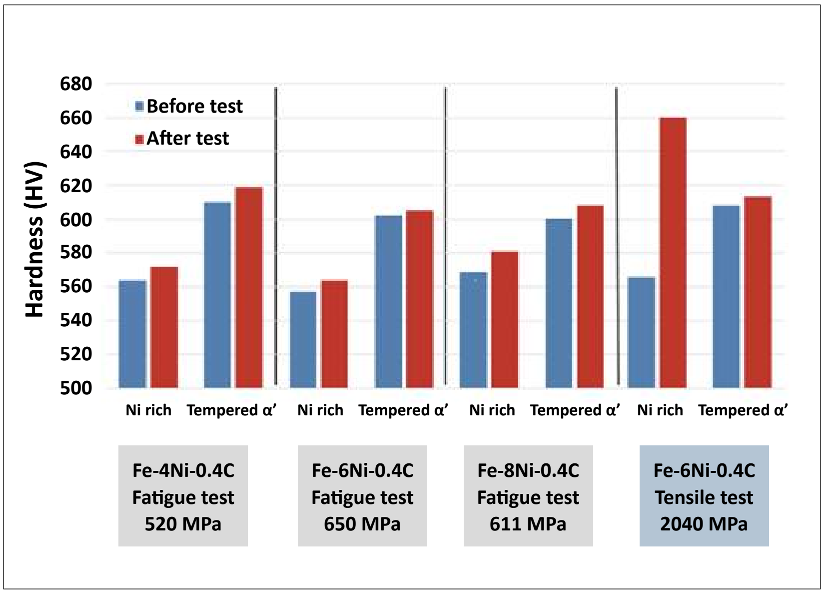


Fig. 7 Vickers microhardnesses of various MIM Fe-Ni steels [1]

		UTS (MPa)	Fatigue Strength (MPa)
Fe-4Ni-0.4C	MIM (Relative density 95%)	1900	520
Fe-6Ni-0.4C		2040	**650**
Fe-8Ni-0.4C		1660	611
4600 steel (Fe-1.8Ni-0.5Mo-0.2Mn)		1900	575
	Powder forged steel (100%)	2120	650
	Press steel (91%)	1920	390

Table 2 Comparison of mechanical properties for various steels [1]

demonstrating the large impact of TRIP in tensile testing. In fatigue testing, the load on the compacts was around 600 MPa, or around one third of that in tensile testing. As a result, the TRIP effect in fatigue testing was not as strong as in the case of tensile testing. This led the authors to conclude that the existence of the heterogeneous microstructure is more significant in relation to fatigue properties.

Table 2 compares the mechanical properties for die pressed steel, powder forged steel and MIM steel. It can be seen that, among the MIM steels, Fe-6Ni-0.4C shows the highest tensile and fatigue strength. From this, the authors inferred that a heterogeneous microstructure is considered to be the key to increasing fatigue strength, but that, to obtain the optimum fatigue strength, the Ni content needs to be adjusted to obtain an appropriate level of heterogeneity.

The Fe-6Ni-0.4C MIM steel, with a relative density of 95%, showed a fatigue endurance limit of 650 MPa, comparable to that of the powder forged steel at full density. The authors concluded that this provided powerful evidence that the heterogeneous microstructure is closely connected with superior mechanical properties.

Microstructure and properties of PIM maraging steels

Microstructure and property relationships in maraging steels processed by MIM were the subject of the paper from Martin Kearns, Keith Murray, Paul Davies and Mary Kate Johnston (Sandvik Osprey Ltd., UK) and Viacheslav Ryabinin and Erainy Gonzales (TCK S.A., Dominican Republic) [2].

Maraging steels emerged during the 1950s as a novel class of steels, deriving their high strength and toughness from controlled additions of Co and Mo to a low carbon Fe-Ni martensite, which produced an unexpectedly strong age hardening response. The discovery that properties could be further enhanced by increasing additions of Ti and Al led to a family of alloys being introduced with strength levels in the range 1400-2400 MPa, corresponding to Ti levels of ~0.2% - 1.8%.(see Table 3). The remarkably high fracture toughness that accompanies these high strength levels made these steels attractive candidates for critical applications such as the construction of aircraft undercarriage forgings and missile cases. In the general engineering sector, maraging steels are also used in the manufacture of press tools and die casting moulds.

In maraging steels made by conventional metallurgy, vacuum casting or double melting (air and vacuum refining) are employed to achieve close control of final chemistry including low oxygen, Mn and Si to minimise inclusion count and thereby maximise toughness. Care is also needed in the design of casting processes to minimise segregation, which can also compromise properties. In these respects, powder metallurgical methods can potentially offer some advantages compared with cast and wrought routes.

HIP consolidation has been applied to maraging steel powders

Alloy and Process Route	UTS, MPa	0.2%PS, MPa	El, %	Density, %TD	HRC
Wrought 18Ni1400 (0.2%Ti)	1340-1590	1310-1550	6-12	100	44-48
Wrought 18Ni1700 (0.4%Ti)	1690-1860	1650-1830	6-10	100	48-50
Wrought 18Ni1900 (0.6%Ti)	1830-2100	1790-2070	5-10	100	51-55
Wrought 18Ni2400 (1.8%Ti)	2460	2390	8	100	58-59
SLM 18Ni300 (as built)	1290	1214	13.3	99.4	39.1
SLM 18Ni300 (aged)	2217	1998	1.6	99.4	58
MIM 18Ni300 (0.5%Ti)	1640	-	1	96	46.5
MIM 18Ni300 (1.0%Ti)	2730 (TRS)	-	-	97	-

Table 3 Published tensile properties for maraging steels (Aged condition unless indicated otherwise) [2]

and impressive property levels, close to those of wrought materials, have also been reported in parts made by additive manufacturing and applications in this sector are growing.

To date, however, maraging steels have not been a popular choice for MIM applications and it is possible that researchers have been discouraged by difficulties with sintering alloys containing Ti and Al, which tend to form tenacious oxides that can retard sintering processes. The purpose of the reported study was therefore to characterise the sintering and densification behaviour of gas atomised, pre-alloyed maraging steel powders at different temperatures using two base alloys, with and without a Ti addition. The opportunity was also taken to examine the effect of powder particle size range on sintering and properties of these two alloys. Primary tensile properties were determined in the as sintered, heat treated and HIPped and heat treated conditions.

The choice of sintering temperatures for the study was guided by preliminary Thermocalc studies on the base alloy and related alloys with modified Ti and O levels. Fig. 8 shows the stability fields of different phases in maraging steel as a function of temperature and titanium content. This figure indicates that as the % Ti increases, the liquidus temperature decreases, with the difference in Ti

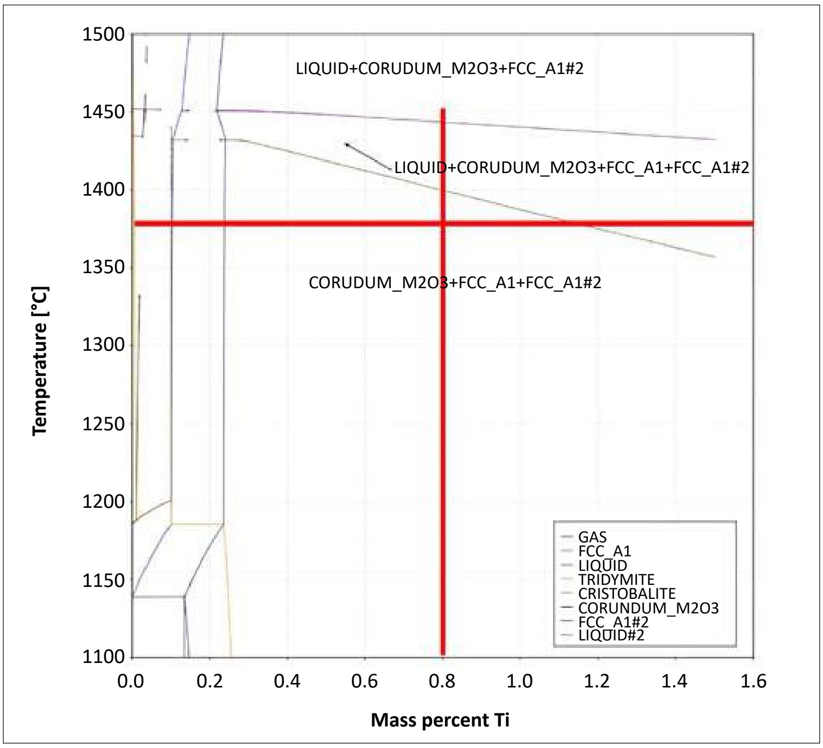


Fig. 8 Phase stability in 18Ni300 Maraging Steel showing the influence of Ti level. The red construction lines relate to the reported study [2]

level of 0.8% in the alloys in this study equating to a difference of liquidus temperature of -40°C. It is known that the activity of Ti and Al will be affected by the presence of oxygen and that a small amount of oxygen is typically picked up during inert gas atomising. The presence of oxygen reduces the activity of Ti and Al leading to a rise in liquidus temperature.

Two batches of maraging steel powder were produced by inert gas atomisation with nitrogen gas. Each of the 'as-atomised' powders was air classified to produce two different particle size distributions favoured by MIM parts makers: 90%-22 µm and 90%-16 µm. The chemistry of each of the powder batches is shown in Table 4. It should be noted that the

Alloy	Fe	Ni	Co	Mo	Ti	Mn	Si	Al	P	S	O	C	N
18Ni300	Bal	18.1	9.0	5.0	0.8	0.05	0.10	0.06	0.01	0.006	0.12	0.018	0.03
18Ni300 (Ti-free)	Bal	18.5	9.1	5.0	0.0	0.01	0.01	0.06	0.01	0.004	0.16	0.007	0.01

Table 4 Chemical analyses of the powders used in the reported study [2]

Alloy	Particle Size (µm)	App. Density g/cm³	Tap Density g/cm³	Pycnometric Density g/cm³	Particle Size Data (µm)		
					D90	D50	D10
18Ni300	90%-22 µm	3.92	4.92	8.114	21.7	10.2	3.9
18Ni300 Ti-free	90%-22 µm	3.76	4.67	8.132	21.2	10.5	4.0
18Ni300	90%-16 µm	3.79	4.63	8.111	15.7	9.6	5.7
18Ni300 Ti-free	90%-16µm	3.69	4.64	8.122	15.7	8.2	3.7

Table 5 Powder Density & Particle Size Analyses [2]

Alloy	Particle Size, µm	AS/HIP HT	UTS, MPa	0.2%PS, MPa	%El	%RA	Density, g/cm³	Density, %TD	Porosity, %	Hardness VHN 10kg
18Ni300	90%-22	AS	776	661	3.7	5.3	7.58	93.2	9.6	233
		HT	1435	1176	1.5	2.0	7.59	93.4		416
		HIP/HT*	1561	1065	3.0	4.5	8.05	99.0	3.1	555
	90%-16	AS	825	626	4.0	11.0	7.67	94.5	11.0	243
		HT	1603	1332	1.5	3.3	7.55	93.0		429
		HIP/HT*	1783	1679	3.0	4.5	7.95	97.9	4.1	568
18Ni300 (Ti-free)	90%-22	AS	826	649	4.3	13.7	7.46	92.0	10.9	218
		HT	1397	841	2.2	5.0	7.60	93.7		363
		HIP/HT*	1614	1025	5.0	36	8.10	99.9	0.5	509
	90%-16	AS	850	662	4.0	14.3	7.60	93.7	9.0	236
		HT	1423	1006	2.7	8.7	7.68	94.7		378
		HIP/HT*	1583	1200	5.0	36	8.07	99.5	0.5	489

*Table 6 Properties of as-sintered (AS), heat treated (HT) and HIP/heat treated (HIP/HT) samples (*average of 2 data rather than 3). Density by pycnometry and porosity by image analysis [2]*

Ti-containing alloy also contained slightly elevated levels of C and N. The particle size distributions of these powder batches are shown in Table 5, along with their apparent, tap and pycnometric density levels.

Feedstocks were prepared by combining each of the powders with TCK's proprietary binder formulation and were then injection moulded to produce tensile and Charpy test pieces, which were solvent debound followed by thermal debinding at 500°C for 3.5 hours and sintering at 1380°C for 60 minutes in a hydrogen atmosphere.

From the groups of 'as sintered' samples, pairs were HIPped at a temperature of 1150°C for a hold period of 3 hours and a pressure of 100 MPa. This served as a homogenisation heat treatment prior to solutionising and ageing at 815°C for 1 hour followed by an air cool and then a further 3 hour ageing heat treatment at 490°C, followed again by an air cool. Another triplicate set of as sintered samples of each type was homogenised without HIPping, after which the same two-stage solutionise and age heat treatment cycle was applied. Samples from each batch were tested to determine density, tensile properties and hardness (Table 6).

Fig. 9 shows metallographic surveys of the HIPped and heat treated materials. The improved properties in Table 6 reflect the major reduction in porosity level in all samples and a well-developed distribution of precipitates in the heat treated microstructure. The micrographs in Fig. 9 show that the

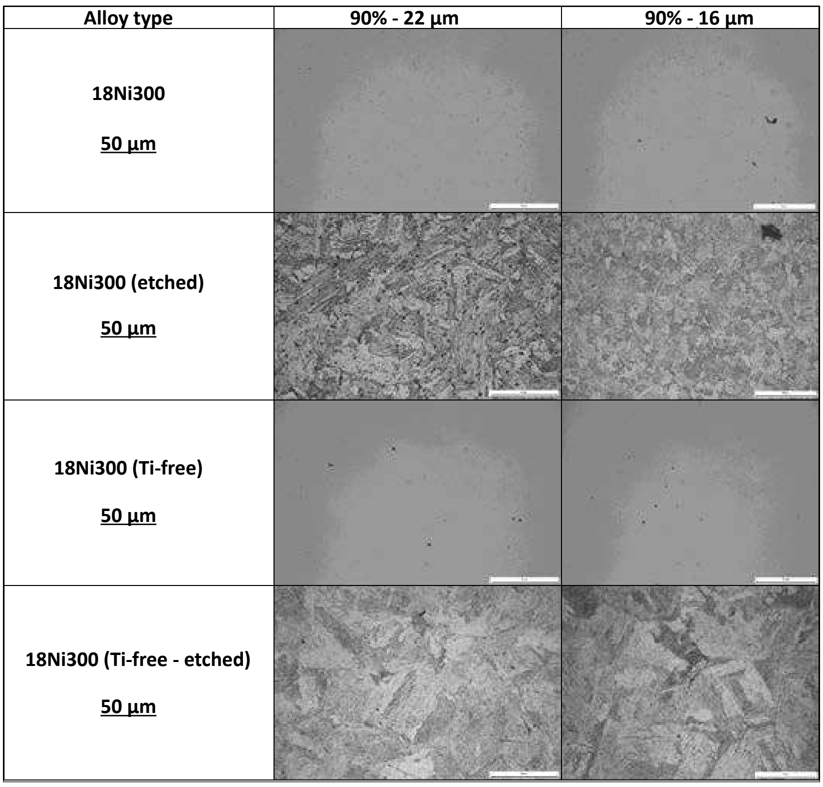


Fig. 9 Micrographs of HIPped and heat treated 18Ni300 and 18Ni300 (Ti-free) variants [2]

presence of Ti has a marked effect in refining grain size and that finer starting powder size also translates into a finer final grain size. It is also notable that the HIPped density of Ti-free samples is higher than that of Ti-containing samples.

The density data in Table 6 show that sintering of the 18Ni300 maraging steel is not straightforward and particularly high sintering temperatures and/or HIPping is required to achieve full densification.

Using a finer powder feedstock results in higher density and superior mechanical properties, but both 90%-16 µm and 90%-22 µm fractions can be sintered to a sufficiently high density at 1380°C to enable HIPping towards full density.

In the heat treated condition, the Ti-containing maraging steel MIM parts can achieve strength levels close to the equivalent wrought properties (compare Tables 6 and 3), while the elongation levels are lower than expected. It is speculated that the presence of Ti/Al oxides, especially at grain boundaries, may retard full densification, weaken interfaces and compromise ductility, as seen in other studies on additive manufacturing and HIPping of maraging steel.

The Ti-free alloy shows lower final strength level after heat treatment, but significantly higher ductility.

Depending on the service environment and the relative importance of strength and toughness, regulating the Ti content may be an effective way of arriving at the optimum property balance.

The authors therefore concluded that gas atomised 18Ni300 powders can be sintered and HIPped to give an impressive balance of strength, hardness and toughness and that reducing the Ti level can be a useful approach to improving sinterability and toughness for a modest reduction in strength level.

Carbonyl nickel powders

The next paper was not concerned with new PIM material development as such, but rather with a report on the recent commissioning of the world's fourth carbonyl nickel refinery. Zhiqiang Yang and Fangzhen Wang (Jinchuan Group Co. Ltd., China), Lou Koehler (Koehler Associates LLC, USA) and Jun Shu (Cnem Corporation, Canada) reported on the consequent advancements in Chinese carbonyl nickel powder production [3]. Carbonyl nickel and iron powders have a long history of MIM application, specifically in Fe-Ni elemental mixes.

Jinchuan Group, China's largest nickel mining and refining company, has commissioned a carbonyl nickel refinery with a design capacity of 10,000 metric tons of carbonyl nickel products. This paper compared the process route and product characteristics of this refinery with those of the three established commercial plants.

The carbonyl process harnesses the ability of nickel in an impure form to be extracted into a nickel carbonyl gas at ordinary temperatures with the process gas carbon monoxide, CO, via the following carbonylation reaction:

$$Ni + 4CO = Ni(CO)_4$$

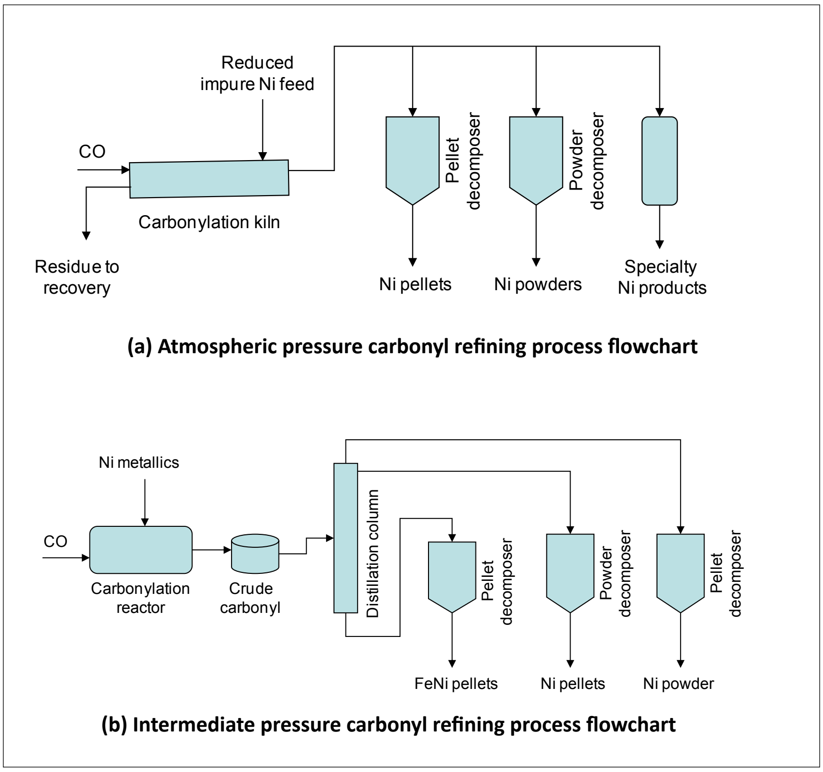


Fig. 10 Carbonyl nickel refining at Vale Canada, (a) atmospheric pressure process at Clydach, Wales and (b) intermediate pressure process in Sudbury, Canada [3]

At ambient pressure, $Ni(CO)_4$ is a volatile liquid with a boiling point of 43°C and can be readily restored into metallic nickel of a high purity and CO by reversing the carbonylation process through gentle heating to approximately 180-250°C.

Of the three existing refineries producing carbonyl powders, the two longest established are operated by Vale in the UK and Canada. These two plants were originally established by The International Nickel Company (Inco), which was subsequently acquired by Vale.

At the Vale Clydach refinery, South Wales, UK, production begins with a nickel oxide feedstock received from mines in Sudbury, Canada. The nickel oxide is continuously fed into a reduction kiln where it is tumbled in a stream of pure hydrogen at ~230°C to produce impure nickel in granular form. In the second stage, the volatilisation kiln, the activated nickel reacts with carbon monoxide at close to atmospheric pressure and 50-60°C to form nickel carbonyl gas. Under atmospheric pressure, iron

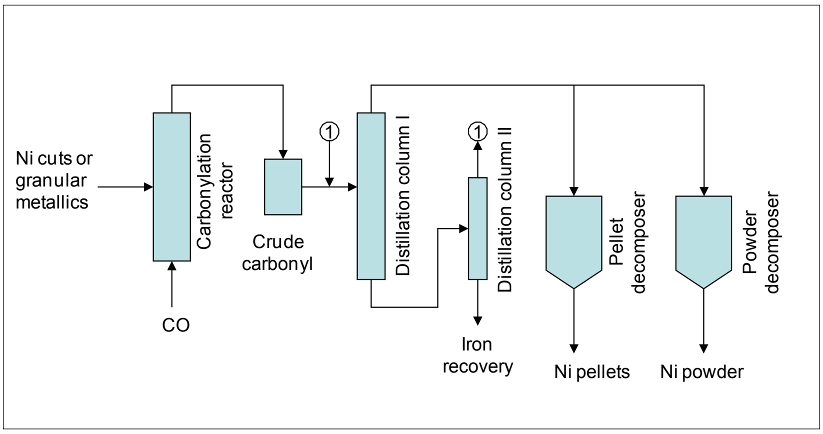


Fig. 11 High pressure carbonyl nickel refining at Norilsk Nickel, Russia [3]

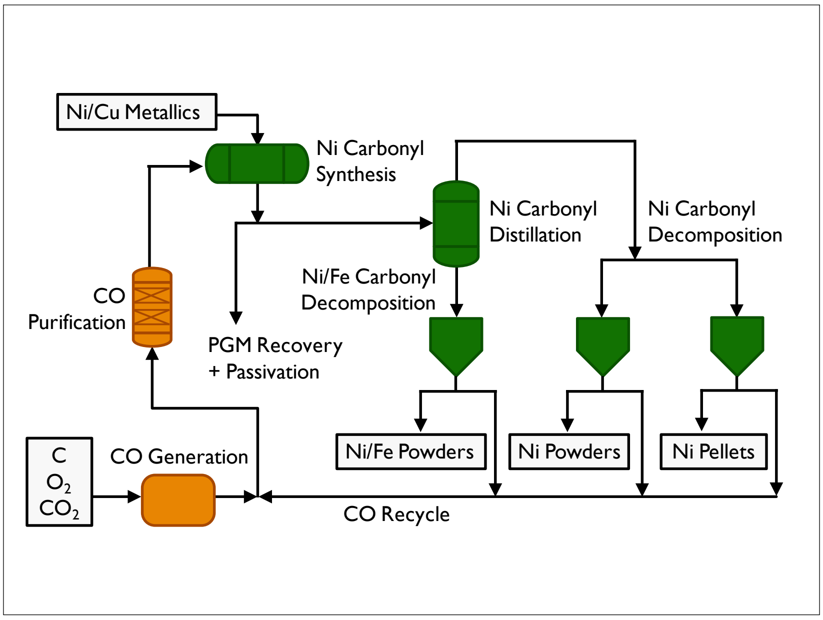


Fig. 12 Jinchuan nickel carbonyl refining process flow-sheet [3]

Grade*	A.D., g/cm^3	FSSS**, μm	Main usage
N04	0.3-0.5	1.2-1.8	Catalyst, batteries
N06	0.5-0.65	2.1-2.6	Batteries, fuel cell, conducting additive, powder metallurgy, hardmetal binder
N09	0.75-1.0	2.0-3.0	Powder metallurgy, hardmetal binder
N11	1.0-1.5	2.5-3.5	Diamond catalyst, powder metallurgy, hard metal binder
N24	1.8-2.7	2.5-4.0	Powder metallurgy, hardmetal binder, anti-seize lubricants, nickel salts and catalysts
N35	3.0-4.0	4.5-8.0	Special industry

** Carbonyl nickel powder trademarks by Jinchuan Group*
*** FSSS – Fisher Sub-Sieve Sizer, refer to ASTM Standard B330*

Table 7 Characteristic properties of Jinchuan carbonyl nickel powders [3]

carbonyl formation is minimised and so no specific iron carbonyl separation is required. The nickel carbonyl gas is then piped to an adjacent plant for thermal decomposition into pure nickel pellets or powders. A schematic of the process is shown in Fig. 10(a). Combined nickel pellet and powder production capacity at this plant is estimated at 45,000 tons per year, of which 10,000 tons is in powder form.

The Vale Sudbury (Canada) refinery, on the other hand, uses an intermediate pressure carbonyl refining process to increase the nickel extraction yield. In intermediate pressure nickel carbonyl refining, nickel containing metallics are batch charged into a rotating carbonylation reactor and allowed to react with CO at ~7 MPa and 170°C . Nickel carbonyl and a fraction of iron carbonyl are condensed for storage, followed by distillation to separate nickel carbonyl and iron carbonyl based on their different boiling temperatures. Pure nickel carbonyl from the top of the distillation column is the feed for production of carbonyl nickel powders and pellets. A schematic flow sheet of the process is given in Fig. 10(b). Estimated annual capacity of the plant is ~60,000 tons, of which 16,000 tons is in powder form. Powder capacity is higher in Sudbury than in Clydach due to the higher carbonyl gas strength (38% versus 13%) generated by the intermediate pressure refining.

Norilsk Nickel (Russia) practises high pressure carbonylation at ~22.5 MPa and 150-250°C . Fig. 11 is a schematic flowchart of the high pressure carbonyl refining process. Off-specification electrolytic nickel cuts and/or granular nickel metallics are batch charged in a fixed carbonylation tower to react with a continuous CO feed, followed by fractional distillation of nickel and iron carbonyls. Subsequent decomposition of nickel carbonyl in decomposer towers yields nickel powder and nickel pellets. Estimated annual capacity is ~5,000 tons, of which 4,000 tons is in powder form.

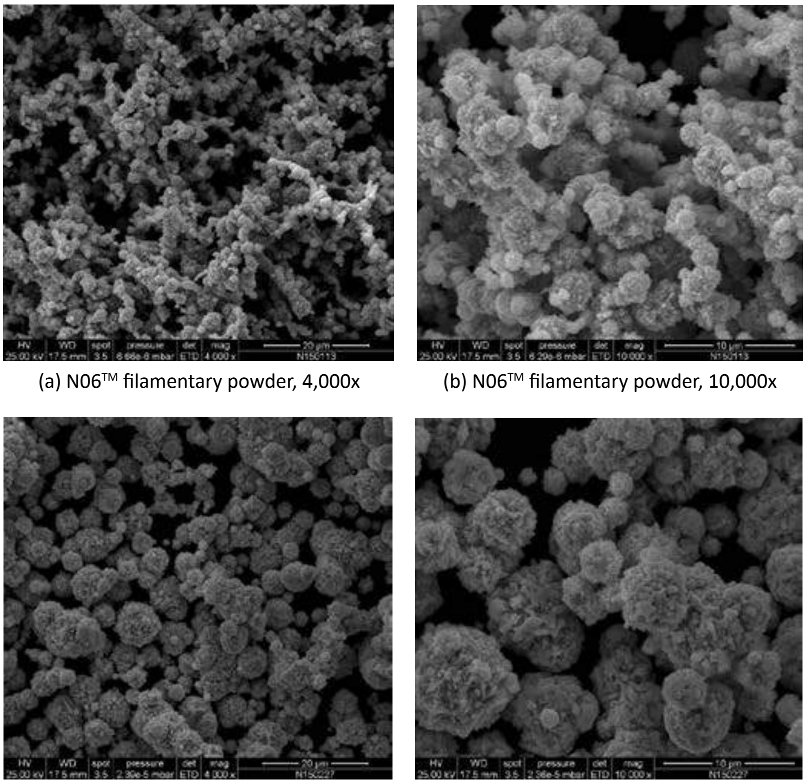
In the new Jinchuan (China) plant, the nickel resource is sulphide ore, similar to Vale Canada and Norilsk Nickel. The carbonyl refining unit operations are based on similar principles. Process deviations are mainly driven by availabilities of feed stocks at Jinchuan Group. In the Jinchuan carbonyl refining process, the starting raw materials include Ni/Cu metallics from smelting, nickel shots and off-specification electrolytic nickel. Carbon monoxide is generated from coal burning and purification. Initially, a pilot plant used the high pressure carbonylation route, but, through extensive assessment and improvement of the technology, the operating pressure was decreased to the intermediate pressure range of 7-9 MPa at 150-220°C in the commercial refining process. Due to the simultaneous carbonylation of iron impurities, distillation is necessary to separate nickel carbonyl from iron carbonyl before the final thermal decomposition into carbonyl nickel products such as nickel powders and nickel pellets. Precise control of nickel powder particle size distribution and morphology is readily achieved through modernised control systems. Fig. 12 shows the basic flow-sheet of the Jinchuan carbonyl nickel refining.

Tables 7 and 8 list typical properties of Jinchuan's carbonyl nickel powder products. The N series carbonyl nickel grades are designated in relation to the apparent density (bulk density), e.g., N24™ is a nickel powder with an average apparent density of 2.4 g/cm³ and N06™ with an average apparent density of 0.6 g/cm³. In general, carbonyl nickel powders with an apparent density lower than 1.0 g/cm³ are referred to as light nickel powders, often in the

Grade*	Chemical composition, less than wt%					
	Fe	Co	C	O	S	Other impurities
N04	0.0015	0.0010	0.15	0.20	0.0015	Trace
N06	0.0015	0.0010	0.15	0.15	0.0015	Trace
N09	0.0015	0.0010	0.15	0.15	0.0015	Trace
N11	0.0015	0.0010	0.15	0.15	0.0015	Trace
N24	0.0015	0.0010	0.15	0.15	0.0015	Trace
N35	0.0015	0.0010	0.15	0.15	0.0015	Trace

** Carbonyl nickel powder trademarks by Jinchuan Group.*

Table 8 Chemical assay of Jinchuan carbonyl nickel powders [3]



(a) N06™ filamentary powder, 4,000x

(b) N06™ filamentary powder, 10,000x

(a) N24™ discrete powder, 4,000x

(b) N24™ discrete powder, 10,000x

Fig. 13 Typical SEM images of Jinchuan carbonyl nickel powders at different magnifications [3]

Producer	A.D. g/cm³	FSSS µm	Ni%	C%	O%	Fe%	S%
Jinchuan N06™	0.50-0.65	2.1-2.6	>99.8	<0.150	<0.150	<0.0015	<0.0015
Vale T255™	0.50-0.58	2.2-2.6	>99.7	<0.200	<0.075	<0.0030	<0.0002
Jinchuan N24™	1.8-2.7	2.5-4.0	>99.8	<0.150	<0.150	<0.0015	<0.0015
Vale T123™	1.9-2.3	3.5-4.0	>99.8	<0.075	<0.080	<0.0010	<0.0001
Norilsk UT3™	1.9-2.5	3.0-6.0	>99.8	<0.090	N/A	<0.0015	0.0007

Table 9 Comparison of typical properties of commercial carbonyl nickel powders [3]

form of filamentary particle shapes, while carbonyl nickel powders with an apparent density over 1.0 g/cm^3 are referred to as heavy nickel powders and are generally of a discrete form.

Typical morphologies of N06™ filamentary nickel powder and N24™ discrete nickel powders are shown in Fig. 13.

Comparison of physical and chemical properties of Jinchuan's nickel powder products with other commercially available carbonyl nickel powders is shown in Table 9. Jinchuan carbonyl nickel powder N06™ is a filamentary powder with a high aspect ratio and chain-like particle characteristics, equivalent to Vale Type 255™ nickel powder and has found application in the production of battery and fuel cell electrodes, conductive paints and plastics, powder metallurgy and high temperature filters. Jinchuan carbonyl nickel powder N24™ is a discrete powder with quasi-spherical shapes of several microns in diameter, equivalent to Vale Type 123™ and Norilsk UT3™ nickel powders and is widely used in powder metallurgy, specialty hard alloys, diamond tools, welding rods, electronics, nickel-based chemicals and catalysts.

In addition to carbonyl nickel powders, Jinchuan Group's carbonyl metal products also include carbonyl iron powders, reduced iron powders and ferronickel powders. Due to the unique advantage of producing intermediate nickel carbonyl and iron carbonyl in the same refinery, Fe/Ni feed ratio can be precisely controlled to produce ferronickel powders. Currently, five ferronickel powder grades are commercially available from Jinchuan Group, NF19™, NF28™, NF37™, NF46™ and NF55™, containing 10 wt.%, 20 wt.%, 30 wt.%, 40 wt.% and 50wt% nickel, respectively.

With continuous carbonyl nickel technology development at Jinchuan Group, more carbonyl nickel and ferronickel powders will become available in the near future.

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