VOL. 10 NO. 4
WINTER 2021

POWDER METALLURGY REVIEW

TESLA MODEL S TRANSMISSION TEARDOWN

JOSÉ M TORRALBA ON PM RESEARCH

HOW TO MAKE METAL POWDERS: PART 1

Published by Inovar Communications Ltd

www.pm-review.com

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Subscriptions
Powder Metallurgy Review is published on a quarterly basis. It is available as a free electronic publication or as a paid print subscription. The annual subscription charge is £125.00 including shipping.

Design and production
Inovar Communications Ltd.
ISSN 2050-9693 (Print edition)
ISSN 2050-9707 (Online edition)

This magazine is also available for free download from www.pm-review.com

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POWDER METALLURGY REVIEW

The path to change is never straightforward

In September this year, for the first time, an electric vehicle topped the list of best-selling cars in Europe: the Tesla Model 3, which saw its sales rise by 58% compared to September 2020.

This is due, in no small part, to the global microchip crisis. The resulting shortage has caused production slowdowns for almost every automotive maker, but some more than others. Another factor in Tesla's success is European consumers taking advantage of the incentives and subsidies for EVs in larger numbers than ever. Prior to the COVID-19 pandemic, just over ten new diesel cars were registered for every electric or plug-in hybrid vehicle in Europe. In September 2021, that number decreased to just 1.3.

Looking beyond the headline, however, there are still other factors to consider in how future EV sales figures will play out, chief among them affordability, charging infrastructure and raw materials supply. History tells us that the path to change is never straightforward, and recent events have proven once again that we cannot take for granted that progress will follow forecasts.

More than ever, it is vital that the Powder Metallurgy industry cultivates its ability to respond to the changing market, and looks ahead to the possibilities offered by the EV sector. This issue's lead article details a timely project with just such an aim: the teardown of a Tesla Model S transmission to identify key potential PM applications.

Emily-Jo Hopson-VandenBos
Features Editor, *Powder Metallurgy Review*

Cover image
Tesla's Model S. A Model S transmission was the subject of a teardown to identify potential applications for press and sinter PM, as highlighted in this issue's lead article


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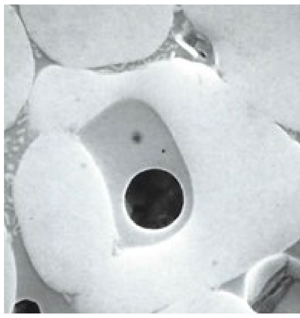

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To submit news for inclusion in *Powder Metallurgy Review* contact Paul Whittaker, paul@inovar-communications.com

6K raises $51M to accelerate battery materials development and metal powder business

6K, North Andover, Massachusetts, USA announced that it has closed a $51 million Series C financing round. With this investment, the company intends to complete its Battery Development Center of Excellence, adding 3,066 m^2 of product development space and doubling its 6K Energy team. Funding will also enable a tripling of production capacity for Additive Manufacturing metal powders at its 6K Additive division, increase the portfolio of powder product offerings, and expand its commercial sales activities globally. The financing round was led by Volta Energy Technologies, joined by new investors Catalus Capital and S Cap/Prithvi Ventures, and existing investors Anzu Partners, Launch Capital, Material Impact, and RKS Ventures.

"This round of capital is a validation of 6K's model to replace wasteful legacy production technologies with the UniMelt® platform, enter scaled production, meet customer needs, move toward profitability, and transform industries," stated Aaron Bent, CEO. "We are joined by world-class investors who are aligned with our vision to transform the way performance materials are produced. And in doing so, we are teaming to solve critical needs of the US and the planet, addressing climate change, supply chain security, and reducing the demand on our fragile and limited resources."

6K intends to use the proceeds of the financing to expand product development and commercial activities across its multiple divisions. At 6K Additive, plans are laid for production to set up sales & distribution in Europe and Asia and expand the production by additional 600 tons/year.

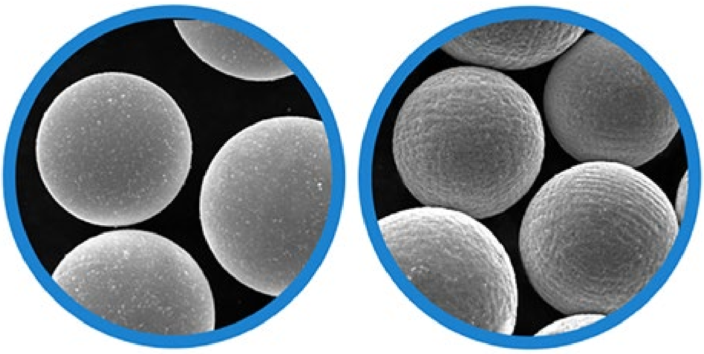
6K has announced its intent to invest $25 million over twenty months in 6K Energy's Battery Development Center of Excellence, enabling partnerships for rapid product development and deployment. The Center will be fully capable of pilot production with UniMelt capacity equivalent of 400 MWh. 6K is currently sampling customers, and developing products across NMC cathode, LFP, silicon-dominant anode, lithium, solid-state electrolyte, and recycled cathode materials.

In response to demand from companies across the performance materials spectrum, 6K intends to invest in the identification and development of performance and electronic materials that can be produced cost effectively and sustainably with its UniMelt plasma production system. 6K has established an advanced R&D team for the development of performance materials including those for a variety of applications, ranging from semiconductors to electronic packaging to bio-ceramics.

Zander Arkin, Volta's Chief Investment Officer, has also joined 6K's board as director, alongside members such as Congressman Joe Kennedy III and Mark Little, previously CTO at GE.

Arkin commented, "Our investment strategy focuses on technologies that bring a positive impact to the environment and contribute to the rapid adoption of electric vehicles and renewable energy on the grid. Not only does 6K and its UniMelt platform align perfectly to our investment strategy, but the company is well poised to impact advanced material manufacturing for electric vehicle batteries with a solution that changes the dynamic of sustainability in the supply chain for battery materials."

www.6kinc.com



Ti-64 (left) and stainless steel 17-4 (right) metal powders produced with 6K technology (Courtesy 6K)

Höganäs joins Connactive to develop electric drive based on metal powders

Sweden's Höganäs AB reports it has joined the Connactive project to help develop new electric drive concepts based on the use of metal powders. The Connactive project was established in 2019 as a way to bring companies together with the goal of fostering innovation. Currently, the work is focused on the production of an enhanced-efficiency motor.

"It's essential for electrical engines to become more powerful and efficient to allow electric vehicles to fulfil their vast potential, and this can be done by using AM-enabled technology and dedicated material solutions that take technology to the next level," stated Deniz Yigit, Director of Global Business Development – Customisation Technologies, Höganäs. "Höganäs AB and Alvier Mechatronics have joined the Connactive project, which is dedicated to achieving high-speed, high-frequency and power density eDrive solutions. This cross-company collaboration will leverage the different areas of expertise of each member, and the results will drive the evolution of the modern electric engines," he added.

Höganäs has joined the Connactive project to develop new electric drive concepts based on the use of metal powders (Courtesy Connactive)

Höganäs's metal powders were used in Connactive's first project: the Dual Drive System, a powersplit planetery gearset and matching RX II unit in combination with the high torque AX motor and highly integrated electronics. Leveraging the abilities of partner companies Dontyne Gears, Moteg and Vishay, the Dual Drive System was brought from blueprint to series production standard prototype within six months.

"Höganäs' vision is to inspire industry to make more with less. By utilising the endless opportunities of our metal powders, we know that we can improve resource efficiency and lead a wave of change for the better," added Lars Sjoberg, Head of System Design at Alvier Mechatronics and former Manager of Application Development at Höganäs. "Co-creation brings a new dimension to our way of working and we expect that this will take us to the next level as well as speeding up market introductions at lowest total cost."

www.connactive.tech
www.hoganas.com

Sandvik increases metal powder production capacity for AM

Sandvik AB, Stockholm, Sweden, has expanded its metal Additive Manufacturing powder production capacity by installing two additional atomisation towers at its production site in Neath, Wales, UK. This expansion follows a recent investment in a new plant for the manufacturing of titanium and nickel-base alloys for AM, in Sandviken, Sweden.

"Sandvik offers extensive capabilities in terms of providing high-quality and consistent metal powders, to customers engaged in a range of Additive Manufacturing processes such as Laser Powder Bed Fusion [PBF-LB], Electron Beam Melting [Electron Beam Powder Bed Fusion, or PBF-EB], and Binder Jetting," stated Annika Roos, Business Unit Manager of Sandvik's metal powder business. "By installing these new atomisation towers – one of which is already fully operational and quality assured, while the other is under construction – we bring our total tower count to twelve, and thereby significantly increase our ability to produce even larger quantities of premium metal powders."

Sandvik offers a wide range of metal powders for AM, including titanium, stainless steel, duplex- and super-duplex steels, nickel-base super alloys, aluminium, copper, and more. The alloys are all atomised in-house and tailored to meet the needs of customers in demanding industries.

"Materials technology is very much integrated with Sandvik's DNA. From our own AM service business, we have first-hand experience of printing in a wide range of materials for Additive Manufacturing – from tool steels and duplex steels to titanium and super alloys for high-temperature applications – and understand the importance of using premium raw materials in order to obtain an optimal end result," Roos added.

The quality management system of the powder manufacturing facility in Neath is certified in accordance with AS9100D, ISO 14001, ISO 45001, ISO 50001, and ISO 9001. In addition, Sandvik's production site for titanium and nickel-base alloys in Sandviken, Sweden, is also ISO 13485 certified for deliveries to the medical segment.

Dr Paul Davies, Technical Solutions Manager at Sandvik Additive Manufacturing, commented, "Additive Manufacturing is in general challenging enough without questionable raw materials. Predictable and consistent powder flow is key when it comes to part quality and final properties – and since we have such a wide range of printing technologies for metals in-house, we can make sure all metal powders are tailored to the customers' specific manufacturing process as well."

www.additive.sandvik

Hyperion executes option agreement to acquire Blacksand Technology

Hyperion Metals, Charlotte, North Carolina, USA, has executed a one-year option to acquire Blacksand Technology LLC, West Valley City, Utah. The two companies have been collaborating on an investigation into the commercial development of spherical titanium metal powders.

"The combination of Hyperion and Blacksand Technology is transformational, bringing together two highly complementary organisations, supported by the world-class metallurgical engineering department at the University of Utah, to create a leader in sustainable low-carbon titanium metal and powders," stated Anastasios Arima, CEO and Managing Director, Hyperion. "Hyperion's Titan Project in Tennessee will supply low-carbon titanium mineral feedstock to produce low-carbon, low-cost titanium metal and powders using the HAMR and GSD technologies. We aim to build on Blacksand's strengths in material science and innovation to scale and commercialise these breakthrough American technologies and make the US, once again, the leader in titanium metal."

Since the founding of Blacksand in 2013, it has developed the Hydrogen Assisted Metallothermic Reduction (HAMR) technology and developed over forty patents worldwide relating to titanium manufacturing, from the supply chain to specific technologies. Over the years, the company has seen a reported investment of around $12 million into these technologies from various government agencies.

Dr Z Zak Fang, Professor of the University of Utah and founder of Blacksand, added, "Blacksand is excited about the prospects of commercialising its suite of titanium technologies through Hyperion Metals. Hyperion recognises the potential of the breakthrough HAMR process based on a simple and elegant scientific principle to lead the titanium production industry away from the old, energy-intensive, and environmentally-challenging Kroll process. This is a historical opportunity to change how titanium is made with an energy-efficient, potentially zero-emission, and low-cost technology."

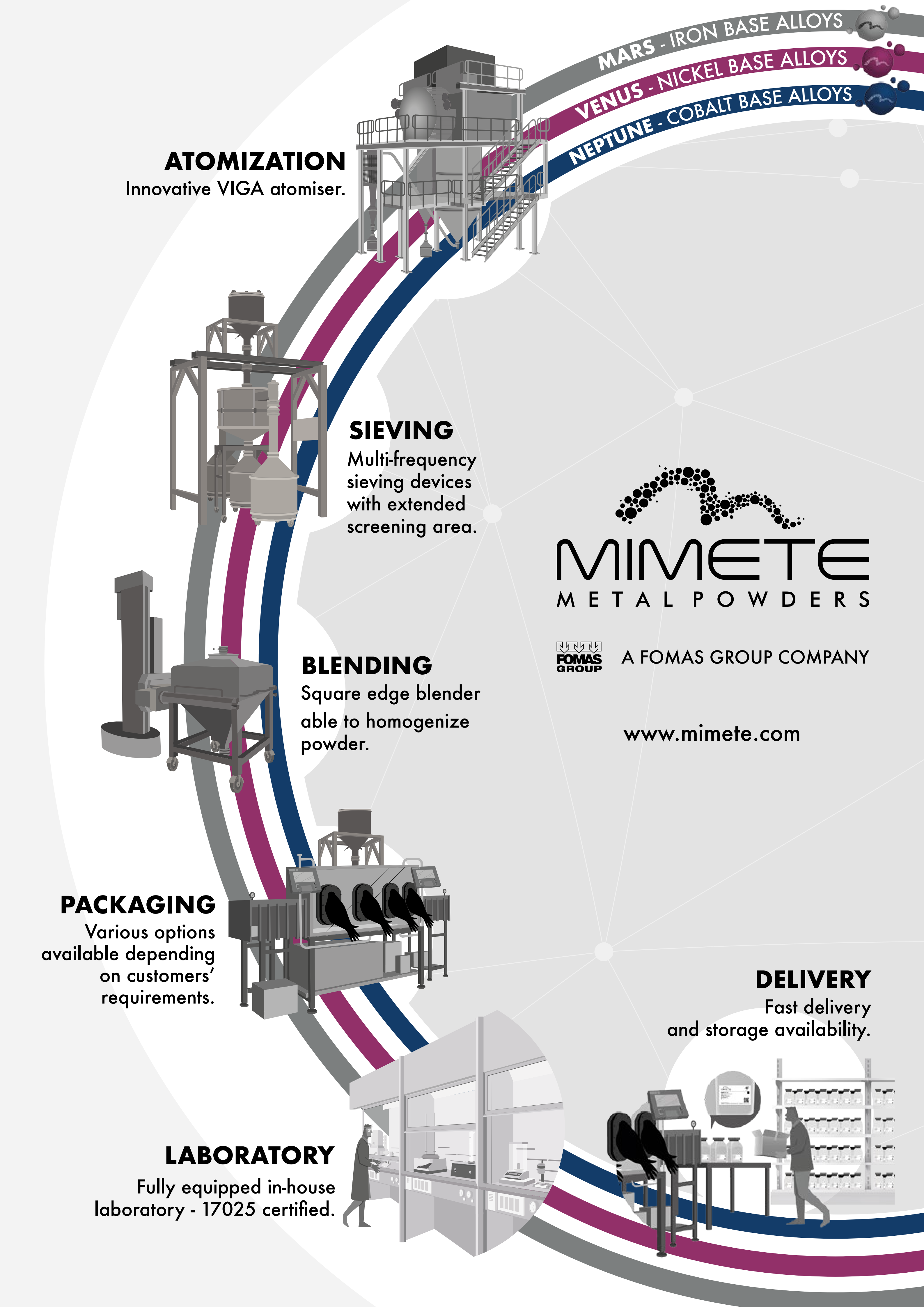
www.hyperionmetals.us
www.blacksandtechllc.com

JPMA celebrates 65 years and moves HQ

The Japan Powder Metallurgy Association (JPMA) has relocated to a new address within the Matsudashoji Building in Tokyo, Japan. The move comes as the association celebrates its sixty-fifth year since its founding in April, 1956.

The JPMA consists of over sixty member companies that represent a number of product areas across the Powder Metallurgy supply chain, including PM equipment manufacturing, powder makers and parts manufacturers.

www.jpma.gr.jp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www.mimete.com

Amsted Automotive forms Joint Venture with China's HOFO to expand global PM capacity

Amsted Automotive, a division of Amsted Industries formed through a merger of its Burgess-Norton and Means Industries subsidiaries, has announced a joint venture with Anhui HOFO Mechanical and Electrical Co. Ltd, headquartered in Bengbu, Anhui Province, China. The new venture, named BN-HOFO Material Technology (Anhui) Ltd, will join the technology resources of Amsted Automotive's Burgess-Norton business with HOFO's manufacturing and technology base, expanding the reach of the company's PM component manufacturing.

Burgess-Norton is a leading producer of Powder Metallurgy parts (Courtesy Burgess-Norton)

"The agreement combines Burgess-Norton's more than sixty years of expertise in the design and manufacture of precision powder metal components with HOFO's world-class facility in China and extensive engagement in the local market," stated Jeremy Holt, president of Amsted Automotive.

The joint venture is said to address the existing demands of the local Chinese Powder Metallurgy market for large, complex components and the growing market for electric vehicle components. BN-HOFO is reported to have the largest PM press in China, which will enable Amsted Automotive to provide solutions for the rapidly emerging need for Powder Metallurgy materials and technologies in Asia, and with global customers.

It was stated that Burgess-Norton will have the unique opportunity to increase its reach into the domestic Chinese market with globally competitive PM technologies and materials, allowing Amsted Automotive to expand its footprint in Powder Metallurgy worldwide. The joint venture is expected to be producing production-ready components in 2022.

www.amsted.com

Schunk focuses on high-tech materials at new Innovation Centre

The Schunk Group, headquartered in Heuchelheim, Germany has opened a new Innovation Centre in Heuchelheim. The facility, in which the company has already invested €20 million, hosts state-of-the-art technology, including plasma torches and Additive Manufacturing machines, and will be used to develop high-tech materials and products.

Schunk also announced plans to open a further Innovation Centre at the Reiskirchen site of Weiss Technik. The company believes these investments underscore the importance of its facilities in the region, having invested around €220 million in the state of Hesse alone over the last five years and creating 340 new jobs. The Schunk Group currently employs 3,700 people at its sites in Heuchelheim, Wettenberg and Reiskirchen, making it one of the largest industrial employers in the region.

"Our new innovation centre at the Heuchelheim site will be our think tank, where we intend to develop new high-tech materials and technologies and transfer them to industrial production," stated Dr Ulrich von Hülsen, a member of the executive board of the Schunk Group responsible for the carbon business. "The world is facing enormous challenges in the areas of climate protection, mobility and energy supply. All these megatrends require new materials to solve the existing problems. We are excellently positioned here by developing components for efficient electric motors or industrialising the production of bipolar plates for fuel cells that are suitable for mass production. Reducing the carbon footprint is an important driver for our materials innovations."

In the Innovation Centre, Schunk's developers are said to have all the development and manufacturing processes at their disposal in one place. The 3,300 m^2 hall is air-conditioned, with precise control of temperature and humidity. Two climate control units, provided by Weiss Technik, make it possible to create three different climates, creating optimal conditions for the development of high-performance materials.

In the Additive Manufacturing technical centre, a variety of different machines are available, with which almost all AM processes can be represented.

www.schunk-group.com

Sandvik Materials Technology to be listed on Stockholm Exchange in Q2 or Q3 2022

The Sandvik Board of Directors has confirmed its previous decision to proceed with the preparation to distribute Sandvik Materials Technology (SMT) to Sandvik's shareholders and list the company's shares on the Nasdaq Stockholm Exchange. The board's current target is to complete the listing during the second or third quarter 2022, subject to approval by Sandvik's shareholders.

"The internal separation of SMT is proceeding as planned and the previously communicated reasons for a distribution and listing remain relevant. We believe that both Sandvik and Sandvik Materials Technology can develop more favourably on their own," stated Johan Molin, chairman of the Sandvik Board of Directors.

Sandvik added that its board intends to formally propose the distribution and listing at a shareholders' meeting in 2022.

www.additive.sandvik

Micro Metals acquired by Alderman Enterprises

Manufacturer of metal powder parts Micro Metals, Inc, Jamestown, Tennessee, USA, has been acquired by Alderman Enterprises, Chattanooga, Tennessee, reported *The Chattanoogan*. Micro Metals has, since 1976, served the automotive and general manufacturing industries.

"Micro Metals represents exactly what we look for in an Alderman business: a successful, well-run operation backed by a strong leadership team and talented employee base," stated Ben Brown, founder and partner of Alderman Enterprises. "The company has specialised equipment and know-how to deliver world-class products to its long-established customer base. And, importantly, Micro Metals is a respected and engaged participant in the Jamestown community."

Scott Edwards, CEO, Micro Metals, added, "I feel very blessed to have entered into this agreement with Alderman Enterprises. Not only will their purchase of the Edwards' family business allow me to focus on other interests, more importantly, it will assure the continued growth and prosperity of Micro Metals for our customers, our employees and the local community."

"I'm more than confident the firm will maintain its preeminent position in the powder metal industry, while continuing to be a valuable asset to Fentress County [Tennessee]. Alderman's leadership combined with Micro's current talented staff is a definite recipe for success," he concluded.

www.powdermetalparts.net

Oerlikon introduces alloy to replace super duplex stainless steels

At Formnext 2021, Oerlikon AM, Pfäffikon, Schwyz, Switzerland, presented a new alloy to match the strength and corrosion resistance of super duplex stainless steels (DSS). The new material is a high-entropy alloy with a nanoscale duplex microstructure.

Said to be well suited to additively manufacturing structural components, such as centrifugal pump impellers, the new alloy is intended to replace DSS by matching its corrosion-resistance standards, while also reportedly providing superior strength properties. It is also said to be less susceptible to changes caused by high-temperature operations and requires only a single-step heat treatment.

An impeller produced using the new high-entropy alloy (Courtesy Oerlikon)

Oerlikon developed the alloy as part of the NADEA project – a European research initiative on high-entropy alloys in partnership with several industrial and academic partners. Using its proprietary Scoperta Rapid Alloy Development tool, Oerlikon was able to significantly shorten the process in developing the alloy. By leveraging the inherent benefits of AM, Oerlikon hopes to enable customers to create complex geometries using this new alloy that super duplex steel cannot address via conventional manufacturing. Smoother surfaces for the same structural application are possible in the build process.

www.oerlikon.com

VBN celebrates opening of new facility

VBN Components, Uppsala, Sweden, celebrated the opening of its previously announced new premises on Nov 10, 2021. While the inauguration was postponed due to the COVID-19 pandemic, the move took place in the spring of this year as a response to growing customer demand.

The new facility is three times larger than its previous premises, and is expected to enable the increase of production capacity and a more streamlined workflow. As well as the additional space, VBN has already expanded its personnel and plans to add more machines in the coming months.

Johan Bäckström, CEO, stated, "It feels good that we can finally inaugurate our new, spacious and production-adapted premises together with our partners, and that it coincides with the fact that we have received new serial production orders."

www.vbncomponents.se

6K Additive acquires Specialty Metallurgical Products

6K Additive, a division of 6K, headquartered in North Andover, Massachusetts, USA, has acquired Specialty Metallurgical Products (SMP), based in Red Lion, Pennsylvania. SMP specialises in titanium and zirconium tablets used as a grain refiner for the metal alloys market. The terms of the acquisition were not disclosed.

The acquisition is said to augment 6K Additive's existing line of Ty-Gem compacts used in similar applications and markets. The new product enables 6K Additive to expand its commercial relationships into both new and existing companies for titanium customers while developing new applications and customers for zirconium additives.

"We have over twenty years of experience supplying our Ty-Gem grain refining products to the aluminium industry," commented Frank Roberts, president of 6K Additive. "Adding SMP's titanium products to our portfolio will complement our existing offering while enhancing our expertise in the process. The acquisition will also add an entire new product line to our current portfolio in zirconium tablets. The quality products SMP brings to 6K Additive enables us to go broader and deeper with our customers providing a quality, sustainable alloying solution no other company in the world can offer."

Jim Clark, former president of SMP and now a strategic advisor for 6K Additive, stated, "We have a long history of supplying the top end of titanium additives to the industry and have established SMP as the leading supplier of zirconium. Becoming part of the 6K Additive team ensures our customers are provided with the same quality product, but backed by a larger organisation that has the logistics and operational infrastructure to support our rapid growth."

Gary Hall named new CFO

In October, 6K also announced the appointment of Gary Hall as Chief Financial Officer. Hall will oversee all financial aspects of the company, including financial planning & analysis, financial reporting, accounting & control, tax, and treasury. Hall will also be responsible for both the HR and IT strategies, staffing and implementation for the company. He will report directly to 6K's CEO Dr Aaron Bent.

www.6kinc.com

Pometon establishes PometonPlus for metal AM powders; joins Dubai 3D Printing Strategic Alliance

Pometon S.p.A., headquartered in Maerne, Venice, Italy, has established PometonPlus, a new business division specialising in the production of metal powders for Additive Manufacturing.

Founded in 1940, Pometon is a manufacturer of metal powders for the automotive, chemical, aerospace and electronics industries, offering a wide range of ferrous and non-ferrous powders, as well as stainless steel abrasives. The company believes that Additive Manufacturing is one of the most promising sectors and, in order to satisfy this trend and meet the needs of its clients, Pometon decided to invest and start producing metal powders specifically for AM.

PometonPlus aims to begin production of new spherical powders for AM towards the end of 2021. Powders will initially belong to six major product families, including:

- Copper and copper alloys
- Steel, stainless steel and alloys
- Cobalt-chromium and alloys
- Nickel-chromium and alloys
- Titanium and titanium alloys
- Aluminium and aluminium alloys.

Pometon metal powders selected for Dubai's 3D Printing Strategic Alliance

Pometon also announced it has been selected to be part of the 3D Printing Strategic Alliance for Dubai, launched in 2020 by HH Sheikh Hamdan Bin Mohammed Bin Rashid Al Maktoum, Crown Prince of Dubai, Chairman of the Executive Council, Chairman of the Board of Trustees at Dubai Future Foundation.

The alliance is made up of a network of institutions around the world, including government entities, academia and AM companies, involved in developing innovative solutions and strategies to accelerate the adoption and use of the Additive Manufacturing technology, and aims to offer a wide range of products, supplies and services in vital sectors to meet market needs and achieve self-sufficiency, supporting government, economic, healthcare and scientific sectors worldwide.

Following the establishment of PometonPlus, the company will produce metal powders for use in a new AM machine being developed by the alliance for medical and dental applications.

www.pometon.com

Höganäs closes Niagara Falls plant due to hydrogen supply issues

Sweden's Höganäs AB has had to end production at its Niagara Falls, New York, USA, plant due to an unforeseen hydrogen supply shortage. Operations at the facility ended November 1 and full plant closure is expected to take place December 1.

"We are deeply sorry to announce that we need to close our production in Niagara Falls," stated Fredrik Emilson, CEO of Höganäs. "Our main priorities are our employees and customers, and we are committed to supporting them through this difficult time. This has not been an easy decision to make, and we have worked very hard to find viable alternatives to solve the current situation."

From its Niagara Falls plant, Höganäs produced metal powder for automotive and aircraft brake pads, food fortification, and water treatment. In August 2021, Höganäs' long-term supplier of hydrogen gas announced it was to close, which resulted in the end of the Niagara Falls facility's hydrogen gas supply. While the company explored alternatives, Höganäs was unable to find a solution. Due to the unexpected shortage in the hydrogen gas supply necessary to run its production process, the company has ended its production, affecting thirty-three employees.

Dean Howard, president of North American Höganäs, added, "We have contacted all possible suppliers, but, with the current severe shortage in the North American market due to high demand, we have – unfortunately – not been able to find a solution given the timeframe needed. Naturally, we are doing our utmost in maintaining the best standards of service to our customers."

www.hoganas.com

Fehrmann adds six new aluminium alloys

Fehrmann Alloys GmbH & Co KG, Hamburg, Germany, has added six new aluminium alloys, suitable for Additive Manufacturing, to its portfolio. After the success of its corrosion-resistant, high-performance AlMgty80 and AlMgty90, the company has now added AlMgty70, AlMgty100 as well as standard cast aluminium AlMgty3, AlMgty5, AlMgty50 and the aluminium-zinc alloy AlZnty5.

In the development of new materials, the company partners with leading institutes such as Fraunhofer Research Institution for Additive Production Technologies (IAPT). In the past, Fehrmann Alloys has developed high-performance aluminium alloys for AM one-offs or small series production, as well as for casting in huge volumes on an industrial scale.

www.alloys.tech

Harper International launches new lab-scale rotary furnace

Thermal processing solutions provider Harper International, Buffalo, New York, USA, has announced the launch of a new lab-scale rotary furnace. The furnace is aimed at producers of advanced materials, enabling them to optimise process parameters on a small scale to ensure capability and quality requirements are achieved, prior to investment in production-scale thermal process equipment.

The lab-scale rotary furnace (Courtesy Harper International)

The new lab-scale furnace is said to deliver superior temperature uniformity for batch or continuous processing of advanced materials, including granular, powder or particulate aggregates at operating temperatures up to 1200°C. Harper also offers add-on options for controlled atmospheres and material handling.

Additionally, the company utilises this furnace in the Ignite® programme at its Technology Research Center. Ignite allows clients to run feasibility demonstrations and experimental campaigns while leveraging Harper's expertise in process development and process optimisation.

"We are excited to offer the lab-scale rotary furnace as an off-the-shelf solution for clients looking to make their innovations become reality," stated Paul Elwell, vice president of Sales and Marketing, Harper International. "With this new product, Harper clients maintain control and access to lab-scale furnace testing and resources to better meet their project timelines and investment profiles."

www.harperintl.com

Sandvik releases interim report for third quarter 2021

Sandvik AB, headquartered in Stockholm, Sweden, has released its interim report for the third quarter of 2021. The company stated that revenues increased organically by 13%, while adjusted operating profit was reported at SEK 3,817 million (Q3 2020: 2,626 million). Order intake saw organic growth of 21% to SEK 26,292 million.

Sandvik Materials Technology

Sandvik Materials Technology saw order intake increase 29%, with a 1% increase in revenue. Strong order intake development was noted in all major regions, compared against the corresponding period in the preceding year, with the strongest development seen in North America. Optimism in oil & gas and aerospace segments continued to improve, with an increase in the number of orders being placed, though levels were still said to remain low.

Sandvik Manufacturing and Machining Solutions

Sandvik Manufacturing and Machining Solutions saw order intake grow 16% and revenues up 18% year on year, driven by the automotive and engineering sectors. Regional order intake growth was seen at 16% in Europe, 19% in Asia and 13% in North America, although lower production volumes in the automotive sector due to semi-conductor shortages were noted.

Sandvik Machining Solutions acquired a majority stake in the solid round tools company Chuzhou Yongpu. Sandvik Manufacturing Solutions increased the pace of its M&A activities, resulting in three strategically important acquisitions in and after the quarter.

Sandvik Mining and Rock Technology

Sandvik Mining and Rock Technology reported order intake and revenue increases of 26% and 12%, respectively. There has been a reported all-time high order intake in aftermarket, with organic order growth of 38%, and strong equipment growth of 13% year on year. Broad-based underlying demand in both infrastructure and mining with order intake growth of 68% in North America; 19%, Europe; and 10%, Asia.

During the quarter, Sandvik Rock Processing Solutions expanded its offering within crushing and screening with the launch of the track-mobile impact crusher QI353. Based on a new modular platform it can operate in both primary or secondary crushing applications, providing a sustainable solution at reportedly lower operational costs.

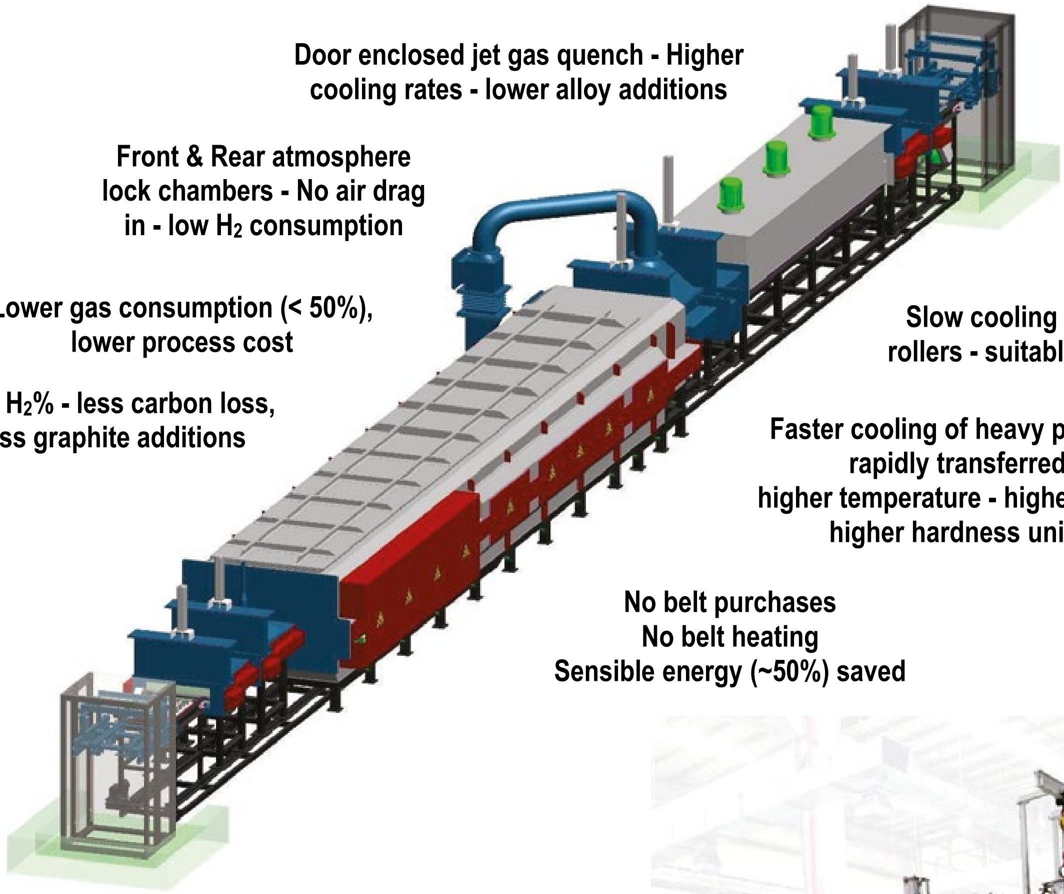
"Sandvik has become a more growth-oriented company. We deliver on strong organic growth and have already added over SEK 8 billion in annual revenues from strategic acquisitions. At the same time, we have taken important steps to become a more digitally focused company," stated Stefan Widing, president and CEO. "With our leading positions, Sandvik has a strong and obvious role in supporting our customers' digital transformation; a shift that will improve productivity, and lead to significant sustainability gains. As a growth-focused, resilient and high-performing company, and with an underlying demand for our solutions, Sandvik is well positioned to execute on profitable growth, and to deliver long-term shareholder value."

www.sandvik.com

ROLLER HEARTH SINTERING FURNACES

MODEL RHF TMax. 1300°C High Temperature Sintering

High temperature sintering + higher quench rate
– lower alloy content, lower compressibility
– higher density – parts with improved mechanical properties.



MODEL RHF TMax. 1180°C

Conventional Sintering...with benefits

- *With doors - lower gas consumption*
- *Higher quench speed*
- *No belts, lower energy*

OTHER FURNACES FOR PM

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www.fluidtherm.com

Alvier AG PM-Technology celebrates 35th anniversary

Alvier AG PM-Technology, a Swiss-based Powder Metallurgy tooling manufacturer, has celebrated thirty-five years of manufacturing PM tools in Europe. The company, established in 1986, develops and produces innovative tooling solutions, supporting the PM industry in the development of a wide range of components.

Alvier's experience lies in the production of all types and designs of press and sizing tools, producing systems for complex, multi-level sintered parts such as synchroniser hubs, belt drive pulleys, sprockets or camshaft adjusters.

The company is also recognised for its development of helical gear systems, including gearbox designs for the upper punch drive and bearing modules for single and multi-platen die-sets. Alvier's client base reaches across four continents, with customers in more than twenty countries. The company was acquired by Sweden's Höganäs AB in 2018.

www.alvier.com

Alvier AG PM-Technology has celebrated thirty-five years of manufacturing PM tools in Europe (Courtesy Alvier AG PM-Technology)

Altair launches consortium to support Material Data Center

Altair, Troy, Michigan, USA, has announced the launch of the Altair® Material Data Center™ consortium, designed to help make its Altair Material Data Center (AMDC) a best-in-class materials information resource to support innovative product design and manufacturing.

The development of sustainable, efficient, minimum-weight designs requires accurate, multi-domain material properties; the selection of these materials is a vital step in product development. The AMDC furnishes users with the material properties needed for tasks such as virtual prototyping and simulation, enabling users to browse, search, and compare materials in a standalone application or through the interface of their simulation and optimisation tools.

The AMDC consortium is intended to shape the growth of this cloud-based database, which gives engineers and designers instant access to accurate data on a vast array of metals, plastics, and composites for use with CAE.

"We are delighted to welcome industry leaders such as Nikola Motors and the National Institute for Aviation Research to the consortium," stated Stephanie Buckner, senior vice president of customer engagement and corporate development, Altair. "Members will play a central role in driving AMDC, maximising its value to engineers and designers as they pursue new engineering challenges."

Consortium members will share real-world experiences and best practices, working to ensure the AMDC roadmap reflects the needs of its customer base. By enhancing the breadth and scale of the AMDC, the consortium is expected to make a valuable contribution to an asset that serves global engineering and manufacturing communities. In addition to providing strategic guidance, organisations serving on the consortium's steering committee will have early access to the latest software and innovations from Altair.

www.altair.com

MPIF names new president and officers

The Metal Powder Industries Federation (MPIF) has elected Rodney Brennen, vice president/CFO, Metco Industries, Inc, as the 31st president of the MPIF, succeeding Dean Howard, PMT, North American Höganäs Co, a subsidiary of Höganäs AB.

Brennen's two-year term began at the conclusion of the MPIF's annual Powder Metallurgy Management Summit and 76th Annual MPIF Business Meeting, October 23–25, 2021, in Nashville, Tennessee, USA. Brennen has worked for Metco Industries for more than twenty-five years, starting as Finance and Personnel Manager and progressing to his current position as vice president/CFO. He most recently served as president of the Powder Metallurgy Parts Association. He is active in APMI International, a past chairman of the West Penn Chapter (1999-2001), and currently serves on the APMI Board of Directors. He received the Distinguished Service to Powder Metallurgy Award in 2021.

Two of the federation's six associations also instated new presidents following the Summit. Nicola Gismondi, PMT, vice president, Sales & Marketing, MPP, has been elected president of the Powder Metallurgy Parts Association (PMPA) and will serve a two-year term.

Christopher Adam, PMT, president & CEO, Valimet Inc, has been elected president of the Association for Metal Additive Manufacturing (AMAM) and will also serve a two-year term.

www.mpif.org

GKN Hydrogen chosen for US Department of Energy hydrogen storage project

GKN Hydrogen, a recently established business unit of GKN Powder Metallurgy, has announced $1.7 million of funding from the US Department of Energy's (DOE's) Hydrogen and Fuel Cell Technologies Office within the Energy Efficiency and Renewable Energy Office awarded to DOE's National Renewable Energy Laboratory (NREL). The funding will enable two HY2MEGA metal hydride hydrogen storage tanks to be added to the hydrogen assets at the Advanced Research on Integrated Energy Systems (ARIES) facility on NREL's Flatirons Campus near Boulder, Colorado, USA.

Two HY2MEGA hydrogen storage tanks will be housed at the US Department of Energy's National Renewable Energy Laboratory (Courtesy GKN Hydrogen)

GKN's HY2MEGA storage subsystem will be connected to the megawatt-scale electrolyser and fuel cell at the ARIES facility and validated by NREL scientists and engineers. The performance of the HY2MEGA installation will be evaluated over a range of operational conditions and simulated use cases using the ARIES facility's capabilities.

With energy storage capacity of over 260 kg hydrogen (~9 MWh of energy), GKN's HY2MEGA is said to be the largest metal hydride storage on the market and is well suited for energy supply applications where safety and compactness are crucial.

"This a tremendous opportunity to collaborate with the DOE National Laboratories to validate and run megawatt-scale use cases with our green, safe and compact metal hydride hydrogen storage solution," stated Peter Oberparleiter, Chief Executive Officer at GKN Powder Metallurgy. "Projects of this scale are needed to accelerate the adoption of zero-emission technologies to help us all meet our future clean energy goals."

www.gknhydrogen.com

Mercedes-Benz to manufacture axial-flux electric motors at Berlin site

Mercedes-Benz has announced it will build ultra-high-performance axial-flux electric motors at its Berlin site, as the company prepares to go fully electric by 2030. With the transformation of the Berlin site, Mercedes-Benz will bring the manufacture of a number of electric drive components in-house, expanding its portfolio of products which will include the assembly of YASA high-performance electric motors.

Mercedes-Benz announced the acquisition of YASA, a British-based manufacturer of ultra-high-performance electric motors, in July 2021, securing access to unique axial-flux technology, deepening its vertical integration and value creation in development and production.

The axial-flux electric motor is recognised as a step-change from legacy radial electric motor technology. The electric motors reputedly deliver the greatest efficiencies and highest power densities in class for the smallest possible size and weight. Containing a number of pressed stator cores, manufactured from soft magnetic composite iron powder, they are suitable for both hybrid and pure electric vehicle applications.

"The transformation of the automotive industry is more evident at our Berlin site than at any other Mercedes-Benz plant," stated Jörg Burzer, member of the board of management of Mercedes-Benz AG, Production and Supply Chain. "The transformation from a production site for purely conventional drive components to a competence centre for digitalisation and production in the field of e-mobility is a significant step for us and our employees. We are offering groundbreaking new opportunities for this traditional location and underlining its role in our global production network – not least as a decisive driver of our digitalisation offensive. With the production of high-performance electric motors, the Berlin plant will become a key pillar of the sustainable Mercedes-Benz electrification strategy."

www.mercedes-benz.com

European Raw Materials Alliance calls for action to ensure supply of rare earths

The European Raw Materials Alliance (ERMA) has released an action plan to secure access to rare earth elements for European industry. With the input of more than 180 industry stakeholders, 'Rare Earth Magnets and Motors: A European Call for Action' was developed to highlight the challenges related to the highly vulnerable global rare earth supply chain, and to provide specific actions that the EU, its member states, industry, and innovation communities should implement.

"The EU has committed to the goal of becoming climate neutral by 2050," stated Bernd Schäfer, CEO of EIT RawMaterials. "The raw-materials needs to facilitate this energy transition are massive, and Europe urgently needs to secure their supply. This Action Plan outlines the steps we must take to ensure that the rare earth elements upon which the EU Green Deal relies remain available for European industry and society."

The demand for high energy density rare earth permanent magnets is growing alongside the demand in applications like wind power, electric mobility, and communications technology, making their supply crucial to the European Union's stated ambition to transition to a green, digital economy. While the EU is a world leader in the manufacturing of electric motors, it is almost fully import dependent for rare earth permanent magnets, more than 90% of which are produced in China.

Thierry Breton, EU Commissioner for Internal Market, explained, "The commission's in-depth review of critical supply chains and key technologies has highlighted the EU's high level of foreign dependency on inputs required for our green and digital transition and our continent's resilience. The EU depends on others – mainly China – for the import of permanent magnets, as well as the rare earth elements they are made of. The European Raw Materials Alliance plays a key role in addressing these dependencies."

The European Raw Materials Alliance is currently working on a second Action Plan covering materials for energy storage and conversion, such as batteries, fuel cells, solar and hydrogen and other alternative energy storage and conversion systems.

'Rare Earth Magnets and Motors: A European Call for Action' is currently available to download in full from ERMA's websites.

www.erma.eu

Tesla shines as it becomes first EV maker to top European car sales

According to JATO Dynamics, September was another significant month for Europe's automotive industry, with new car registrations falling by 25%, the list of best selling cars topped by an electric vehicle for the first time and, also for the first time, a vehicle manufactured outside of Europe occupying that top spot.

In September, new car registrations fell to just 964,800 units, due to on-going component supply issues. Year-to-date, Europe's twenty-six markets continued to outperform in comparison to 2020, although the gap has narrowed. By the end of the first half of the year, total registrations were 27% higher than over the same period of 2020. Results through September show that this gap has narrowed to just 7%.

"Dealers continue to face issues with the availability of new cars due to the chip shortage. As a result, unwilling to wait more than a year for a new car, many consumers have turned to the used car market," stated Felipe Munoz, Global Analyst at JATO Dynamics. "This year, the industry has responded well to the pandemic, but it is now facing new supply chain challenges. The growing popularity of EVs is encouraging, but sales are not yet strong enough to offset the big declines seen across other segments."

OEMs with a large offering of pure electric and plug-in hybrid cars are said to have been less impacted by the current crisis. Diesel vehicles, however, have been impacted by both the chip shortage and the growing severity of the climate crisis. In September, low-emission vehicles posted a monthly growth of 44%, to 221,500 units, while the registrations of diesels decreased by 51%, to 167,000 units. Before the COVID-19 pandemic, there were 10.3 new diesel cars registered for every electric or plug-in hybrid vehicle. Today, that ratio has decreased to just 1.3.

"Shifts of this magnitude are rare, and a number of factors have contributed to the current state of play," added Munoz. "In addition to incentives, OEMs have enhanced their offering with more models and better deals, and many are shifting their limited supply of semiconductors to the production of EVs, instead of ICE vehicles."

The move to electric vehicles reached a milestone, with the Tesla Model 3 topping the European sales rankings in September, with 24,591 registered units (2.6% market share). The strong performance of the Model 3 is, in part, said to be explained by Tesla's intensive end-of-quarter sales push. Since its entry into the European market, the Model Y has also performed well, securing second position in the BEV ranking. Due to the success of these two models, Tesla leads the BEV market with a share of 24%, ahead of the Volkswagen Group (22%), Stellantis (13%), and Hyundai-Kia (11%). Tesla also registered more new cars than established brands including Fiat, Nissan or Seat.

www.jato.com

Overall			vs Sep 20	vs Sep 19
1	Tesla Model 3	24,591	+58%	+42%
2	Renault Clio	18,264	-23%	-27%
3	Dacia Sandero	17,988	-9%	+41%
4	Volkswagen Golf	17,507	-39%	-45%
5	Fiat/Abarth 500	16,349	-3%	0%
6	Opel/Vauxhall Corsa	15,502	-41%	-45%
7	Peugeot 2008	14,931	-16%	+5%
8	Hyundai Tucson	14,088	+40%	+7%
9	Peugeot 208	13,895	-31%	-12%
10	Renault Captur	13,715	-36%	-22%

Top 10 best selling automobiles in Europe, 26 September 2021 (Courtesy JATO)

2021 Howard I Sanderow Outstanding Technical Paper awarded

The Metal Powder Industries Federation (MPIF) has announced that the paper 'Mix Solution for High Green-Strength and Green Machining' by Amber Tims, Roland Warzel, Bo Hu (North American Höganäs) and Per Knutsson, Asa Ahlin, Angelica Hansen (Höganäs AB), was selected as the 2021 Howard I Sanderow Outstanding Technical Paper Award. The paper was chosen from manuscripts that were presented at the PowderMet2021 conference in Orlando, and critically evaluated for the prestigious award.

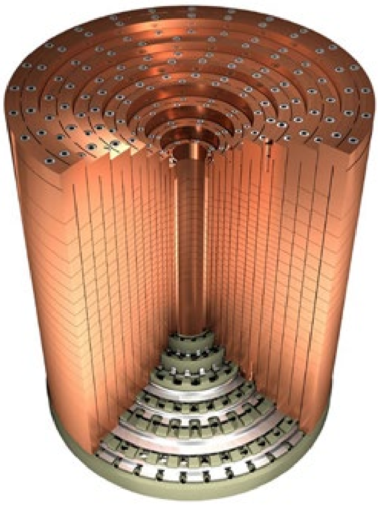
The Howard I Sanderow Outstanding Technical Paper Award (renamed in 2009) was established in 1993 to recognise authors of manuscripts for excellence in scientific and technical written communications from papers presented and submitted for publication from the annual technical conference organised by the MPIF and APMI International; to enhance the quality of technology transfer in the PM literature by increasing the professional level of papers submitted for the annual technical conference; and to enhance and promote the science and technology which is fundamental to Powder Metallurgy products, processes, and materials.

The winning paper is available for download on the MPIF website. The authors will be officially recognised during PowderMet2022 in Portland, Oregon, USA, June 12–15, 2022.

www.mpif.org

Safina's copper powder used in one of the world's strongest magnets

Over its 100-year history, Safina, Vestec, Czech Republic, has established a strong position in the processing and manufacturing of precious and non-ferrous metal products such as thermocouple wires, PGM wires, plates and tubes, spray targets, laboratory supplies, chemicals, metal powders and more.



A Safina customer has additively manufactured a 35 tesla magnet (Courtesy CNRS/Bertrand Maclet)

Now, with the company's adoption and development of cold spray Additive Manufacturing, it is enabling its customers to produce high-power magnets. There are reported to be only four companies in the world able to operate with steady high magnetic fields, and one of them is a customer of Safina based in France. This customer is reported to have achieved a record induction of a magnetic field of more than 35 tesla, making it one of the strongest magnets in the world.

The internal electro-magnet was made of fourteen polyhelices, allowing a very high magnetic field in a series of parts which have to support thermal and mechanical constraints (up to 440 MPa and 170°C). With cold spray Additive Manufacturing, it is possible to achieve higher properties than possible with forging (with forging, there is a limitation of yield strength and electrical conductivity).

The higher properties allow the installation to increase the available magnetic field for researchers. Such a high magnetic field is made possible by running up to 30,000A per cm^2 in the helices, with AM enabling a cooling system to be integrated. It is also possible to tune several properties, such as yield strength and electrical conductivity, with different heat treatments.

Safina helped the company develop a bespoke copper powder based on very specific custom requirements. It was the ability to supply a metal powder from the alloy, in such a high quality, which was said to enable the customer achieve a high magnetic field induction.

The magnet has since been used by research institutions and universities for various physical experiments, such as understanding the processes of magnetic fields in space.

www.safina.cz

Pfeiffer Vacuum offers cloud-based service management

Pfeiffer Vacuum GmbH, Asslar, Germany, has introduced a new Virtual Service Management (VSM) web-based app that makes it possible to manage vacuum equipment from different manufacturers. The app is integrated into Pfeiffer Vacuum's new Select & Request Portal, allowing interested parties, who register, direct access to the new service.

The app allows users to create their own locations, departments and machines, to which the various vacuum components are assigned, enabling management of the vacuum equipment more easily. The corresponding product data and operating instructions are stored and made available in the system.

A clear display of organisational units and vacuum components is expected to make planning and documentation (such as service activities, maintenance and repairs) over the entire service life much easier. The dashboard on the start page can be customised, and frequently required components can be marked as favourites and, if desired, displayed directly on the dashboard.

Customers can also store additional information, such as maintenance intervals, the average running time and the last service date. This makes it possible for the software to organise servicing and maintenance intervals worldwide, and to involve the relevant Pfeiffer Vacuum service center in good time.

Pfeiffer states that system downtimes can be minimised by synchronising maintenance activities, improving decision making and planning reliability. Creating a service request is also quick, since the data can be filled in automatically.

Each vacuum component is uniquely identified via an ID code and QR code. The tool offers the option of exporting QR codes in several formats (e.g., for a label printer). With the mobile app (Android and iOS), the QR code can be scanned by smartphones or tablets, providing an instant overview of the most important data (such as the article number, operating manual or service tickets).

www.pfeiffer-vacuum.com

Eltra marks forty years of elemental analysis

Eltra GmbH, Haan, Germany, is celebrating forty years of innovation in elemental analysis, since the development of its first carbon and sulfur analyser in 1981. Its focus from the beginning, the company states, has been on the design of analysers for the precise determination of carbon (C), hydrogen (H), nitrogen (N), oxygen (O) and sulfur (S) element concentrations in solids, and over the years the product portfolio has been further expanded and refined.

Eltra's ELEMENTRAC ONH-p 2 can be equipped for single element or full configuration analysis (Courtesy Eltra)

Today, the company views its ELEMENTRAC series as a milestone for C/S and O/N/H analysis in Powder Metallurgy and Additive Manufacturing, offering ease of use, fast analysis times and reliable results for metal powders and processed samples. In addition to providing high precision and detection sensitivity, Eltra states that the ELEMENTRAC systems are also robust enough to provide reliable measurement results in challenging conditions.

Eltra became part of the Verder Group in 2012 and was integrated into its Scientific Division, which is home to other companies from the laboratory and analytical sector, including Retsch and Microtrac. Eltra is represented in more than eighty countries by a broad sales and distribution network.

www.eltra.com

thyssenkrupp Automotive to rebrand alongside powertrain business growth

thyssenkrupp's Automotive Technology segment, headquartered in Essen, Germany, is pressing on with the transformation of its powertrain business. The current Camshafts business unit is being aligned to stronger growth in e-mobility; the unit is reported to be one of the world's leading suppliers of components for internal combustion, hybrid and electric powertrains. The product spectrum mainly includes assembled camshafts and valve train systems for conventional powertrains as well as rotor shafts for electric motors.

"We initiated the transformation of our powertrain components business at a very early stage," stated Dr Karsten Kroos, CEO of the Automotive Components division at thyssenkrupp. "Starting out from traditional valve train systems for internal combustion engines, around ten years ago we started developing and industrialising new products for electric powertrains. Today, we already manufacture rotor shafts for renowned OEMs and are achieving faster-than-market growth with this product. We are now continuing our transformation with new products beyond the internal combustion engine."

The company has already started developing complete rotors for electric motors. Further development projects are also underway for new products in the area of thermal management for battery electric vehicles. The repositioning of the business with a significantly expanded product portfolio will also be reflected in a new name: at the start of the new fiscal year on October 1, this business unit of thyssenkrupp's Automotive Technology segment was renamed Dynamic Components.

Frank Altag, CEO of the Camshafts business unit, added, "The transformation of our business is following a two-pronged approach. Based on orders received from customers, we will continue to achieve profitable growth with our products for internal combustion and hybrid engines in the coming years – even though the overall market is shrinking. We will use the profits from this business to finance the development and industrialisation of the new products, gradually making ourselves independent of the traditional internal combustion engine."

In recent years, thyssenkrupp's Automotive Technology segment has systematically realigned its product and service range to serve the technological trends towards e-mobility, autonomous driving and sustainable mobility. Today, the business segment is an international automotive component supplier specialised in chassis, powertrain and body technologies.

www.thyssenkrupp.com

Japan's Powder Metallurgy industry showcased in JPMA Awards

The Japan Powder Metallurgy Association (JPMA) has announced the winners of its annual awards, which, once again, brought the ongoing developments of Japan's PM industry centre stage. The winners showcased innovations in component development and processing technology, demonstrating the design and commercial benefits of using Powder Metallurgy as a manufacturing technique for mass production in numerous end-user categories.

JPMA awards: New design

Parking parts in a plug-in hybrid electric vehicle's transmission.
Sumitomo Electric Industries, Ltd, recieved an award for a parking lock mechanism component (Fig. 1) used in a transmission developed for PHEVs (plug-in hybrid vehicles). The part consists of a tapered section, used to guide a locking rod mechanism activated when the transmission is shifted to the park position.

The conventionally made part required extensive machining, which accounted for 50% of the total production costs. Sumitomo worked closely with the customer to re-design the part. The near-net shape incorporatres a slope formed with a punch, bolt holes formed with the core and the void formed with the die. As a result, Sumitomo succeeded in reducing the machining costs by about 40%.

Development of Soft Magnetic Powder Cores for Axial Gap motors
Sumitomo Electric Industries, Ltd, also recieved an award for the devel-

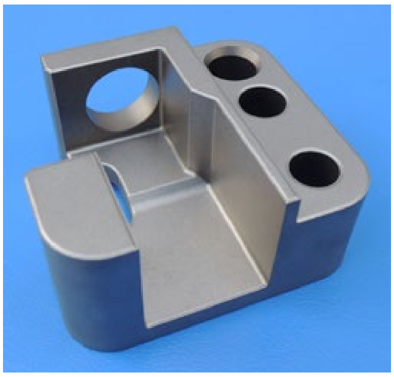


Fig. 1 Parking lock mechanism (Courtesy JPMA)

opment of stator cores for axial gap motors (Fig. 2). The cores are used in pumps, and generate the rotational force of the rotor by becoming an electromagnet when an electric current flows through the wound coil.

With a move to smaller, lighter and more efficient motors, the adoption of axial gap motors is expected to become widespread. They offer a number of advantages when compared to conventional motors, being thinner and with high torque. Soft magnetic powder cores are particularly suitable for the three-dimensional magnetic circuit required for axial gap motors, due to their magnetic isotropic properties and high design flexibility.

Sumitomo has achieved mass production of the soft magnetic powder cores by optimising the manufacturing process in a number of ways. This included the use of insulation-coated soft magnetic powder, a heat treatment to remove distortion, machining of the bolt hole for fixing and a surface coating.

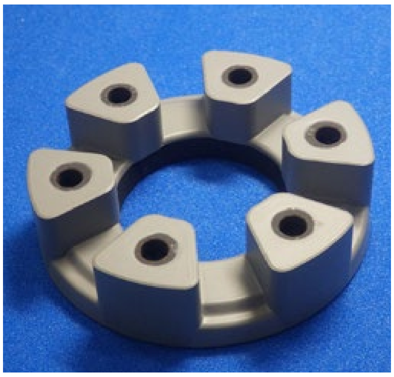


Fig. 2 Stator cores for axial gap motors (Courtesy JPMA)

Fig. 3 Oil pump parts for HEV clutch (Courtesy JPMA)

Fig. 4 Sprocket drive used in single-motor hybrid vehicles (Courtesy JPMA)

High-efficiency electric oil pump parts for HEVs clutch engagement (high pressure applications)

Sumitomo Electric Industries, Ltd, recieved a further award for these internal gear rotors and body (rotor case), used for an electric oil pump in HEV clutch engagement (high-pressure application) (Fig. 3). The parts require an extremely high dimensional accuracy to ensure high efficiency and quiet operation.

In the original part, the inner diameter of the inner rotor was machined to improve the coaxial accuracy of the inner and outer diameters. However, in addition to machining, there was also a shaft press-fitting process by the customer, which increased the unit cost. Therefore, in order to omit the inner diameter machining, and maintain the coaxial accuracy of the inner and outer diameters of the inner rotor, Sumitomo modified the compacting tools and applied uniform powder-feeding technology. As a result, they achieved inner tooth tip runout accuracy equal to, or higher, than machining. By applying uniform powder-feeding technology to the outer rotor to improve roundness, the company was also able to reduce the tolerance width of the tip clearance (a gap formed when the tooth tips of the outer/inner rotor face each other) by about 50% compared to the conventional part.

Sumitomo also addressed the casing of the oil pump. The body of a conventional electric oil pump is often made of die-cast aluminium, which can result in oil leakage at high oil temperature due to the difference in linear expansion coefficient with the iron-based sintered rotor. To prevent this, the body was changed to an iron-based sintered material. This also improved accuracy and tolerance of the machined body, where the width of axial clearance (defined by the overall length difference between the body and the rotor) has been significantly reduced to less than 50% of the conventional part, reported to be the smallest level in the industry.

Development of sprocket drive for single-motor hybrids

Fine Sinter Co Ltd received an award for a sprocket drive (Fig. 4) used in single-motor hybrid vehicles, where the inverter is closely integrated and the conventional torque converter section is replaced by a high-output flat motor and clutch. In this, the number of parts has been reduced by using an integrated two-stage gear design. The newly developed clutch mechanism also requires high response and high precision in hydraulic pressure.

The involute spur gears were required to have the precision of the former JIS Grade 4. Both sprockets and spur gears require high-frequency quenching and tempering to improve wear, and the spur gear tips were required to have a chamfered shape in order to improve productivity in the assembly process.

Fine Sinter optimised the shape of the filling adjustment groove, which controls the amount of powder filled, and improved the rigidity of the die and die adapter to achieve two-stage gearing with an integrated die step. The coil shape and quenching conditions were optimised and, by establishing high-frequency quenching conditions with one coil and one shot, Fine Sinter was able to control the decline in spur gear precision.

As a result, near-net-shape sintering became possible, and cost reduction of around 50% was

Fig. 5 Downhole plug component (Courtesy JPMA)

Fig. 6 Stator cores for axial gap motors (Courtesy JPMA)

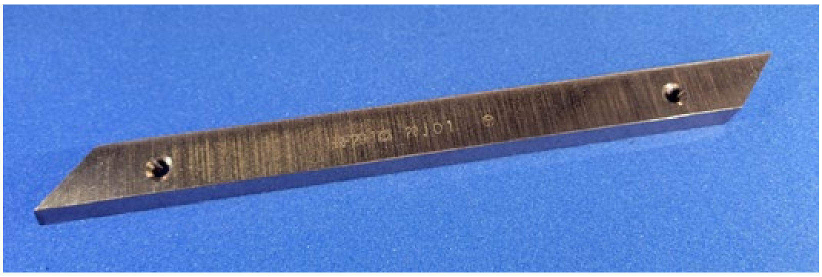


Fig. 7 A copper-based sintered alloy used for manufacture of railway components (Courtesy JPMA)

achieved, when compared to a machined forging.

Development of plug parts for shale gas drilling tool

Porite Corporation receievd an award for this downhole plug component (Fig. 5) used in the shale gas drilling process. To collect shale gas, engineers need to first excavate the well and then create extensive artificial fractures around well bores by hydraulic fracturing (fracking).

In the hydraulic fracking process, plugs can be used to divide the well into smaller sections, alowing the sections to be fractured sequentually. After fracturing, the plugs are drilled through and the well is depressurised. This creates a pressure gradient so that gas flows out of the shale into the well.

The plug therefore needs to be strong enough to withstand ultra-high water pressure, yet easily destroyed after use. Porite used a Fe-Cu-Mn-Mo-C material which can obtain the necessary strength with high-temperature sintering. It underwent an optimised heat-treatment process that limited the depth of cure, but ensured surface hardness, resulting in a high strength and good destructivity.

Sintered bearing for suction motor of robot vacuum cleaner

Porite Corporation also received an award for this sintered oil-impregnated bearing (Fig. 6) used in the suction motor of a robotic vacuum cleaner. In recent years, there has been an increase in demand for devices that reduce the burden of housework, and the convenience of automatic robot vacuum cleaners has been widely accepted by the market and is gaining popularity.

Until now, the majority of bearings used in the suction motors for robot vacuum cleaners have been expensive ball bearings. In order to enter this market, Porite worked to develop a sintered oil-impregnated bearing that meets the required characteristics (quietness, long life, low friction, and high-speed rotation).

The shape of the bearing was designed to have a centre relief bore, and the load was evenly distributed by lengthening the sliding surface with high load and shortening the sliding surface with low load. Porite used a copper-coated iron powder, optimised the sintering conditions and product density, and added zinc. A polyalphaolefin-based impregnation oil with low evaporation rate to extend the service life, was also developed.

As a result, the bearings have been adopted for a number of vacuum cleaners. The cost ratio to ball bearings is less than half, contributing to the overall cost reduction of the suction motors.

JPMA awards: New materials

Development of copper-base sintered alloy slider with low trolley wire wear

Fine Sinter Co Ltd received an award for this copper-based sintered alloy, used for manufacture of a railway component (Fig. 7). The slider part is attached to the top of a pantograph installed on the top of a railway vehicle, and connects with the electified trolley wire. The slider is required to have high conductivity, high mechanical strength, high wear resistance, and high self-lubrication that does not attack the trolley wire. The copper-based sintered alloy material has the characteristic of being highly conductive.

The base material of both the copper-based sintered alloy's slider and the trolley wire are copper. This can result in a large amount of abrasion and loss of the trolley wire, which is a problem for copper-based sliders.

In the conventional material, FeMo was added as a hard particle and (Cu,Fe)S was added as a lubricating component. In the development of the material, Fine Sinter partially replaced FeMo with FeTiNx which has a lower hardness than FeMo to reduce the aggressiveness to the trolley wire. To improve the lubricating performance, the solid lubricant was changed from (Cu, Fe) S to MoS2 and the amount of sulfur component was increased accordingly.

The above changes caused a decrease in the mechanical strength however, so to raise the mechanical strength of base materials, pure Fe powder was added so that the mechanical strength of the entire slider could be maintained. As a result, the wear resistance was higher than that of the conventional material, and the trolley wire abbration was reduced to 1/5. Although the material cost of the slider increased slightly, the reduced maintenance costs involved with replacing the sliders and the trolley wire far outweighted this.

Fig. 8 Gear used in the electric parking brake unit of medium-heavy duty vehicles (Courtesy JPMA)

JPMA awards: Effort Prize

Adoption of sintered parts in EPB units for medium-heavy duty vehicles

Fine Sinter Co Ltd also received an Effort Award for this gear used in the electric parking brake unit (EPB) of medium-heavy duty vehicles (Fig. 8). EPB units for these vehicles are equipped with speed control and stop-and-hold functions for low-speed automatic operation. In the future, it is expected to become a standard feature in all automobiles, improving the performance of these safety devices.

In this example, each EPB unit consists of six types of gears, with twelve units required in total. Sintered parts have the great advantage of low cost and high strength. Also, this unit has many rotating parts that require lubrication, suited to the oil-bearing properties inherent in PM.

In the produciton of the components, Fine Sinter made use of warm compaction. A coining stage was used to create a chamfered edge, and a high-purity anti-rust oil was selected. The company devised ways to place the products during quenching and tempering, and automated the visual inspection process. As a result, the six parts have been adopted, and Fine Sinter expects a significant increase in volume is possible as the global use of this part expands.

www.jpma.gr.jp

Hastings' hydrometallurgical rare earths plant gains environmental approval

Rare earths company Hastings Technology Metals Ltd, headquartered in Perth, Australia, has announced that the Australian Federal Government's Department of Agriculture, Water and the Environment (DAWE) has finalised environmental approval for the construction of the Onslow Rare Earths Plant, a hydrometallurgical plant, which will be located at the Ashburton North Strategic Industrial Area (ANSIA), near the coastal town of Onslow.

The plant will perform the hydrometallurgical processing of rare earth oxide concentrate from Hasting's Yangibana Rare Earths Project, located in the Gascoyne region of Western Australia, into mixed rare earth carbonate (MREC) containing high levels of neodymium and praseodymium concentrate (NdPr). NdPr is vital in the manufacture of the permanent magnets that are required in advanced technology products, ranging from electric vehicles to wind turbines, robotics, medical and digital devices. Construction is scheduled to begin in 2022 after the completion of early works at the Yangibana mine site, in line with Hastings' target to produce its first MREC in early 2024.

Charles Lew, Hastings Technology Metals' Executive Chairman, stated, "This is a significant milestone for our Yangibana Rare Earths Project and further endorses Hastings' decision last year to decouple the processing plant from the Yangibana mine site. The commonwealth environmental approval will allow Hastings to construct the Onslow Rare Earths Plant for a full production rate of 15,000 tonnes of MREC per annum, unlocking the high-quality and NdPr-rich rare earths carbonate that we will produce at Yangibana."

"Importantly, the commonwealth approval is another positive step in Hastings' journey to become Australia's next rare earth producer," he continued. "Debt financing talks are advancing well and scheduled for conclusion before the end of this year and early stage civil works at the Yangibana mine site are in progress."

www.hastingstechmetals.com

Höganäs expands production capacity for Thermal Barrier powders at Laufenburg site

Sweden's Höganäs AB reports that it plans to invest several million euros in a far-reaching programme to modernise and expand its production capacities for Thermal Barrier Coatings (TBC) powders at its production site in Laufenburg, Germany. The expansion programme aims to ensure that the growing demand for TBCs from global customers can be met. TBC powders are used in the energy and aviation sectors, where thermal barrier coatings can increase the efficiency of turbines.

"By the summer of 2023, we will have significantly increased the production capacities for TBC powders through utilising several state-of-the-art production units as well as making improvements along the entire process chain," stated Peter Thienel, Head of Operations for Höganäs in Germany.

Gas turbine technology in the energy sector is regarded as a bridging technology that should pave the way from fossil energy production to CO_2-neutral energy production in the form of renewable energies. Shashi S Shukla, president EMEA at Höganäs, added, "Our powders are thus part of this solution and a vital part in driving the transition to clean energy in societies."

Höganäs states that it has been sourcing fossil-free electricity exclusively at its German production sites in Laufenburg and Goslar since 2021. These plants are now one step closer to becoming net-zero climate neutral, contributing to the group's objective to reach net-zero value chain greenhouse gas emissions no later than 2045.

www.hoganas.com

University of Birmingham project successfully recycles rare earth magnets from loudspeakers

The University of Birmingham, UK, has announced the successful completion of the Rare-Earth Extraction from Audio Products (REAP) project which demonstrates that the rare earth magnets in loudspeakers, currently lost to landfill, can be successfully recycled.

The REAP project was led by HyProMag, a company established by Professor Allan Walton from the School of Metallurgy and Materials, University of Birmingham, with founding directors Professor Emeritus Rex Harris, former head of the university's Magnetic Materials Group and two Honorary Fellows, Dr John Speight and David Kennedy, who are leading experts in the field. The project also involved European Metal Recycling Ltd, which has a global footprint in metal recycling and sustainability.

European Metal Recycling performed a comprehensive assessment of scrap, encompassing extraction, characterisation of components, degree of pre-processing and potential for automation. The analysis showed that the flat screen television sector holds significant promise for recycling, with approximately 85% of the products containing NdFeB. REAP confirmed the quantity of scrap available from this market, the commercial viability, the suitability of the material for HPMS (Hydrogen Processing of Magnetic Scrap), the properties of the magnets in this sector and provides a strong platform to initiate access to the wider loudspeaker market in the future.

The University of Birmingham has completed the Rare-Earth Extraction from Audio Products (REAP) project (Courtesy University of Birmingham/Maxx-Studio)

Despite the differences between the two sectors, the average magnet grade is said to have remained fairly consistent. Following extraction and processing, the resulting powders were analysed to confirm the feasibility of using waste from flat screen televisions as feedstock for recycled magnet making.

HyProMag's strategy is to establish a recycling facility for NdFeB magnets at Tyseley Energy Park in Birmingham to provide a sustainable solution for the supply of NdFeB magnets and alloy powders for a wide range of markets including automotive and electronics.

William Dawes, Chief Executive of Mkango Resources, stated, "This is a significant milestone for HyProMag, University of Birmingham and European Metal Recycling, demonstrating another potential source of both feedstock and route to market for recycled rare earth magnets. Recycling is a key component of Mkango's 'mine, refine, recycle' strategy via its strategic interest in HyProMag, and will become an increasingly important part of the rare earth supply chain in the UK, Europe and elsewhere. HyProMag is well positioned to unlock that supply chain with access to the technology, expertise and network of partnerships to make it happen, and Mkango looks forward to supporting the company as it scales up to commercial production."

www.birmingham.ac.uk

www.hypromag.com

Scientists engineer bacteria to extract rare earths

A study recently published in *Nature Communications*, 'Generation of a Gluconobacter oxydans knockout collection for improved extraction of rare earth elements,' has described the use of genetically engineered micro-organisms to process rare earth elements (REE) in a way which is sustainable, efficient and cost effective. The paper was written by Alexa M Schmitz, Brooke Pian, Sean Medin, Matthew C Reid, Mingming Wu, Esteban Gazel and Buz Barstow, researchers at Cornell University, Ithaca, New York, USA.

The demand for REEs is growing, as applications such as wind power generation, electric mobility, and communications technology continue to increase. In the US alone, annual REE needs amount to approximately 10,000 kg, which is extracted from 71.5 million tonnes of raw ore.

Currently, separating the rare earth elements is usually done by dissolving rock with hot sulphuric acid, followed by the use of solvents. The authors of this paper sought to create a micro-organism that does the job succinctly by leveraging the gram-negative bacterium *G. oxydans*, which produces an acid called biolixiviant which dissolves rock. On its own, the bacterium uses this acid to pull phosphates from rare earth elements; the research team have begun to manipulate the bacterium's genes so it can extract elements with even more efficiency.

The researchers used 'Knockout Sudoku', a technology which allowed them to disable *G. oxydans*' 2,733 genes one by one. This enabled the curation of mutants with specific genes removed, allowing the identification of the specific genes which support the bacterium's ability to separate elements from rock.

Schmitz identified two such relevant genes: one which accelerates acidification, and one which stops it. This allowed the team to create a mutant which doesn't regulate its production of biolixiviant, the dissolving acid at the core of the bacterium's use potential.

In the study, Gazel's lab at the Department of Earth and Atmospheric Sciences at Cornell helped develop mass spectrometry techniques to measure concentrations of REEs from solutions where mutants were exposed to the ore. According to Gazel, some mutants were seen to gather very high REE concentrations.

Now, the team is working to regulate the gene that accelerates acid production, in an effort to create a system wherein mutated G. oxydans run on cellulose-derived sugars for energy.

"I am incredibly optimistic," stated Gazel, co-author of the article. "We have a process here that is going to be more efficient than anything that was done before."

www.cornell.edu

IOM3 invites nominations for 2022 Ivor Jenkins PM Award

The Institute of Materials, Minerals and Mining (IOM3), London, UK, is seeking nominations for its 2022 awards. Of particular interest to the Powder Metallurgy sector is the institute's Ivor Jenkins Award, presented annually to individuals in recognition of a significant contribution that has enhanced the scientific, industrial or technological understanding of materials processing or component production using Powder Metallurgy and particulate materials.

The Ivor Jenkins Medal is judged by the Particulate Engineering Committee of the Materials Science & Technology Division. The institute presents a range of awards, medals and prizes for published work and contributions to industry. Recent winners of the Ivor Jenkins award include Roger Lawcock (2021), Prof Herbert Danninger (2020), Dr Leo Prakash (2019), and Dr David Whittaker (2018).

The closing date for nominations for the 2022 awards is January 31, 2022. Further information regarding nomination requirements is available via the institute website.

www.iom3.org

EPMA award recipients named at Euro PM2021

The European Powder Metallurgy Association (EPMA) announced the recipients of the 2021 Distinguished Service Awards and annual Fellowship Awards during the opening session of Euro PM2021, held this year as a digital event from October 18–22 due to the ongoing coronavirus pandemic.

EPMA Distinguished Service Award

Since 1998, the EPMA's Distinguished Service Awards have been presented in recognition of individuals who make an outstanding contribution to the European PM industry. This year, the Distinguished Service Award was presented to Martin Bloemacher and Harald Neubert.

Martin Bloemacher: After studying physics at the University of Duisburg, Germany, Martin Bloemacher joined BASF, Ludwigshafen, Germany, in 1987 and began work within the Carbonyl Iron Powder (CIP) Plant. Having built up an application lab for CIP, he started to work on Metal Injection Moulding (MIM) as a part of his research. He went on to co-invent the Catamold system for MIM, and was a founding member of the Catamold group at BASF in 1990.

Bloemacher was instrumental in building Catamold production and application services in Ludwigshafen and the company's site in Asia. He was a recipient of BASF's innovation award in 1996 and has been a member of the EPMA Council since 2000. He retired from BASF in March 2021.

Harald Neubert: Harald Neubert received his diploma and PhD from the University of Essen, Germany, and went on to join Krebsöge Group in 1988, which later became part of the GKN group. He began working in Powder Forging at the Pulverschmiede Hueckeswagen facility and became plant manager in 1989. During his time at the company he progressed to several senior management positions, becoming President, Asian Pacific and South American Operations in 2005.

In 2007 he joined Miba Sinter Group, Laakirchen, Austria, and was responsible for the group's technology and R&D. He became its CEO in 2008, retiring in January 2021. Neubert holds a number of patents and is a long serving member of the EPMA Board and Council.

EPMA Fellowship Award

The EPMA Fellowship Award recognises individuals in the scientific and/or academic community for significant contributions to the development of the PM industry.

Prof Didier Bouvard: The author of around 100 papers in international journals and 160 papers in conference proceedings, Prof Didier Bouvard has advised twenty-eight PhD students. He has chaired several international conferences and meetings, and has also taken on a number of responsibilities in Grenoble, including the director of a joint CNRS-university research laboratory for eight years and the vice president for research at the Institut Polytechnique de Grenoble for four years.

Within the EPMA, Prof Bouvard is a long-standing member of EPMI and previous academic groups. In particular, he has been involved in the development of the numerical simulation of PM processes such as die pressing, sintering and HIPing. He has twice organised the EPMA Summer School and coordinated the PM Life educational project.

Prof Lars Nyborg: Prof Lars Nyborg has been chair professor at Chalmers University of Technology since 2001, and has devoted his whole career to PM, including active involvement in PM conferences, the EPMA's PM Summer Schools and, in particular, research and co-operation with commercial companies.

In total, he has supervised twenty-two PhD students, with other fields of activity including SiC/metal contacts with extension into intermetallic thin film synthesis and tool material/work material interaction with focus surface integrity of work in forming and machining. Overall, this has resulted in Nyborg being listed as a contributor or author on more than 300 international journal papers and conference contributions.

Prof Nyborg has been involved in the development of the Powder Metallurgy and Additive Manufacturing group at Chalmers, with a particular focus on PM surface science and materials/process development, now including more than twenty-five research staff. Activities include basic science, new processes and new materials that are brought to the market in close cooperation with industry.

www.epma.com

Left to right: Martin Bloemacher, Harald Neubert, Prof Didier Bouvard and Prof Lars Nyborg (Courtesy EPMA)

Tesla teardown: Identifying potential uses for PM in electric vehicle transmissions

Whilst the future looks electric, with ever more electrically-powered vehicles entering the market, there are still lucrative opportunities for the Powder Metallurgy industry. Höganäs AB's Dr Anders Flodin, a long-time advocate of PM transmission gears for conventionally powered cars, and Babak Kianian, PhD candidate at Lund University, believe that one such opportunity is for PM gears in EV transmissions. To understand more, a Tesla Model S was the subject of a teardown and its transmission components analysed to understand if PM alternatives are suitable for such an application, and what advantages they might bring.

The automotive industry is evolving towards electromobility faster than we might think. There are very few vehicles under development propelled by fossil fuel-driven internal combustion engines (ICEs) alone; most are hybrid electric vehicles (HEVs), battery electric vehicles (BEVs), or use hydrogen as an alternative fuel source, either for combustion or for powering fuel cells. The future is electric, and there is no doubt that, as the years progress, we will see more and more battery-powered vehicles entering the market. Some countries have announced a ban on future sales of ICE cars; Norway is one of the countries leading this trend and, in two years, the city of Bergen will ban ICE cars. By 2025, that ban will extend to the whole country [1]. South Korea and some US states plan to follow between 2025 and 2040.

For the Powder Metallurgy industry, this has been an ongoing source of concern for some years, since automotive engine and transmission parts represent an important application for PM technology – but it could also offer new opportunities. Is the glass half empty, or half full?

In this article, the typical BEV drivetrain will be investigated in more detail, using a Tesla Model S transmission as the example (Fig. 1), to understand the opportunities present and the challenges that the PM industry must tackle if it is to protect its market share in the automotive supply chain when ICEs, manual, automatic, and transfer case transmissions cease to exist.

Fig. 1 A Tesla Model S was used as the example BEV for this case study

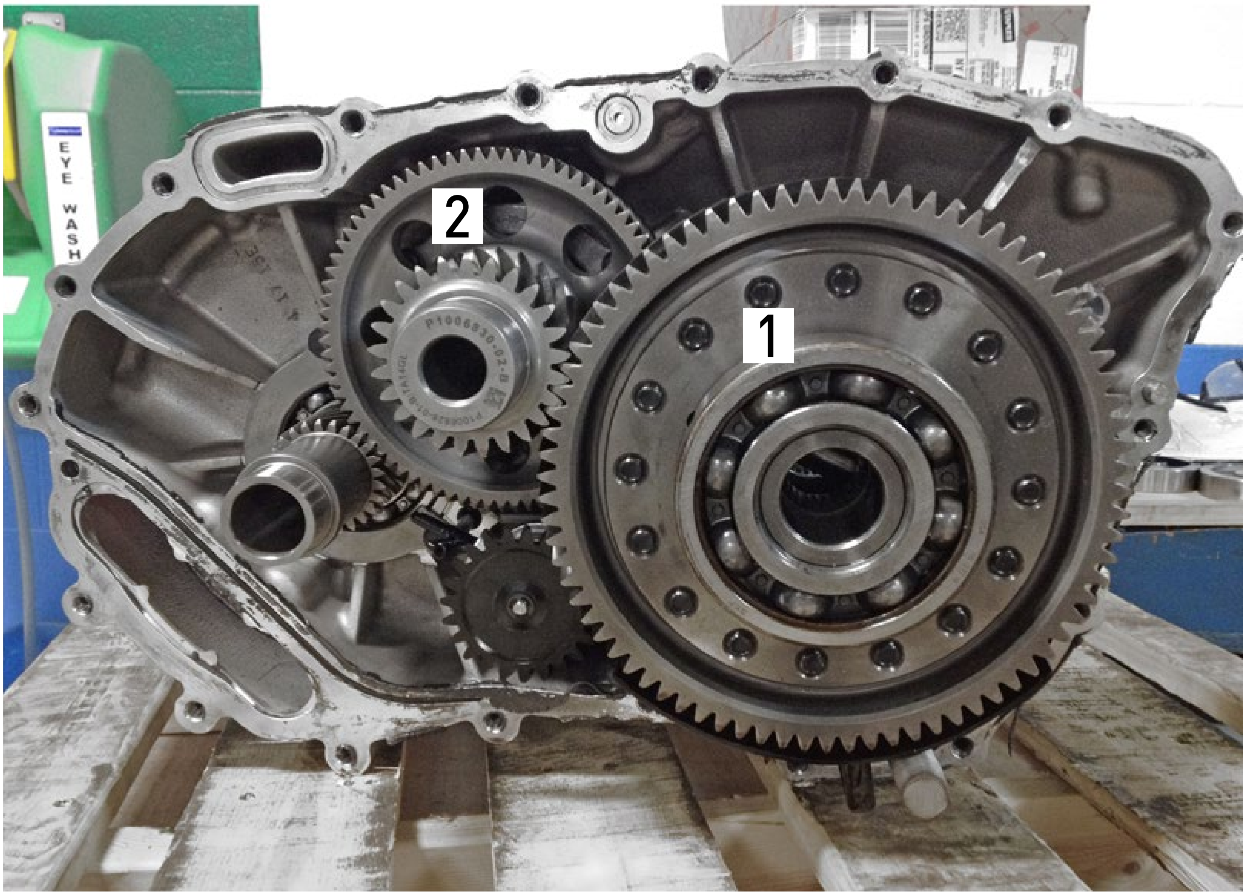


Fig. 2 Tesla Model S transmission. Gear 1 is the output ring gear and gear 2 is the intermediate gear

Battery electric vehicle drivetrains

The drivetrain of battery electric vehicles can be configured in different ways, but the bulk are likely to be single e-motor and single-speed reduction transmissions. For heavier vehicles, there will be 2-speed automatic transmissions, and, for niche cars like the Porsche Taycan, we may see even more convoluted transmission designs. For the PM industry, the main applications are likely represented in the single-speed, single-e-motor segment. At present, the pioneer in this segment is Tesla, which offers single-speed, single-motor models such as the Model 3 and Model S. For that reason, we selected the Tesla Model S to serve as our example.

Another change which can be seen in the configuration of modern drivetrains is in BEV four-wheel-drive (4WD) vehicles, which hope to offer an electrified replacement for the SUVs and trucks that dominate the North American market. The transfer cases on these vehicles typically feature 7 kg of PM per vehicle, depending on supplier and design. So far, the BEV trucks that have been introduced into the market – including the Ford F150 Lightning and the Tesla Cybertruck – feature no transfer case or prop shaft, replacing them with batteries, inverters, cables, and e-machines.

The one machine element that will likely remain in place is the differential, which continues to contain powder forged PM gears. The differential case could potentially be made in PM as well.

Analysis of single-speed reduction drive from a PM perspective

To conduct this analysis, a Tesla Model S motor and transmission were sourced through engineering company KBE+ in Syracuse, New York, USA, which was also responsible for teardown and documentation.

Once the gears had been removed from the housing, a reverse engineering study was started to measure and calculate a design close to the original design from Tesla. The key points for PM in this transmission are manufacturing cost and durability of the gears. The durability was calculated by taking into account the torque-speed curve of the motor, the gear geometry, and by assuming a certain service life for the transmission. The cost was then modelled for both PM and conventionally-machined gears.

Two major differences between a 6-speed gearbox, like the M32 analysed in a previous teardown [2], and a fixed ratio gearbox like the one seen in this article, must be noted. Firstly, in this gearbox, all of the gears are engaged for 100% of cycles. The second difference that must

Fig. 3 A Nissan Leaf output ring gear

be dealt with is the regeneration of energy to the battery that loads the gear teeth on both the drive and coast flank. This regeneration will reduce the bending fatigue life of gears in a fixed ratio gearbox, as compared to gears only loaded on the drive side. The ISO 6336 [3] standard offers some guidance on how to account for reversed loading, but is open to interpretation and requires data that is not easily available. For this reason, all the rating factors have been kept identical when analysing PM and wrought steel, even though PM has less notch sensitivity. The reverse loading factor Ym has been omitted due to a lack of data for a gear that sees a substantial amount of reversed loading, but which can't be regarded as a fully reversed load case.

Gear geometry

Gear data was obtained by measuring the gears and trying different modules and profile shift coefficients to achieve a design that was as close as possible to the original. The gears were also modelled in CAD to obtain accurate surface areas for press tonnage calculations. In the transmission, there are two gears of primary interest, shown in Fig. 2. The input gear from the motor is machined directly onto the shaft, and is not an ideal candidate for PM since it would require a two-piece design, with shaft and gear manufactured separately. The cost advantage with PM is not obvious in this case – for a PM part maker, it could represent added value if price competitive, but it is of less value for a material supplier. For this reason, the two gears machined directly onto the shaft were left out of this investigation. This left the output ring gear and intermediate input gear as the more interesting candidates for PM.

These two gears are big and heavy parts for PM, and represent a high-end BEV transmission. There are a couple of drivers for the large gears:

- High torque from the e-motor over a wide RPM span
- The gears are always engaged
- Power is transmitted on both drive and coast flank
- The input RPM can go up to 20,000 at 250 km/h and needs to be reduced to the wheels
- The final drive encompasses the differential

Using the Nissan Leaf as an example (Fig. 3), we can see that a smaller car has a gear ratio of 8.193 with an intermediate gear diameter of 106 mm and a final drive ring gear of 205 mm, coupled to an e-motor putting out 110 kW at max 320 Nm. These transmissions might not be the most optimised; the same gear ratio could be obtained by increasing the intermediate gear size and reducing the final drive gear size. But even if it were possible to reduce the gear size of the final drive gear, the differential housing has to be put somewhere, which requires that the output gear

Fig. 4 CAD models for the gears for press area calculations

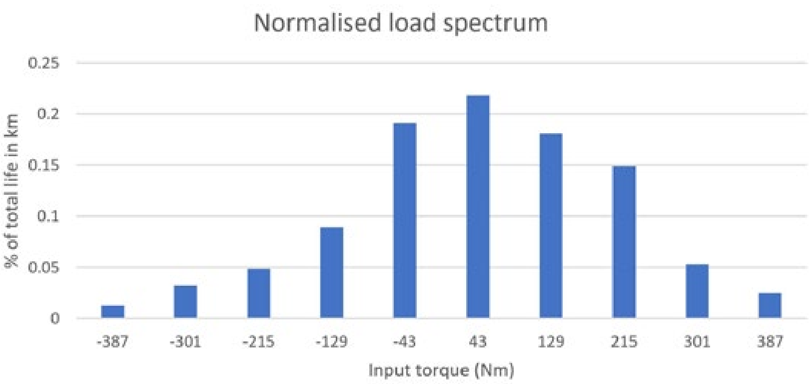


Fig. 5 Torque bins for different km during service life

be manufactured within certain dimensions, or else requires a very different configuration of the transmission, raising complexity and cost.

The point is that even smaller BEVs will have relatively big gears, despite the lower power output. Gear 1 in Fig. 2 weighs 3.7 kg and gear 2 weighs 2.5 kg, with an assumed density of 7.2 g/cc. The surface area requires a 1,600 ton press for gear 1 and a 1,200 ton press for gear 2, assuming 800 MPa compaction pressure with three upper and three lower punches, plus a helical gear adapter. Fig. 4a and b shows the CAD models obtained for the gears. As can be seen, the designs are not PM optimised, but can be adapted to work in a press tool with maintained functionality.

Service life

One issue that needs to be addressed is the service life of the gears. What density, material, and processes are needed for the gears to survive in the vehicle? The following assumptions must be made: service life is 300,000 km and a load cycle, including regeneration, must be designed.

The disassembled drivetrain was for the first-generation Model S. Torque was 430 Nm, and a known drive cycle was adopted for this example (Fig. 5).

The regeneration of power is reported as 60 kW or above [4], and how much torque that is put through the gears at different speeds is set by software and unknown. In Fig. 5, it is assumed that more power is used to propel the car forward than is recuperated in regeneration; it can be argued that the max regeneration torque is too high in Fig. 5 to be comfortable for the people in the car, but, for the sake of argument, let's assume that the above distribution is acceptable, as this will give an indication as to which processes are needed for a PM gear to perform in this application.

With a tyre circumference of 2,000 mm and a life of 300,000 km, the total number of cycles for gear 1 is the same as for the wheel (i.e., 150,000,000 rotations). The number of cycles for gear 2 is 3.12 times higher. This is in the domain of ultra-high cycle fatigue, and there are not many PM materials that have been tested in gear rigs at these high cycles in sufficient sample sizes (over 40) to generate reliable S-N curves.

In 1924, Palmgren proposed a linear damage hypothesis which states that the total fatigue life of a component or material is the sum of the proportions of life consumed at each stress level, or

$$\sum_{i=1}^{k} \frac{n_i}{N_i} = C$$

where n_i is the number of cycles at a particular stress amplitude level and N_i is the number of cycles of life at the stress amplitude level. When C=1 failure occurs; the component still works as long as C is less than 1.

From the drive cycle in Fig. 5, C can be calculated and, if the sum is less than 1, the gears should be able to work. By utilising the S-N curve for a case-carburised Astaloy Mo gear, the N_i can be calculated for each stress level, and the n_i is given in Fig. 5 by multiplying the percentage for each torque bin by 150,000,000, in the case of gear 1.

This calculation is performed for the tooth root bending case and the contact fatigue case. The stresses can be obtained by gear software or by following ISO 6336-3.

The result for gear 1 was that contact fatigue was not an issue with C=0.43, which gives a healthy safety factor against pitting. The damage due to tooth root bending from the equation was 1.06, indicating a failure before reaching 300,000 km. A solution to this problem can be a root modification to reduce bending stress, according to Fig. 6. The reduction is 13% with the elliptic root in Fig. 6, but that has a dramatic impact on the accumulated damage (C), which drops to 0.13.

The reason for this has more to do with the fact that the 13% reduction in bending stress puts the bending stress below the fatigue limit, where, according to the original Palmgren-Miner model, there should be infinite life. In this exercise, the fatigue limit is at 2,000,000 cycles for tooth root bending and 50,000,000 cycles for pitting, and after that the slopes of the S-N curves will be reduced from -1/7 and -1/14 respectively, to -1/30, known as a modified Palmgren-Miner S-N curve. However, very little is known about high-cycled PM gears and their slope in the S-N diagram. -1/30 is an assumption; Sonsino [5] has made some suggestions for how to set a slope that have been considered here.

For gear 2, the accumulated damage in bending is 0.1 and, for contact, it is 0.48. The lower stresses offered by this ratio play a significant role in reducing the accumulated damage. Despite seeing more than three times the cycles, the equivalent reduction in torque is much more dominant, as stress does more damage than cycles.

Under the assumptions made with this analysis, there is a good chance that a PM gear could meet the demands in a Tesla Model S for at least 300,000 km. For a more in-depth analysis, a more detailed drive cycle and a deeper understanding of the slope of the S-N curve in the ultra-high cycle regime are needed.

Manufacturing cost model

The manufacturing cost comparison presented here is for the output ring gear, denoted 1 in Fig. 2. Before going into cost analysis for both the PM and wrought steel ring gears and their comparison, let's take a look at the utilised cost model approach in this article, called Performance Part Costing (PPC).

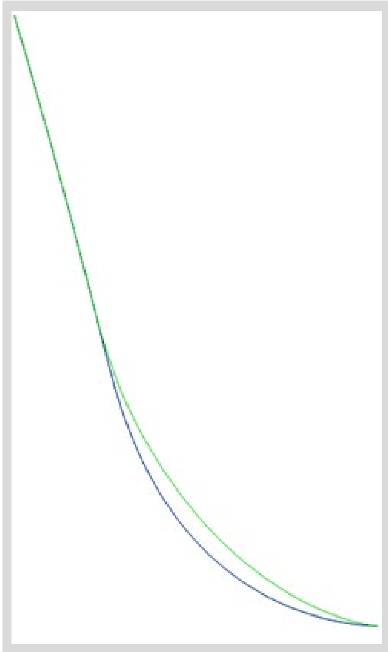


Fig. 6 The blue curve is the radius from cutting the gear with a hob. The green curve is the elliptic shape reducing bending stress in a compacted gear

The PPC model is designed for discrete manufacturing processes according to production batch size, and follows each production step. PPC gives a part's cost per unit [6]. It combines technical performance parameters and economical parameters to evaluate the effect of production performance on cost, and recommends improvement scenarios for the best cost efficiency. The PPC is structured according to cost drivers (e.g., raw material, tool, equipment during operation, downtime/idle, personnel, maintenance, and quality cost). The total manufacturing cost is

"Under the assumptions made with this analysis, there is a good chance that a PM gear could meet the demands in a Tesla Model S for at least 300,000 km."

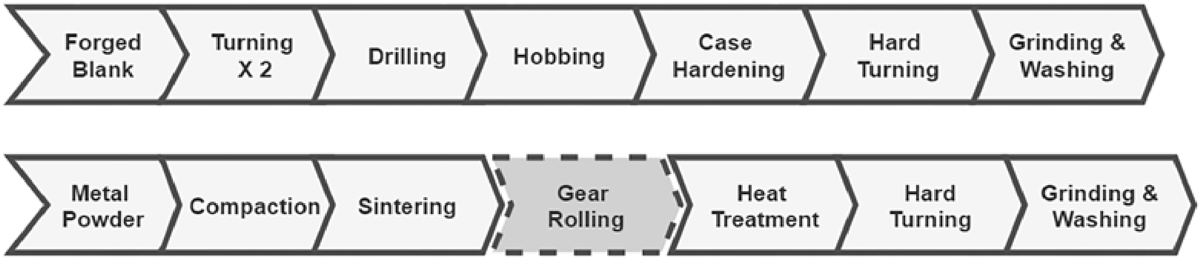


Fig. 7 Conventional machining (top) and PM (bottom) processing routes for the studied output ring gear

> *"The transmission in BEVs has few, but high-value, parts, and to capture that market requires investments in large presses with three upper and three lower punches, plus a helical gear adapter."*

quantified in an aggregated process, as each manufacturing step's cost is added as the input cost for the next. Raw material cost, however, is included in the first manufacturing step, hence any quality related cost that might come about during the processes can be identified and monitored [6].

Manufacturing processing routes

Fig. 7 shows processing routes for wrought steel and PM manufacturing for the ring gear in this study. A gear rolling process is considered optional for this ring gear; we can, therefore, compare the PM gear manufacturing cost against the wrought steel cost with and without gear rolling. Table 1 illustrates some general assumptions considered in this comparative study; the manufacturing location is assumed to be Northern Europe, and general parameters related to it for both manufacturing techniques are considered to be the same.

Data point	Amount	Unit
Throughput time	25	days
Annual volume	100,000	units
Batch size	30,000	parts
Cost of capital	7%	%
Facility rent	Confidential	Currency / m^2
Electricity cost	0.5	SEK / kWh
Annual work time	5200	hours
Labour cost	Confidential	SEK / hour

Table 1 General data chosen for both gear manufacturing technologies

Manufacturing cost comparison results

A cost calculation tool with cost driver breakdown structures for both gear manufacturing routes was designed. The manufacturing cost comparison results indicated that the PM gear manufacturing cost per part, utilising the processing route shown in Fig. 7, is 20% lower/cheaper in comparison to the utilised conventional wrought steel processing route. In scenario 1, if gear rolling is added to the PM processing route as a second densification process, the PM gear would, instead, be 18% less expensive in comparison to its counterpart. In scenario 2, if the yearly production volume is increased to 400,000 parts, the PM gear is 27% cheaper to manufacture in comparison to the wrought steel gear. If a gear rolling process is included the PM cost advantages slightly changes to 26%.

Fig. 8 illustrates the share of total gear manufacturing cost per part for both the selected conventional machining processing route, and the selected PM processing routes excluding and including gear rolling process. These figures are for the base scenario shown in Table 1 above, with the annual production volume of 100,000 parts.

One vital element of the PPC model is Overall Equipment Efficiency (OEE), which assists in the evaluation of the cost effect of improved quality yield and decreased downtime. OEE is often measured by its three main factors of availability (A), performance (P) and quality (Q), and is presented in percentages (%) [7]. This article's final scenario (scenario 3) investigated the influence of different OEE values on the total gear manufacturing cost per part. The baseline OEE value of 70% (A:70%, P:100%, Q:98%) was considered to calculate the manufacturing cost of the Tesla Model S output ring gear with both processing routes shown in Fig. 7. Scenario 3 combines the previous two scenarios; hence it considers three variables of increasing annual production volumes, including a gear rolling process and changing OEE values. Scenario 3 is then designed where a low bound OEE value of 50% (A:55%, P:96%, Q:95%) and a high bound OEE value of 85% (A:85%, P:100%, Q:99%), representing the world-class OEE for non-process industry [8], were selected. The results are shown in Table 2.

Conclusions

The PM industry faces some very real challenges this decade, with volumes of traditional PM parts declining as combustion engine platforms are phased out. The transmission in a BEV has few parts, but the parts it does have are high-value ones. For PM to capture that market will require investments in large presses with three upper and three lower punches, plus helical gear adapters. A market approach similar to Stackpole's, which offers complete engineering services and testing for BEV drivetrains, is a good way forward [9]. This approach has become more accessible to the PM industry with the growth in fixed ratio gearboxes, as developing this type of gearbox requires less resources than are required to develop, for example, a 10-speed automatic gearbox with accompanying integration and millions of lines of code.

It can be seen, from the numbers in Table 2, that improving and/or impairing the OEE values has a rather significant impact on total manufacturing cost per part for the output ring gear assessed in this

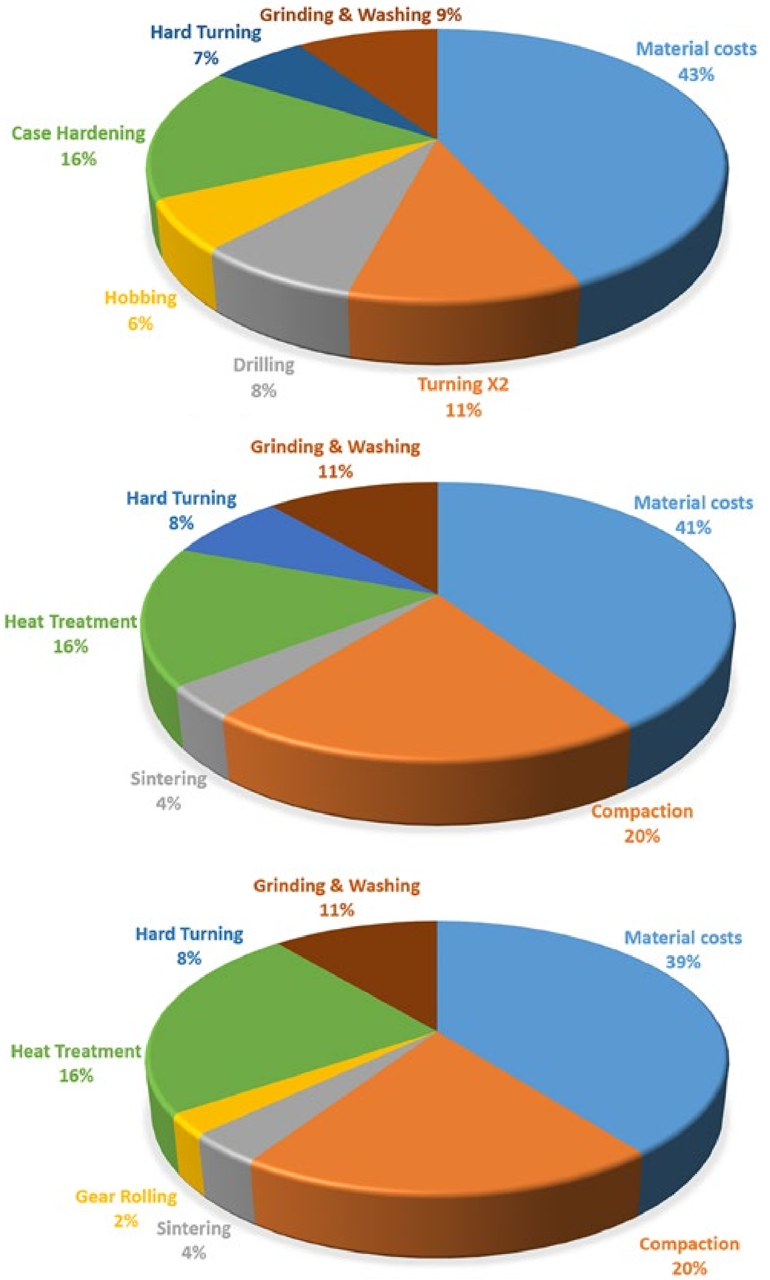


Fig. 8 Top; Total wrought steel gear manufacturing cost allocation across all production steps, Middle; Total PM gear manufacturing cost allocation across all production steps, Bottom; Total PM gear manufacturing cost allocation across all production steps, including gear rolling process

% change in total manufacturing cost per part versus baseline case of OEE 70%						
	PM (excl. gear rolling)		PM (incl. gear rolling)		Conventional machining	
Number of parts annually	100,000	400,000	100,000	400,000	100,000	400,000
OEE 50%	↑ 23%	↑ 26%	↑ 24%	↑ 27%	↑ 18%	↑ 18%
OEE 85%	↓ -10%	↓ -11%	↓-10%	↓-12%	↓-7%	↓-8%

Table 2 Overall Equipment Efficiency (OEE) scenario sensitivity analysis

article, by both PM and conventional machining processing routes. As the cost shares presented in this article's figures and tables are relative, it is important to elaborate a bit more on how OEE influences cost.

Equipment costs in downtime went up with a lower OEE of 50%, and went down due to the improved availability and quality issues seen with a higher OEE of 85%. Even if the availability is set to 100%, there will still be a percentage of equipment downtime cost due to the inclusion of setup time. Labour costs, too, rose with a lower OEE of 50%, and fell with the higher OEE of 85%, because operators are still occupied even if the equipment is idle or in downtime. Tool and equipment costs during operation are decreased with an OEE of 50%; this could be due to the equipment's poor availability. Both tool and equipment costs during operation increased after OEE improvement, as the availability of equipment increased and its standby mode and downtime decreased. This again underscores the importance of top-of-the-line manufacturing facilities and practices.

From a durability perspective, a PM gear can sustain the loads and cycles in a BEV gearbox. To manage the competition that is sure to emerge now that high-end transmission design no longer requires the traditional armada of engineers, and the threshold has lowered for new players to enter the market, will be a matter of clever gear design, first-class materials and state-of-the-art production technology. It has been shown that, when comparing apples to apples, net-shape manufacturing using PM can be cost effective in gear production.

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Can European research still claim to be 'world class'? Prof José M Torralba on the changed PM research base

In the history of the Powder Metallurgy industry, Europe has been a research leader, with major European universities and research institutes paving the way to the identification of new materials, processing techniques, and applications for the technology. But is that still the case in 2021? In this article, Dr David Whittaker speaks to Prof José M Torralba, a leading expert in the European PM research landscape, and hears his views on the current state of global PM research, the factors limiting development in the European PM industry, and directions for future research and development.

When it was suggested by the team at *Powder Metallurgy Review* that I contact Prof José M Torralba to explore his views on the status of Powder Metallurgy research, I was pleased; José and I have an association that dates back around thirty years. He is widely recognised as a leading expert and participant in the field of PM research in European academia. Alongside his co-editor Herbert Danninger, his work on the UK Institute of Materials, Minerals and Mining (IOM3) journal *Powder Metallurgy* equips him with an excellent perspective on global activity in the field.

During his career, Torralba has been Head of the Materials Science and Engineering (MSE) Department of the Universidad Carlos III Madrid (UC3M), Spain, vice-rector for Academic Infrastructures and vice-rector for Research and Innovation in MSE at UC3M, as well as Deputy Director of the prestigious research institute IMDEA Materials, Director-General for Universities and Research of the Madrid Regional Government and Higher Artistic Arts Studies. He is currently a Professor of MSE at UC3M and Director of IMDEA Materials Institute.

As reported in the Autumn/Fall 2021 issue of *Powder Metallurgy Review*, he also received the FEMS (Federation of European Materials Societies) Gold Medal, in recognition

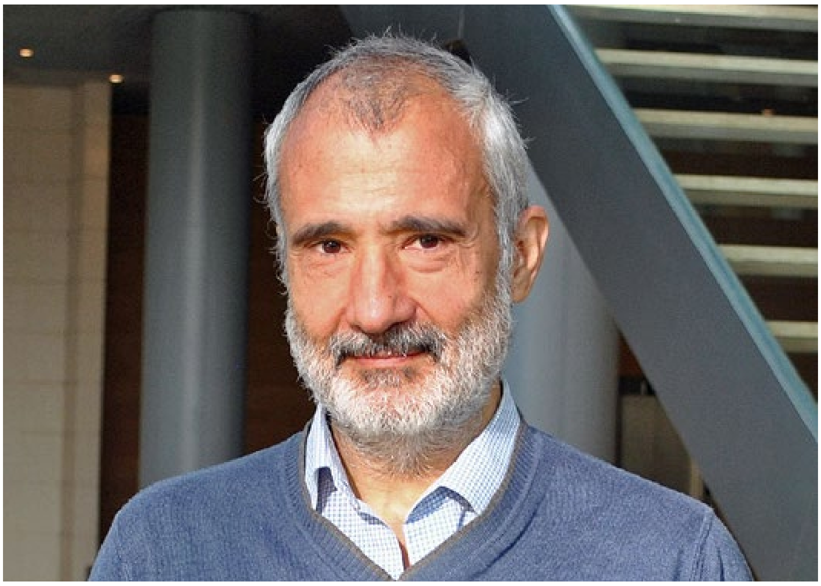


Fig. 1 Prof José M Torralba is a leading expert in the European PM research landscape

Fig. 2 A 'Höganäs Chair' dinner. From left to right: Prof Torralba, Prof Mónica Campos (PhD student at the 1st Höganäs Chair, now professor at UC3M), Prof Alberto Molinari, Prof Herbert Danninger, Prof Eduard Hryha (PhD student at 2nd Hoganas Chair, now professor at Chalmers Univesity of Technology)

of his outstanding contributions to the field of Materials Science and Engineering, particularly of PM.

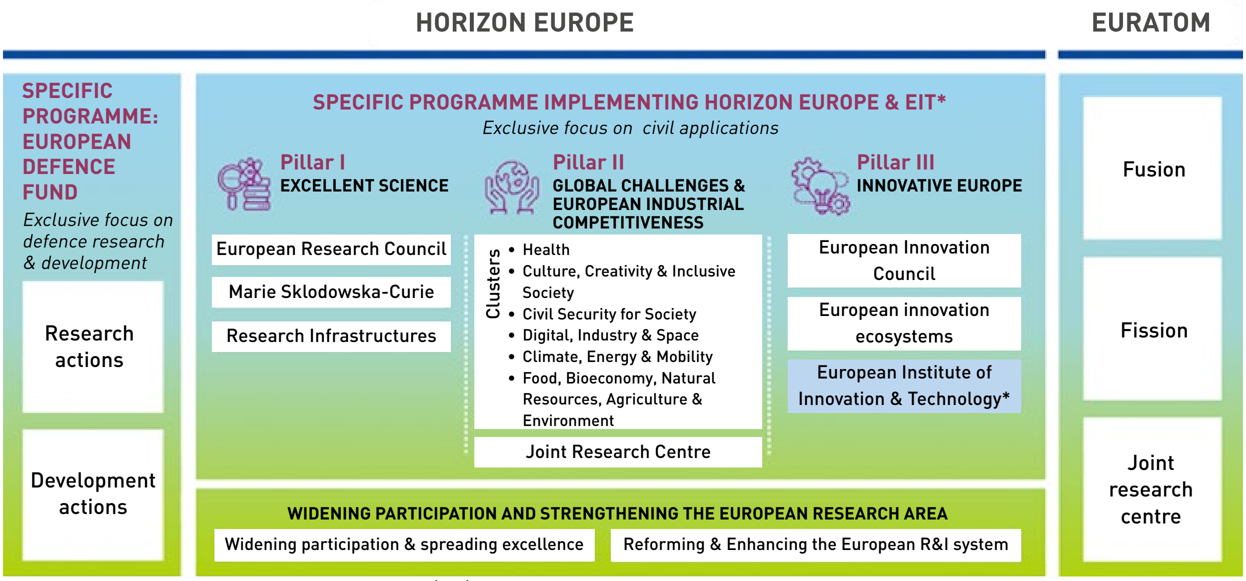
A past activity which Torralba looks back on with significant pride was his involvement in the 'Höganäs Chair' programme (Fig. 2). This scheme was established around twenty-five years ago by Höganäs AB, Sweden, and endowed professorial chairs and associated PM research activity – not just at UC3M, but at the University of Trento, Italy (Prof Alberto Molinari), the Technical University of Vienna, Austria (Prof Herbert Danninger) and the Slovak Academy of Sciences (Prof Eva Dudrova). Although the scheme is no longer operational, it ran for at least five rounds of PhD studentships (longer than fifteen years), and Torralba was keen to highlight its achievements, stating, "In addition to the important research results generated, more than twenty-five highly educated PhDs were created, most of whom are still working at high levels in the PM industry or in academe and continue to make important contributions."

A changed PM research base

We both recognised the increasingly important roles played by academic groups and research institutes within the overall PM research base. In the past, the major powder suppliers, in particular, had provided a prime driving force in pursuing innovative developments, aimed at enhancing product properties and control of the manufacturing processes. This drive was now much less evident.

An important issue enabling the ability of academic groups and research institutes to pursue their research ideas is the securing of appropriate public funding. Within Europe, the EU R&D Framework programmes are important sources of such funding and the competition for that funding is only increasing; currently, no more than 10% of proposals find success.

While, in the past, programmes might have included opportunities to



**The European Institute of Innovation &Technlology (EIT) is not part of the Specific Programme*

Fig. 3 To find EU funding opportunities, research proposals must fit into a strict set of EU research focuses, shown in 'Global Challenges & European Industrial Competitiveness' above (Copyright European Union 2021) submit proposals based on material or processing developments, the focus now is chiefly geared towards meeting UN sustainability goals. "To find EU funding opportunities, proposals need to be written in such a way that the envisaged developments are perceived to be pulled by the achievement of these objectives, rather than pushed by the underlying material or process developments," Torralba explained. As such, an increasing number of successful proposals are now written by professional proposal writers and focused strictly within the (perhaps limited) scope of resource and energy efficiency, CO_2 emissions & waste reductions, and any possible health-related topics that can be identified (Fig. 3).

"Although anyone with an understanding of PM processing can recognise strong competitive advantages against other process technologies in the areas of material utilisation and energy efficiency, and that these advantages could be used to generate opportunities for PM research in the present scenario, the industry may need to do more in convincing the funding organisations on these criteria," Torralba noted. "Indeed, perhaps we may need to do more to convince ourselves!"

While this issue is one affecting Europe on both a continental and regional level, research funding in other areas of the world is not necessarily subject to the same shrunken scope.

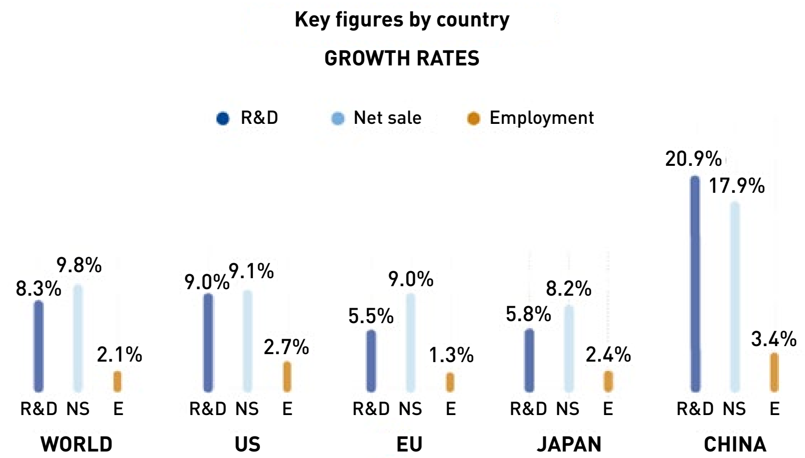


Fig. 4 By 2018, R&D growth in China dwarfed that of the EU (Copyright European Union 2018)

European PM research: Still world class?

In days past, European PM research could have reasonably claimed to be world class – perhaps even world leading. However, Torralba expressed doubt that this claim could still be considered valid in 2021.

"In Europe, there may be around fifteen to twenty active PM research groups, each with no more than twenty researchers," he stated. "Contrast this with the situation in China, where the interests of the PM sector are served by multiple key state research centres, each with over 200 staff. It must be recognised that the scale of research effort in China now dwarfs that in Europe." (Fig. 4).

Two examples of those key Chinese state labs are one devoted to Powder Metallurgy and one devoted to Metal Matrix Composites (MMCs), which also employs Powder Metallurgy. Linked to universities with a high degree of expertise in materials science and engineering (Central South University and Shanghai Jiao Tong University, respectively), the state also supports undergraduate and masters degree programmes related to Powder Metallurgy.

A key aspect of these national labs is the high concentration of researchers (more than eighty permanent researchers in each), first class equipment and high level of government funding available to research teams. The research and development conducted in those labs is highly linked with the priority research areas established by the Chinese government, mostly linked with the country's defence and aerospace programmes, including the development of new generations of liquid oxygen engines, rockets, the space station and more.

"In this context, it would be difficult to disagree with the

"In Europe, there may be around fifteen to twenty active PM research groups, each with no more than twenty researchers. Contrast this with the situation in China, where the interests of the PM sector are served by multiple key state research centres, each with over 200 staff."

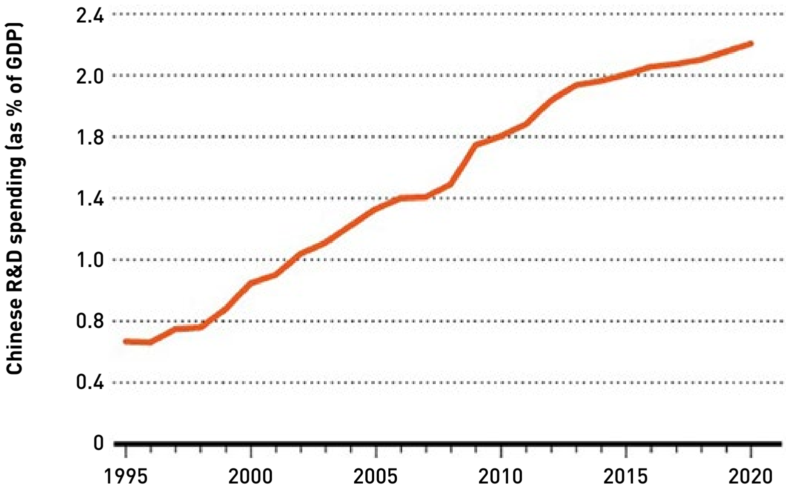


Fig. 5 R&D investment in China from 1995–2020 (Courtesy OECD / National Bureau of Statistics of China)

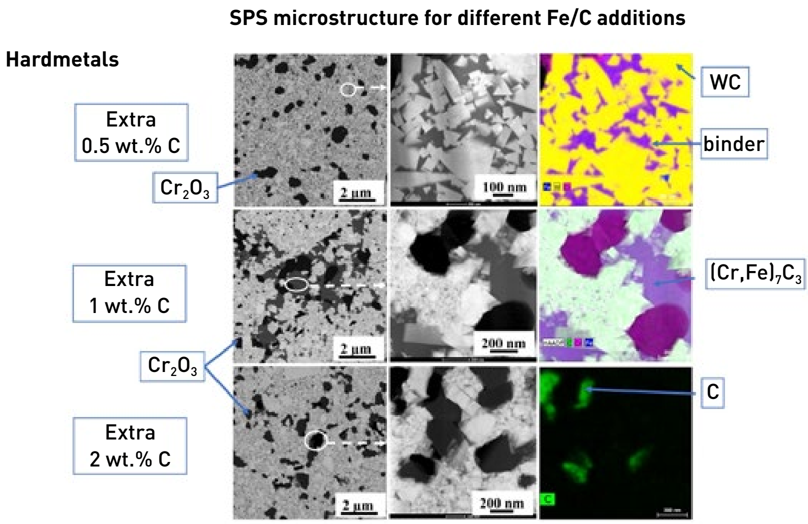


Fig. 6 Microstructure of spark plasma sintered hardmetals with different Fe/C additions (Published in García-Junceda, A; Sáez, I; Deng, X.X; Torralba, J M, 'Development of a Cr-based hard composite processed by Spark Plasma Sintering,' in Metall Mater Trans A, 49, 1363–1371 (2018))

view, expressed by Cesar Molins in his article in the Autumn/Fall 2021 issue of *Powder Metallurgy Review*, that the disaffection of many European policymakers with manufacturing industry has allowed China the opportunity to grow their industry to capture the market and, not surprisingly, to grow their research and teaching infrastructure to support this," Torralba noted. The growth in R&D investment in China from 1995–2020 is shown in Fig. 5.

Implications of the sustainability agenda & opportunities for innovative PM research

Despite the apparent limiting of European research opportunities, several growth areas have opened for PM as a result of the EU sustainability objectives, including energy storage and the hydrogen economy as a whole, wherein topics like storage and avoiding embrittlement offer future use cases for PM developments.

As Torralba stated, "These sustainability issues are advancing the requirement to develop multi-functional materials; it is no longer sufficient to select materials to combine, for instance, strength and corrosion resistance, but is becoming necessary to also offer other performance attributes, such as, for example, hydrogen embrittlement resistance. This is the case for some recently developed high-entropy alloys, with a full FCC structure that can provide good mechanical behaviour at high temperature, good corrosion performance, and which are suitable for hydrogen storage, avoiding embrittlement."

As well as supporting other industries, a further sustainability aim could be coming from inside the PM house: the need for raw material substitutes. "This need is partly driven by the desire for cost savings, but also addresses concerns regarding health issues with existing materials, limitations on availability of these materials and security of supply, where raw material supplies are concentrated in potentially politically-sensitive countries," Torralba stated. "Anyone who needs to convince themselves of the significance of this last issue needs only to recognise the recent disruptions caused to automotive production schedules by the micro-chip supply crisis."

Torralba and his research team have been tackling one sustainability issue concerning raw material: cobalt, often used as a binder in hardmetals. Using enablers of nano-sized powders and Spark Plasma Sintering (SPS), Cr-Fe hardmetals have been created which are said to offer properties equivalent – and, in some cases (e.g., wear resistance), superior - to WC-Co hardmetals (Fig. 6).

"PM has a lot of development possibilities in new processing technologies for high-performance applications," he noted. "Spark Plasma Sintering or Field-assisted Sintering would seem likely to have an important role in this area. I would also see this as a driving force for

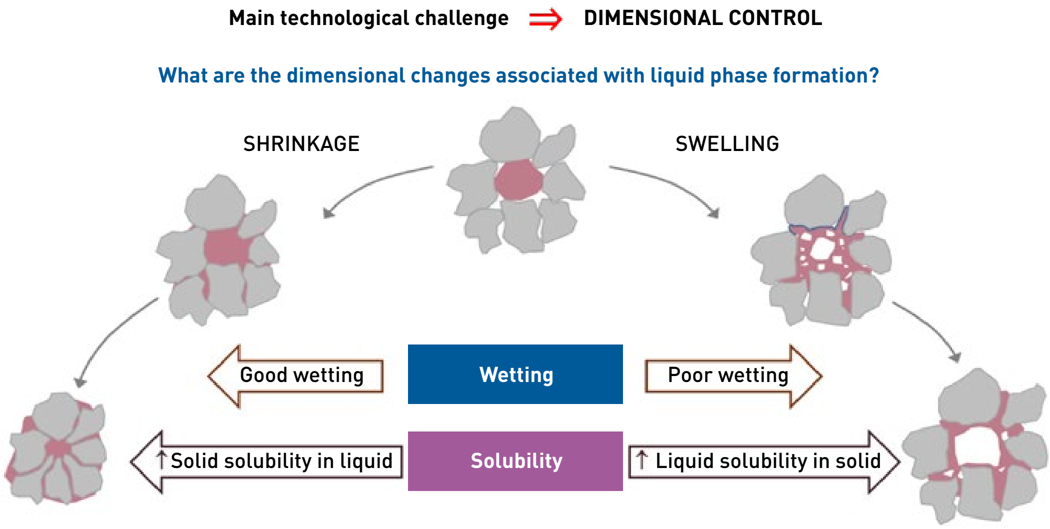


Fig. 7 A look at the dimensional changes associated with liquid phase formation in sintering with master alloy additions (Published in E Bernardo, M Campos, J M Torralba, R Frykholm, and O Litström, 'Influence of powder particle size on the mechanical properties of PM low alloyed steels obtained by additions of Cu-Ni-Zn master alloy,' presented at PM World Congress, Yokohama, Japan (2012))

the increased market penetration of metal Additive Manufacturing."

Alongside these up-and-coming technologies, Torralba stated that he will "remain bullish regarding the future of conventional press and sinter PM, which is still a good technology for many applications. There is a continuing need for innovative research in the field, including improvements in alloying techniques for enhanced product performance and material and process developments aimed at improved sinterability." As an example of improvements in alloying techniques, Torralba referenced work on master alloy additions, both within his own group and elsewhere (Fig. 7, 8, 9).

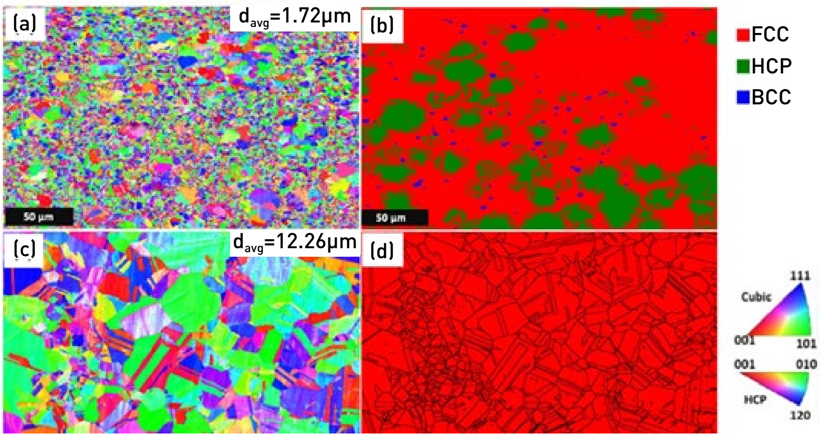


Fig. 8 Electron Backscatter Diffraction (ESBD) image of NiFeCrCoMo alloy in the as-sintered state (a, b) and after annealing at 1200°C for 24hrs (c, d) (Published in José M Torralba and S Venkatesh Kumarán, 'Development of competitive high-entropy alloys using commodity powders,' in Materials Letters, Volume 301 (2021))

Impact of electrification

Although the future of vehicle electrification will clearly entail the loss of some existing PM structural parts business in automotive internal combustion engines, Torralba was considerably more optimistic for the future of PM in automotive than some industry observers. "I envisage that many new opportunities for PM will emerge in electric and hybrid cars," he stated. "These might include battery applications and soft and hard magnetic parts in electric drivetrains."

These types of applications, however, may require more than just an overhaul within the factory: many industry statistics have traditionally focused on tonnage of powder and number of parts produced as the barometer for the industry's health. "A more reasonable tack in future may be a focus less on tonnages and more on the added value in parts produced," he predicted.

More observable trends in global PM research

Based on his observation of PM literature, particularly through his hands-on involvement as co-editor of the journal *Powder Metallurgy*,

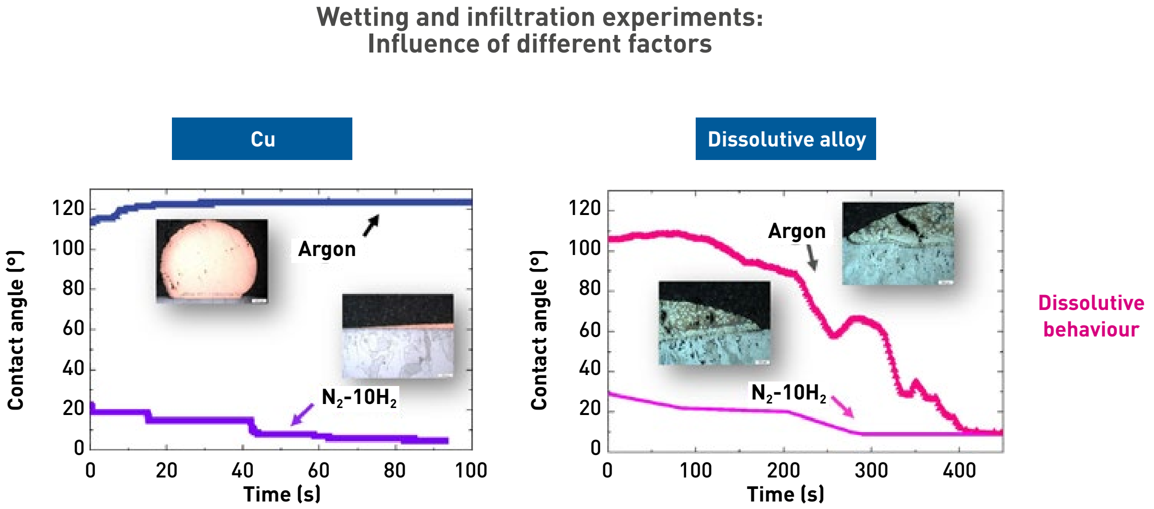


Fig. 9 An experiment on wetting and infiltration found that dissolutive systems improve wetting phenomena, even in less favourable conditions (Published in R Oro, M Campos & J M Torralba, 'Study of high temperature wetting and infiltration for optimising liquid phase sintering in low alloy steels,' in Powder Metallurgy, 55:3, 180-190, DOI: 10.1179/1743290111Y.0000000007 (2012))

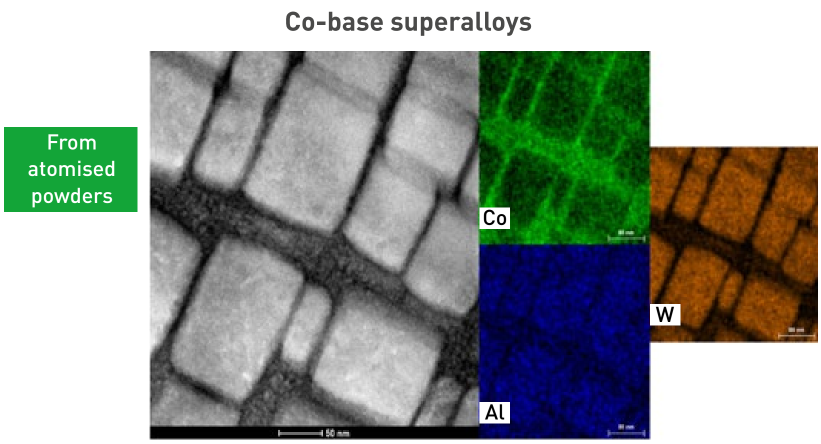


Fig. 10 EDX-TEM of γ/γ′ dual phase mapping analysis in Co-9-9-At sample after ageing heat treatment (Published in Marta Cartón-Cordero; Mónica Campos; Lisa P Freund; Markus Kolb; Steffen Neumeier; Mathias Göken; José M Torralba, 'Microstructure and compression strength of Co-based superalloys hardened by γ′ and carbide precipitation,' in Materials Science and Engineering: A, Volume 734, 2018, 437-444)

Torralba reflected on some strong current trends in PM research directions.

"Development in new material types is a strong area. One field, in which my own group has had some activity, is that of the processing of high entropy alloys from powders. Our group has also been involved in the development of Co-Al-W superalloys that depend on similar γ/γ′ precipitation strengthening mechanisms to Ni-based superalloys. A vital processing step in these new superalloy materials involves the pre-treatment of the powders to create so-called 'harmonic' structures (comprising a fine-grained shell with a coarser-grained core)." (Fig. 10)

In this new family of superalloys, Torralba explained, the high-temperature behaviour that can be obtained by using PM techniques is outstanding, but this behaviour is improved even more with harmonic structures, due to the grain refinement in the surface of the powders, which is further enhanced during the sintering process.

"Full-density processing is also field of high activity," he noted. "The use of both field-assisted processing and laser-based methods should be mentioned, in this context."

The use of SPS has recently appeared as an interesting alternative to HIP for some applications. Using this technology, full-density materials can be produced, but with much lower grain sizes in the microstructure of the material, potentially allowing much better properties. This allows the replacement of a process that usually takes hours (HIP) with the comparatively very short SPS process, which is sometimes as quick as minutes long, and can also be conducted at lower temperatures. "We are presented with a full density method where the grain growth is inhibited," Torralba stated. "Also, new Laser Beam Powder Bed-based AM methods allow the production of full-density materials, with the advantage of producing a part almost to its final shape in a very short time."

"There are also signs that PM experts have been finding opportunities to contribute to enhancing the viability of Additive Manufacturing serial production. In the early days, when AM technologies were growing out of rapid prototyping, much of the emphasis was on the ability to build complex and intricate geometries, with little or no attention on the control of powder characteristics and process conditions to produce high integrity, defect-free parts. Now, expert knowledge on the influence of powder characteristics on the powder filling/spreading step across a broad range of Powder Bed AM technologies is being brought to bear. Perhaps of even more importance, PM expertise is of vital significance in controlling the debinding and sintering stages in the emerging sinter-based AM technologies. It comes as no surprise that industrial up-take of such technologies is currently largely in the hands of established Metal Injection Moulding companies.”

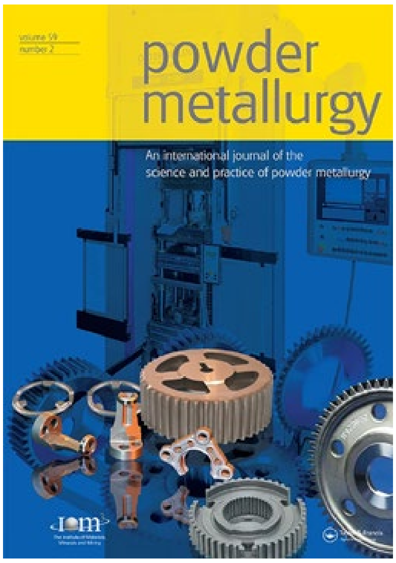


Fig. 11 Powder Metallurgy journal, published by the UK's Institute of Materials, Minerals and Mining (IOM3), is the only fully peer-reviewed academic journal strictly related to PM (Courtesy IOM3)

Recognising the value of the industry's peer-reviewed academic journals

Torralba is rightly proud of *Powder Metallurgy* journal's place in the PM publications field, as the only fully peer-reviewed learned journal. Learned journals are judged by the research community based on impact ratings and, given the limited size of the community that it serves, the journal will never fully scale the heights in this regard. However, Torralba and his co-editor, Herbert Danninger, have had a good deal of success, in recent years, in improving the rating – but they need more support from the industry in taking this process further.

“We have on-going needs for a supply of high-quality papers and, also, for expert reviewers, who are ready and willing to assist in the assessment of submitted papers,” Torralba stated. “I would like to make a plea to the community to help us address both of these constraints.”

Those interested, and qualified, in fulfilling these goals are welcomed to contact José Torralba at the contact information provided here.

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How to make metal powders. Part 1: An introduction to atomisation, process fundamentals and powder characteristics

The rise of metal Additive Manufacturing has resulted in renewed interest in metal powder production. A market once dominated by a small number of specialist powder producers has now seen the arrival of a diverse range of competitors, all hoping to capitalise on the promised opportunities of metal powder-based part production. As many are discovering, however, making powders with the required characteristics, to the necessary standards, and profitably, is far from easy. Here, in the first instalment of a four-part series, two masters of metal powder atomisation, Joe Strauss and John Dunkley, introduce the process.

This portion of our series on atomisation is an overview to provide the reader with some understanding of the general science and attributes of the various methods of atomisation. The overall influence of the melt properties on the resultant powder particle properties will be presented along with the effect of the powder particle features on the bulk powder characteristics. Subsequent sections will provide greater detail on the individual atomisation processes.

There are numerous industrial and commercial uses for metal powder. Most of these applications remain invisible to the end user, because the powder has been transformed to a solid by sintering or fusion, contained in paints and coatings, consumed as a fuel or in a chemical reaction, or as an ingredient in food. Visible or not, metal powder production exceeds 1,500,000 tons per year globally.

In the Powder Metallurgy sector, the main applications for metal powders include the manufacture of structural and machine parts, cutting tools, and bushings and filters; two examples are shown in Fig. 1. All of these PM technologies process the powder via sintering, either in the solid state or with a partial formation of liquid. This includes the new sinter-based Additive Manufacturing technologies such as Binder Jetting.

Laser and Electron Beam Powder Bed Fusion (PBF-LB and PBF-EB, respectively) Additive Manufacturing technologies produce three-dimensional parts by binding the powder using direct melting. Melting, or fusing, is also the mechanism used to process metal powders for solders and brazes, welding, thermal spray, and dental amalgams. In these examples, the powder becomes a three-dimensional object, film, coating, or an amalgam. Fig. 2 shows a brazed joint that used a paste containing powder as the filler material.

Other uses of metal powder include the current carrier in conduc-

Fig. 1 PM porous bronze filter, Capstan California (left); PM worm gear, ARC Group (right) (Courtesy Metal Powder Industries Federation)

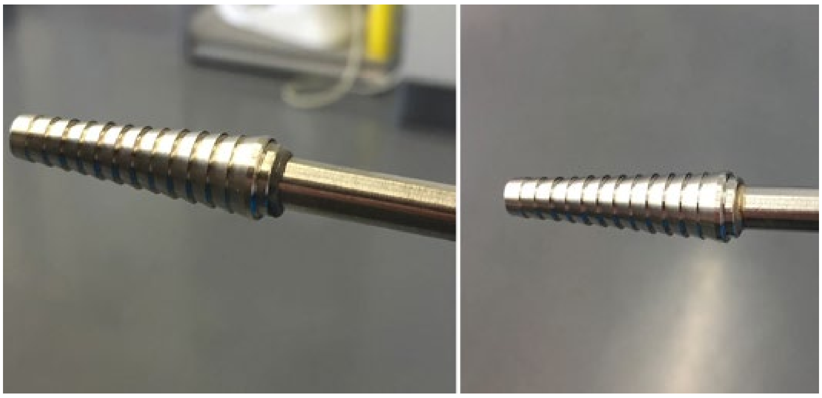

Fig. 2 An assembly being joined with brazing paste. On the left is the assembled part with the dark grey paste applied at a junction between the two parts. On the right is the brazed part showing the braze fillet joining the two parts (Courtesy Prince & Izant, USA)

tive inks, magnetic recording media, uses in chemical reactions, applications in food and pharmaceuticals, and as fuel/propellant in rockets, ballistics, and flares.

In all the above cases, the material being processed needs to be in a form that allows it to be easily and conveniently manipulated with respect to location, volume, or weight. Powder fits this bill.

Metal powder can be produced in a variety of processes, the four major methods being:

1. Reduction of oxide
2. Chemical reaction (precipitation, decomposition)
3. Comminution of a solid (grinding, milling)
4. Atomisation of molten metal

Atomisation, in its most fundamental description, is the disintegration of a liquid into droplets. If the liquid is a molten metal, then the liquid droplets solidify and become the particles that make up the powder. The majority of metal powder is produced by atomisation. Atomisation offers the greatest economy of scale and, unlike the other processes, is able to produce fully alloyed powders with the greatest diversity of particle sizes, morphologies, compositions, and microstructures.

The disintegration of the bulk liquid into droplets can occur from impingement with a second fluid (gas, water, or oil, for example), by imposing centrifugal forces via the rotation of a disk, cup, or electrode; by applying other mechanical forces such as ultrasonic perturbations; or by spraying the liquid under pressure where it breaks up into droplets via Rayleigh instabilities.

In the absence of any other force, a liquid droplet will form a sphere, which represents the lowest energy shape for a volume. There is a surface energy or tension associated with every liquid. The smaller the amount of surface area, the lower the surface energy is for that body. Since a sphere has the lowest surface area per unit volume, a sphere represents the minimum energy shape. However, in most atomisation events, the droplets are subjected to many other influences that may prevent or destabilise the formation of a perfect sphere.

Fundamental atomisation principles

Before presenting details on the various methods of atomisation, this review will provide a description of the general science of atomisation without being method specific. These points are universal and apply to all metal atomisation methods.

All atomisation processes include three fundamental steps: melting, atomisation of the melt, and collection of the solidified powder (Fig. 3).

The liquid droplet undergoes a metamorphosis of shapes as the driving forces of surface tension act to shape the drop into the minimal energy spherical shape while those of viscosity, shearing from the motive fluids, and interactions with the ambient environment – such as oxidation of the surface – act to prevent this. In the same time frame, cooling is occurring and limiting the time needed to form a sphere. The balance between the time scales of spheroidisation and solidification and the formation of an oxide shell are the primary events that dictates the morphology of the particle. Slow cooling enables spheroidisation prior to solidification and favours spherical particle morphologies. Fast cooling precludes the ability for the droplets to achieve the equilibrium shape (spheroidise) and the particle morphology is irregular. And, even if the time to spheroidise is sufficient, the formation of an oxide shell stops or greatly reduces the ability to spheroidise. In addition to this primary balance, contributions from material properties (viscosity, reactivity with the environment, liquidus to solidus separation, etc), process variables (melt superheat, droplet velocity) and equipment variables (droplet concentration, trajectory, location of impingement surfaces, etc) influence the final morphology of the powder particle. Thus, many factors can influence the characteristics of the powder and its particles.

There are many theories on the breakup of molten metal into droplets. Some are derived from first principles and some are based on empirical testing and observations. The authors believe that none to date is capable of fully predicting the resultant powder attributes. However, some of the relationships are universally valid and will be presented here in general as a guide to what process parameters and details can affect the powder characteristics.

Since atomisation is a result of subjecting the liquid metal to forces, the liquid properties of surface

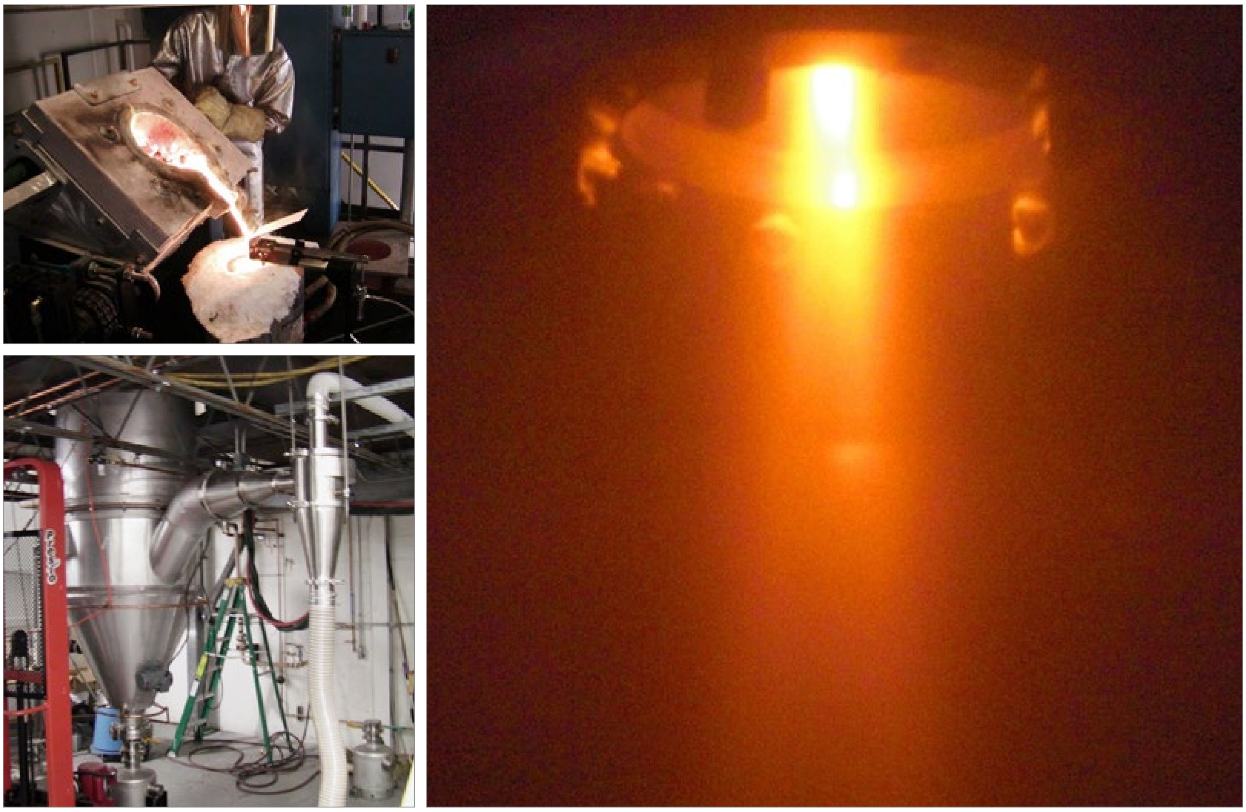

Fig. 3 All atomisation processes include three fundamental steps: melting (top left), atomisation of the melt (right), and collection of the solidified powder (bottom right) (Courtesy Cimini & Associates, USA)

energy and viscosity must contribute to the manner in which the liquid breaks up and the behaviour of the droplets prior to solidification. In a very general sense, and independent of the atomisation method, the increase in surface area going from the melt stream to that of the sum of the droplets, a very large increase, is essentially an increase in surface energy of the system. This additional energy must be supplied by the mechanism being applied to disintegrate the melt stream. It follows that low surface energy melts would more readily 'atomise' into finer droplets since less energy is required. Viscosity, on the other hand, is a property that resists the breakup of the liquid so that increasingly viscous melts would produce coarser powder particles. In seeking high yields of fine powder, one would choose to minimise both the surface tension and viscosity. However, these properties are essentially fixed by the alloy. Fortunately, both the surface tension and the viscosity fall with temperature. Thus, increasing the melt temperature is a tool that can be used to increase the yield of finer powder across all methods of melt atomisation.

It follows that if energy transfer to the melt controls the droplet size, more energy would produce smaller particles. Energy is embodied in the pressure of the gas or water in two-fluid atomisation, the rotational speed of the disk or electrode in centrifugal atomisation, or the amplitude and frequency in ultrasonic atomisation. Thus, increasing the pressures, speeds, amplitude/frequencies of the atomisation process will decrease the size of the droplets formed.

Once the droplet has formed, spheroidisation is favoured by higher surface energies and lower viscosities. The high surface energy/tension is the driving force to minimise the surface area, which results in the production of spherical droplets. The viscosity acts to dampen the liquid trying to change shape. Droplets of

"There are many theories on the breakup of molten metal into droplets. Some are derived from first principles and some are based on empirical testing and observations. The authors believe that none to date is capable of fully predicting the resultant powder attributes."

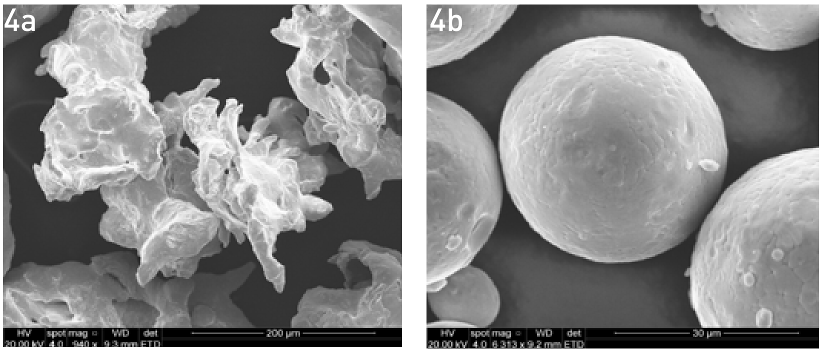

Fig. 4 Stainless steel powder particles produced by water and gas atomisation. The difference in their morphologies is very apparent (Courtesy ASL, UK)

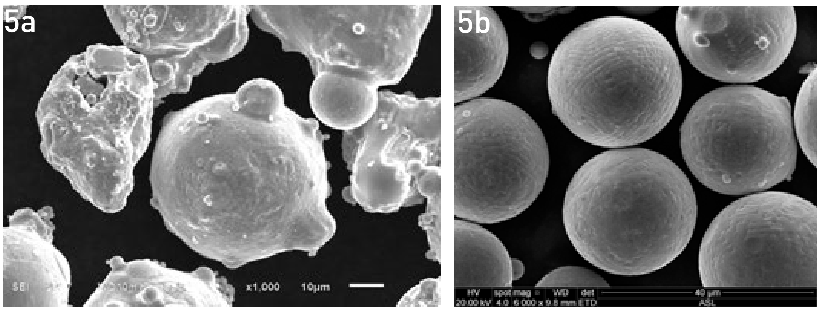

Fig. 5 A comparison of gas atomised powder that is satellited and one made with hardware that reduces satelliting (Courtesy ASL, UK)

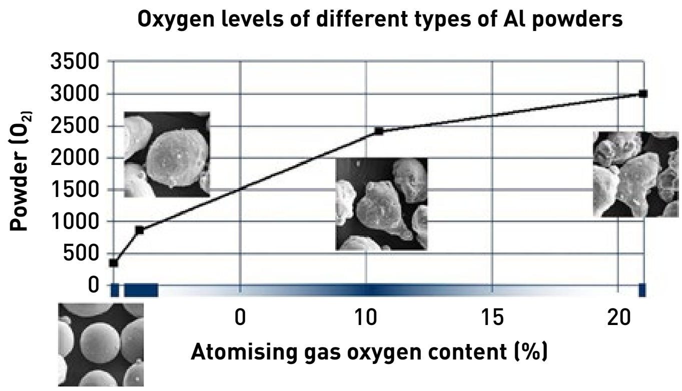

Fig. 6 Comparison of aluminium powder morphologies as a function of the oxygen content of the atomisation gas (From 'Commercial Atomization Processes for Aluminum Powder Manufacture,' George T Campbell, Roy W Christensen, Valimet, Inc., presented at TMS Annual Meeting, 2000)

lower surface tension alloy have less 'incentive' to spheroidise than those of alloys with higher surface tension. However, cooling occurs from the surface inward so the surface tension increases while change in the interior viscosity lags, which help promote spheroidisation.

As mentioned previously, the tendency for the droplet to form a sphere – and, subsequently, a spherical particle – is based on the ability of the droplet to spheroidise prior to solidifying. Parameters that will slow the cooling rate of the droplet effectively lengthen the time that the droplet is molten resulting in more spherical droplets. Increasing the melt superheat (relative to the liquidus temperature) increases the time while fluid and can help form more spherical droplets. The liquidus to solidus temperature range, to some extent, can also influence the sphericity. Wide liquidus to solidus ranges can delay the time to solidification. Elements, which have a single solidification temperature, solidify uniformly, which takes less time than an alloy that solidifies over a temperature range.

The quenching ability of the environment surrounding the droplets is a significant parameter that affects the morphology of the resultant particles. Increasing the quenching power of the environment increases the cooling rate and reduces the time to solidify. This is most obvious in the difference in morphologies of gas atomised powder vs that of water atomised powder. The heat transfer rate between the molten metal and water is much higher than that between the molten metal and the atomisation gas, which is essentially an insulator in comparison to water. Thus, in the water atomisation process, the droplets may solidify before they are able to spheroidise – more so as oxidation may preclude the ability to spheroidise.

In general, inert gas atomised powder particles are spherical, whereas water atomised particles are irregular in shape. Fig. 4 shows stainless steel powder particles produced by water and gas atomisation. The high-melting film of chromium oxide greatly affects the shape in water atomisation, and the difference in their morphologies is very apparent. There are, of course, exceptions. Recent advances in very high-pressure water atomisation show that very fine spherical powder can be made. The droplets formed by the high pressure are small (typically less than 15 µm) and the surface tension can act on these very small droplets very quickly, apparently quickly enough so that the droplet spheroidised prior to solidifying. Another exception is satelliting in inert gas atomised powder. Although the process generates spherical powder particles, collisions in the atomisation vessel can cause the particles to bond. These agglomerates are not spherical, although the individual particles within are primarily spherical. Fig. 5 shows a comparison of gas atomised powder that is satellited and one made with hardware that reduces satelliting. This will be covered in more detail in the later sections on the specific atomisation technologies.

The environment in which the droplets are formed and solidified also plays an important part in the final morphology. If the molten metal reacts with the local environment, the reaction product may impede spheroidisation. Fig. 6 shows a comparison of aluminium powder morphologies as a function of the oxygen content of the atomisation gas. For example, aluminium atomised in an inert atmosphere will form spherical droplets and powder particles. However, if atomised in air, in an atmosphere with a significant amount of oxygen, or steam, the molten droplets will form a tenacious oxide film on the surface. This film is a strong solid at the melting point of the metal and will preserve the shape of the droplet on which it forms and prevent spheroidisation. Similarly, although droplets formed by water atomisation are already at a disadvantage for spheroidising due to the high cooling rates, the addition of an oxide film from reaction with the water may further inhibit spheroidisation. This will also be covered in more detail in the later sections on the specific atomisation technologies.

Powder characterisation: from particle parameters to bulk powder properties

There are very few uses for a single powder particle. Powders are mostly used in a collection of many thousands, millions, and billions of particles. The manner in which the powder behaves as a collection of these particles (e.g., flowability and packing density) is determined by the individual particle characteristics and their size and distribution of sizes. It must be noted that atomisation processes are inherently chaotic and do not produce powder in which all the particles are the same size and shape. Thus, the bulk powder needs to be described in terms of the

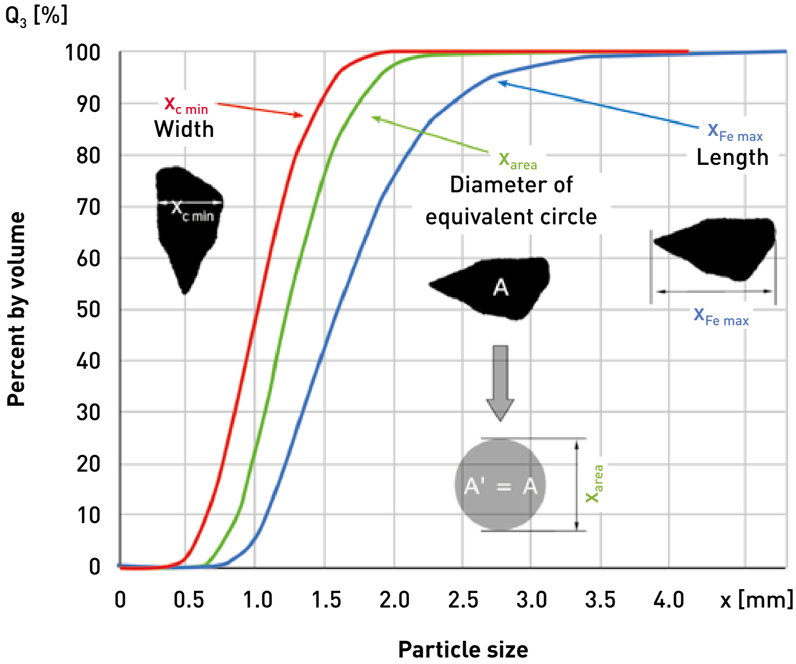

Fig. 7 Data output of a typical particle size analysis by laser scattering (Courtesy Microtrac/Verder Scientific)

statistical distribution of sizes and shapes. The powder size distribution can be measured by sieving through different size sieves, which will provide a rough histogram of the amount (weight) of powder in each size fraction. However, this method will not provide enough resolution to determine conventional size distribution parameters such as mean and median size (diameter), standard deviation, and maximum and minimum size percentages within the distribution. Instead, we must use measurement methods that are capable of measuring a sufficient number of individual particles (thousands) so that the collection can be described by conventional statistical parameters. This level of sampling and resolution requires more sophisticated techniques such as those based on laser scattering or dynamic image analysis that can measure size and shape of thousands of individual particles per test, yielding the statistical parameters used to describe the entire distribution. Fortunately, these tools are readily available to provide a description of the powder in relatively few understandable terms (although reconciling results from different instruments can be a challenge).

With respect to characterising, the particle size and the particle size range (distribution) the terms mean, median, standard deviation, and percentiles are used. There are many other descriptors, but, together, these parameters provide the particle size, the distribution, and the amount of powder in each percentile range (Fig. 7 shows the data output of

"It must be noted that atomisation processes are inherently chaotic and do not produce powder in which all the particles are the same size and shape."

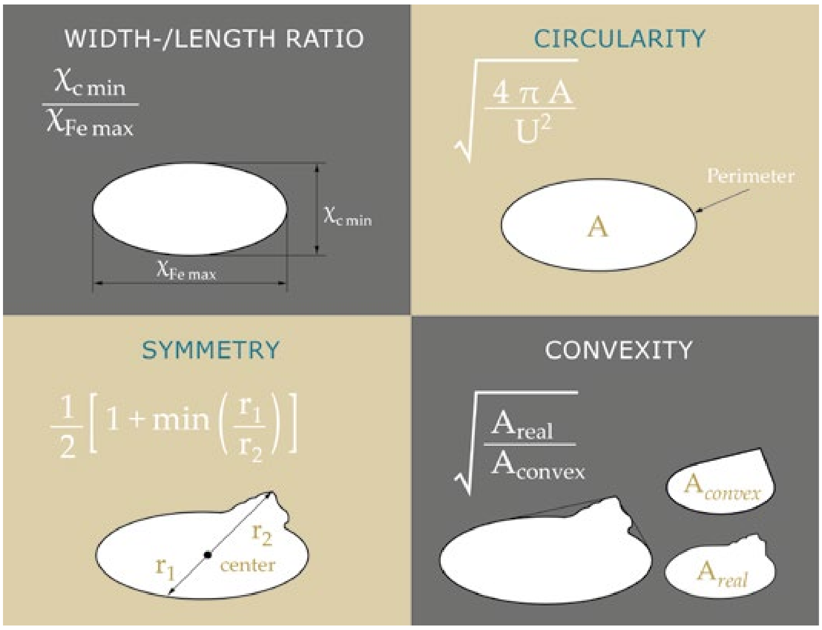

Fig. 8 A particle's morphology is commonly characterised using the sphericity parameters of radius ratio, roundness, and circularity (Courtesy Microtrac/ Verder Scientific)

a typical particle size analysis by laser scattering).

Quantifying the morphology is more difficult, as not only does the shape of one particle need to be characterised, but the shapes of the collection of particles needs to be measured as well. A particle's morphology is commonly characterised using the sphericity parameters of radius ratio, roundness, and circularity. Fig. 8 shows a schematic of some of these parameters. Again, the individual parameters are statistically tallied so we have an indication of the sphericity of the collection of powder as a whole: their mean and deviation, as well as the overall range.

Perhaps the most important, in practical terms, are the bulk properties of powder, such as packing efficiency and flowability. Packing efficiency is the measure of how well a powder fills a given volume under processing conditions. The most common tests for packing efficiency are the apparent and tap densities; the former as the density of powder loosely poured into a volume, the latter as the density after tapping the container to settle the powder. Flowability is the property that describes how the powder behaves when transported, dispensed, mixed and blended, and doctored and layered, and, in most cases, is tested by the time required for a given weight of powder to flow through a funnel with a known exit orifice size.

Particle size, size distribution, and morphology all contribute to these properties, but interparticle friction plays a significant role as well. For packing, perfect spheres take up the least unit volume and perfect mono-sized spheres can pack up to 74% of solid density if they all are in a perfect ordered arrangement, which implies that all spheres must be able to move around freely without constraint. If you add a frictional factor, the spheres cannot all move to their optimum positions and the packing-factor decreases. If the spheres are made less spherical, they no longer represent the minimum volume and the packing factor decreases.

The packing factor of powder can exceed 74% if the size distribution is widened. Smaller particles can fit in the interstices between larger particles. However, even for perfectly spherical particles, surface friction exists and each contact point is a source of frictional constraint. Thus, as the particle size distribution widens, the packing efficiency can increase but the flowability often decreases due to the increase in interparticle friction. Thus, mono-sized particles will have the maximum flowability, but at a reduced packing efficiency. In reality, mono-sized distributions in industrially used powders rarely exist but narrow particle size distributions (e.g., max/min ratio of 1.5:1) will exhibit higher flow properties than wide particle size distributions (e.g., max/min ratio of 10:1) of the same mean particle size.

As the mean particle size of the distribution decreases the inter-particle friction within the powder bulk increases so even a narrow particle size distribution around a small mean size (perhaps less than 20 µm) has poor or even no flow properties, such as in the case of most gas atomised MIM-grade powders. On the microscope scale the particles can be very spherical and the distribution may only have a total range of less than 25 µm, but, typically, powders like this will not flow, whereas a spherical powder with a mean size of 100 µm and a 25 µm total range will flow well.

So, from this introduction, the link between the mechanisms of how the particles are made and their characteristics and the behaviour of bulk powder is made. This will aid in understanding the types of powder that can be made for each atomisation technology to be discussed in the articles to come.

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Starting out in powder production: The story of Fomas Group's Mimete metal powder business

Spun out of Fomas Group in 2017, Mimete S.r.l has quickly carved out a position in the metal powder market as a provider of high-performance, gas atomised iron, nickel and cobalt-base alloy powders for metal Additive Manufacturing. But how did a company born of a forging specialist make the transition to advanced metal powder producer? In this article, Luca van der Heide speaks to senior employees from Fomas Group and Mimete, who share how the company has acquired the necessary technical expertise for powder production, providing special insight into the techniques and products they have developed to live up to the challenges of a new, fast-changing market.

In the years leading up to 2017, the international Fomas Group, a manufacturer of forgings and seamless rolled rings in steel and non-ferrous alloys headquartered in Osnago, Italy, observed a surge of interest in new manufacturing technologies, and began to conduct its own R&D into technologies that could compete with or complement its standard processes. Among the technologies investigated, Additive Manufacturing attracted the group's attention the most. As Fomas started to become aware of the great interest in metal powders for advanced manufacturing amongst its clients, it realised that powder production was the point in the metal AM value chain that was closest to its competences and resources. "We were already familiar with the melting of metals, which is the first phase of the atomisation process," explained Giulia Conti, Strategic Marketing Analyst for Fomas Group. "Seeing how many of our clients started looking at AM rather than other technologies, we decided to support them, offering our own metal powder."

The group established Mimete S.r.l. in 2017, specifically for the production of metal powders for AM. "The whole structure of the company is designed to respect the strict quality standards that industry requires for AM products," stated Conti. "At the same time, the plant, although optimised for additive, can also be used for other technologies like Hot Isostatic Pressing (HIP) and laser cladding, which makes it extremely versatile."

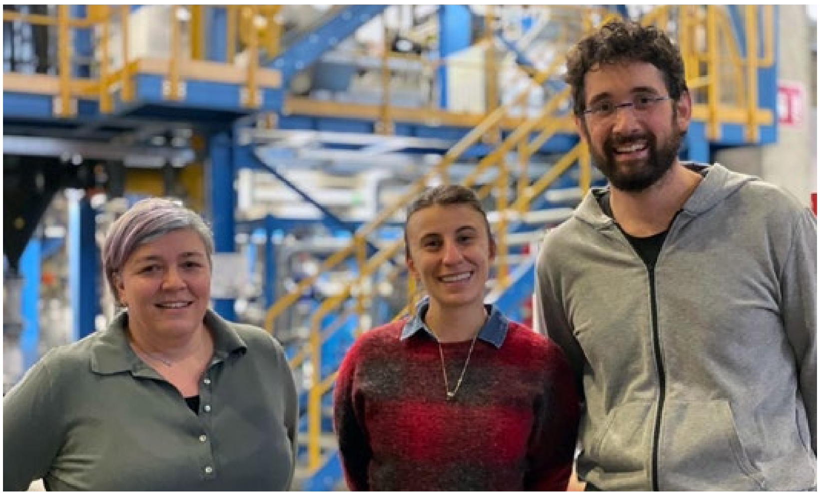

Fig. 1 From left to right: Francesca Bonfanti, Technical Development Manager, Mimete; Giulia Conti, Strategic Marketing Analyst, Fomas Group; and Andrea Tarabiono, Production Manager, Mimete

Fig. 2 Matteo Brambilla, head of Mimete's internal laboratory, checking the chemical analysis of a sample with the XRF spectrometer

The journey: challenges and objectives for Mimete

Fomas Group is used to working with hot metal, and the plastic deformation of heated metals. However, as its forging-based production started to have to compete with metal powder manufacturing technologies such as Metal Injection Moulding (MIM) and Additive Manufacturing, the company was faced with the question of how to adapt to a changing market and turn a potential threat into an opportunity. Apart from its standard operations of hot metal forging, Fomas owned an electroslag re-melting (ESR) plant in Italy. This meant that there was some synergy to be found between its preexisting expertise in melting metal feedstock and the need for atomised metal powders. Identifying this synergy was followed by extensive research by the R&D department to look for a technology that could offer great added value, and develop the technical expertise required. The result was the company's investment in AM and the construction of a powder metal production plant: Mimete.

At the beginning of Mimete's journey, the clear goal was to achieve metal powders of very complex and high-quality chemical composition that could fulfil the increasingly demanding quality requirements of Fomas's clients. This, however, presented many challenges.

"The first challenge," explained Andrea Tarabiono, Production Manager at Mimete, "was to develop the atomisation plant together with the plant manufacturer and understand the technical features of the atomising systems. We spent the first months trying different configurations, following parameters first provided by the manufacturer and then developed by Mimete's team, to find the so-called 'recipes' for atomisation." This process was especially problematic because the team was dealing not only with a new technology, but with a customised plant that presented many additional variables compared to traditional machinery. Lacking any reference for comparison, the challenge was to learn directly from the technology, in a long phase of

"The first challenge was to develop the atomisation plant together with the plant builder and understand the technical features of the atomising systems."

testing and experimentation.

As Tarabiono explains, the process of trial and error turned out to be something of an advantage, allowing Mimete to consolidate very strongly its knowledge of the parameters of atomisation, as well as parameter variations. "The most valuable thing we learned," he said, "is the knowledge of how the plant reacts to the variations of our parameters, and how to use that to our advantage. I believe the flexibility that Mimete is showing today in managing to serve a variety of sectors is owed to the fact that we had time, thanks to this very useful phase of experimentation, to understand how to modify parameters to benefit different types of market."

The ability to adapt to the demands of the market proved to be particularly important. Since its foundation, Mimete's objective to support clients in the production of special alloys has been continuously tested by the instability of a market that still hasn't reached its full potential. Although Additive Manufacturing techniques bear much promise for a variety of reasons, Giulia Conti explained, the exponential growth that was predicted did not end up being as significant as the team had expected. "The same clients who we thought would use exclusively AM technologies are today using metal powders not only for AM, but for other technologies as well. This is why we had to keep evaluating other processes like HIPing and laser cladding. The situation is more varied that we thought."

Therefore, from a company focused on one process and one type of product, Mimete was pushed by its experiences and contact with its clients to broaden its offering. Today, the company is engaged in the constant work of fine-tuning its powder recipes to raise quality standards, further increasing yields and maintaining corporate sustainability goals. "This is our daily challenge," stated Conti, "to evolve as a company to adapt to a market that is more complex than we initially envisioned."

Fig. 3 SEM equipment within Mimete's powder testing laboratory

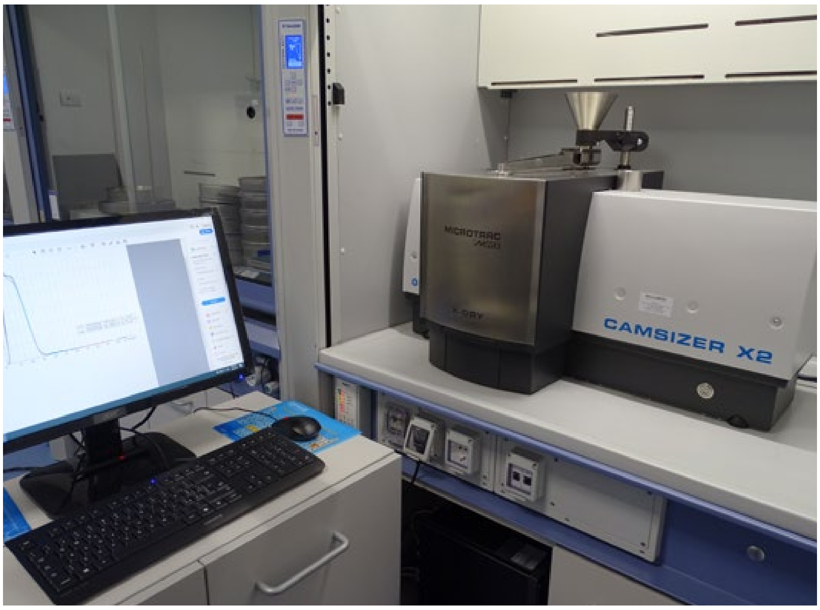

Fig. 4 Dynamic image analyser within Mimete's powder testing laboratory

Challenges for the AM sector mid-pandemic

During the COVID-19 pandemic, which has dominated the past nearly two years, the metal Additive Manufacturing sector has faced exceptional challenges. Over this period, polymer AM gained a lot of visibility for its potential, particularly in the medical sector for personal protective equipment (PPE) and rapidly produced medical spare parts, which had the positive effect of exposing the technology and showing what AM has to offer to the industry. However, while the bigger producers of metal powder managed to sustain production without substantial losses, for the smaller producers and newcomers to the technology, the two-year paralysis of the global market has resulted in a slowdown and much uncertainty.

"The fact that AM is a fundamentally new technology," commented Tarabiono, "means that before being able to reach their stability threshold, every company needs to make a considerable investment in research

Fig. 5 Mimete's VIGA plant, where its metal powders are produced

and parameter optimisation. In such a difficult period, it is hard for a producer to invest in making industrial a process that has been, thus far, confined to very specific applications. At the same time, it is easier to take a step back and rely on standard processes, validated by a longer tradition of industrial uses."

One of the main reasons for this is that the added value of AM is not widely enough understood, and, as a consequence, its costs are considered too high. For sectors like aerospace and power generation, which have a high degree of funding and resources at their disposal, and which represent two of the major client bases for the AM industry, the value AM components bring to their markets is virtually inestimable, which allows the technology to be easily recognised as being worth the investment. But more economically conservative sectors of general industry struggle to see the potential of AM, and are reluctant to invest. "What needs to happen is a shift in the mentality of designers and engineers towards recognising the value of a complex design," stated Francesca Bonfanti, Mimete's Technical Development Manager. "The customised, geometrically complex designs made possible by AM have the potential to prevent additional operations later on in the process. An example is the combination of different parts: a complex part that would normally be obtained by welding different components together can instead be made directly in the machine, as one, more complex, more optimised piece."

This does not mean that AM will supplant conventional manufacturing technologies. Once a component is made by AM, Bonfanti explains, it still must be finished and go through post-processing. In some cases, machine builders even combine additive technologies with subtractive technologies in a hybrid machine. AM is not meant or expected to overhaul pre-existent technologies, but rather to improve the industrial process by shortening production times and simplifying the production of complex components. "The integration is not only of the techniques, but of the different phases of production," said Bonfanti. "The added value of AM therefore becomes apparent when we zoom out and consider the operation in its totality, which is something that might go beyond the evaluations made by the single designer."

Atomisation technology and powders: the production process

Mimete's most important technological asset is its vacuum inert gas atomisation (VIGA) plant, in which its powder is produced (Fig. 5). After the source metal is melted in the furnace, the VIGA process turns liquid metal into particles of metallic powder that range from 1 to over 500 µm in size through a process of atomisation. Mimete chose VIGA, Bonfanti explains, because of the very high flexibility this type of atomisation offers when it comes to the types of alloys and chemical compositions that can be produced:

"VIGA makes it possible to create customised alloys, giving us maximum flexibility of production as well as the widest possible span of combinations at a chemical level," she explained. "Thanks to this technology, we can create our own recipes according to the exact chemical composition required, which is the main competence of our technicians at Mimete: to tailor chemical recipes to the specific demands of the client."

Mimete specialises in three types of alloys: nickel-base, iron-base and cobalt-base. Each alloy and its variants are suited for a specific market and application. The interest in nickel alloys, for example, in the power generation sector, relates to their mechanical properties, mainly their durability and capability to resist high temperatures. They are, therefore, ideal for applications such as turbines, which require a high level of heat resistance. On the other hand, cobalt-base alloys are required in the biomedical sector because they are the most biocompatible, and are perfectly suited for making prostheses. Iron-base alloys, typically steels, are already widely available in the industry at large, and in the context of AM, are mainly requested when a component that is normally manufactured by conventional techniques needs to be metal additively manufactured.

These alloys are now in standardised production at Mimete, but the company noted that the process of development in terms of the alloys' performance and mechanical properties is ever ongoing. "Our technical team is always at work to further improve these alloys in order to make them more processable from the point of view of additive," said Bonfanti. "This is a slow process, but already set in motion by the need of the user to achieve more highly performing powder characteristics and better processability."

Once the metal has been atomised and made into powder, the product goes through a series of very sensitive stages. First, the powder is moved into sealed containers, where the same conditions of inert gas and low oxygen level are preserved to prevent the atmosphere in the production environment from interfering with the chemical composition of the alloy. What follows are operations of selection through sifting machines that allow the powder to be sorted according to the particle sizes required; this is because particle size requirements can vary widely depending on the final application. Whilst some processes, like laser cladding, require powder particles of a hundred or more microns, and some might even encompass the whole range, industrial metal AM machines can only work within the very narrow range of about 15–45 µm.

The crucial phase of packaging and delivery then follows. Even if the product has reached this phase unharmed, the powder could still be irreversibly spoiled and arrive with different properties than those expected by the client if, for example, the powder is exposed to humidity or other environmental changes during transport. Throughout the whole process of packaging and delivery, the powder must never leave sealed containers. This is of paramount importance, and not only for the safeguarding of the powder itself, but also the operators who work with it. "The operators who handle the powder have to utilise equipment coming from the medical sector, usually employed to handle pathogenic agents," explained Tarabiono. "A production system that is required to deal with metal powders needs to take into consideration that they might be harmful to the health of those who have to make the components. In a company like Mimete, safety is a matter of absolute priority."

Fig. 6 Mimete's powder blending equipment allows the company to combine powders from different atomisation runs in order to obtain a unique and homogeneous batch of powder

Quality assurance and safety concerns

Mimete's quality assurance system, recently upgraded to meet the quality criteria of the aerospace sector, ensures that every stage of powder production is closely monitored and proceduralised. Safety steps include the chemical analysis of liquid metal and powders, as well as post-process controls of physical properties of the powder. Bonfanti commented, "The initial specifications of the client are translated into internal procedures,

Fig. 7 Mimete's equipment for measuring the physical properties of its powders

physical and chemical requisites, etc. Each phase is supervised by our internal laboratory, so that everything is always under control and nothing is overlooked."

Part of this process of strict regulation is a series of cleaning procedures of the machines to prevent what, in the world of Powder Metallurgy, is a well-known, much-feared issue: cross-contamination. Tarabiono explained the issue as follows: "If I'm first melting a cobalt-base alloy in the plant, then, shortly after, an iron-base alloy, how can I make sure not to mix cobalt with iron?" The result of blending the powders would of course be catastrophic, and clients, says Tarabiono, often require reassurance that cross-contamination could never occur. "We are often examined by clients in this respect, and we always receive positive feedback. The client knows that to check thousands of minuscule powder particles and find, let's say, three grains of cobalt on 10,000 grains of iron, is a long and complicated task. But it is a task that we have always been able to perform, simply because we have developed the correct procedures to provide an uncontaminated product."

All these procedures have the singular goal of executing the required operations in the safest environment possible. For this reason, great attention is paid to European Waste Catalogue (EWC) codes for waste disposal; waste disposal procedures are particularly problematic in the Italian legislative landscape, where waste management policies for Additive Manufacturing are only now starting to emerge. All the same, Mimete stresses that powder containers for disposal must be handled with extreme care. Despite evident legislative shortcomings in this area, the company is paying special attention to this problem and has implemented self-imposed internal regulation to keep the production process under control from start to finish. To be exact, the team specifies that waste disposal policies at Mimete follow the same regulations that are usually applied to casting and welding – manufacturing processes that are, famously, much dirtier and more wasteful than atomisation.

Circular economy

The production chain of metal powder for Additive Manufacturing embraces the concept of the 'circular economy.' In a nutshell, this means that a product, once it has been used, can be fed back into the production cycle, rather than disposed of. Thus, the feedstock that goes into the atomisation plant can come from so-called 'virgin', pure elements, or from old components kept in storage that, being at the end of their lifecycle, can be re-melted and turned back into powder. At the same time, it is also not uncommon for clients to send used pieces back to the producer for repair through toe use of an additive technology such as

Fig. 8 Glovebox equipment used for packaging of the powder

Directed Energy Deposition (DED). The result, Bonfanti remarks, is indistinguishable from the original product. "Thanks to procedures of standard metallurgy, as well as to a series of controls pre-atomisation, it is possible to obtain a product that is in every respect the same as a product derived from pure elements."

Additive Manufacturing is known as a manufacturing process that is overall more sustainable than conventional processes. Apart from being less wasteful as a technique in itself, as it works by adding material rather than subtracting from a pre-existing piece of metal, AM machines also consume less material, and components produced by AM are optimised to prevent waste and reduce energy consumption. However, as is apparent in this first stage of the production chain, AM is also, like press and sinter PM, more sustainable in terms of the entire life cycle of the product, due to the possibility of recycling the vast majority of pieces that do not make it to market.

The main markets for AM

AM mainly benefits markets that need complex designs for special applications. Markets such as aerospace, power generation, automotive racing and biomedical invest in the technology because of the specific advantages AM presents. In the case of the aerospace sector, for example, a sector where the final weight of the component is extremely important, the appeal of AM is identified in the possibility of making much lighter components – sometimes as light as a third of the conventionally-made part's weight, Tarabiono comments. Another massive market identified by Mimete is that of power generation, which, as asserted by Conti, "embraces all other powder-related technologies." Rather than lightweighting parts, this sector is interested in optimising the design of objects in order to obtain complex and more functional pieces without resorting to the welding of more pieces into one. This, in turn, saves

"Thanks to procedures of standard metallurgy, as well as to a series of controls pre-atomisation, it is possible to obtain a product that is in every respect the same as a product derived from pure elements."

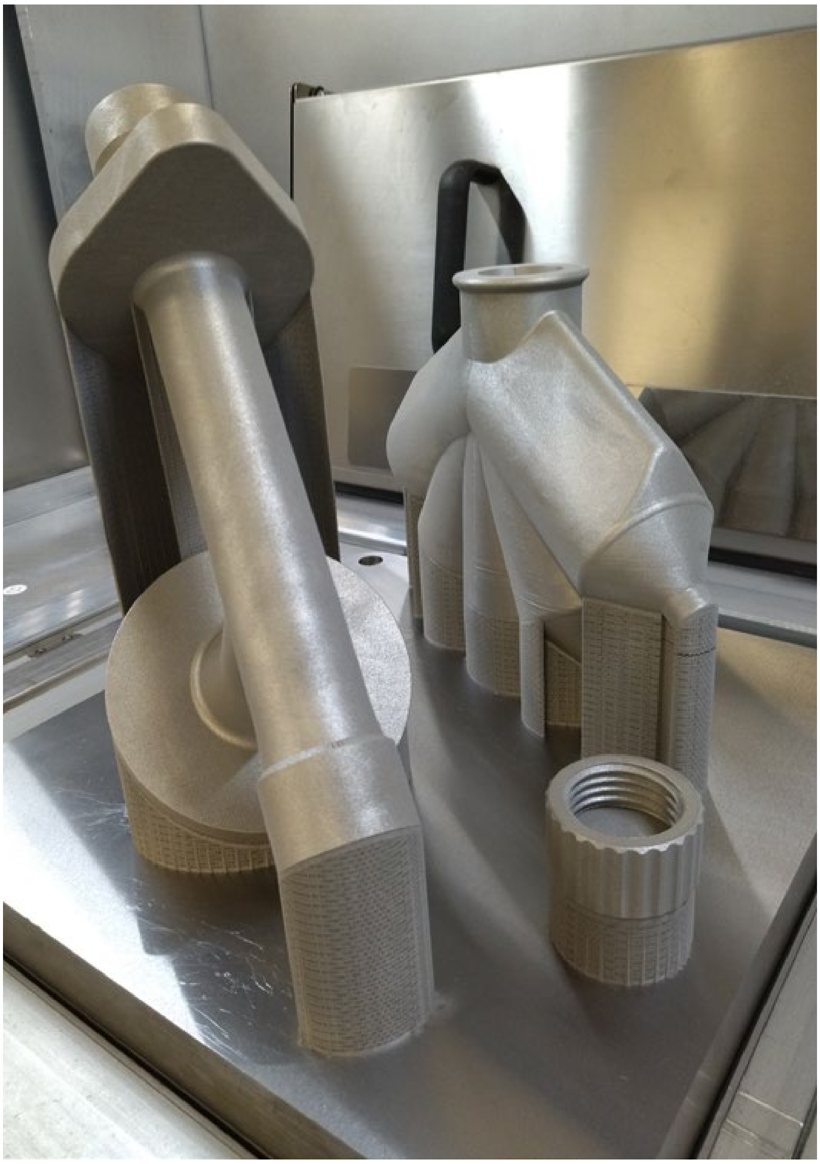

Fig. 9 Parts additively manufactured from Mimete's Mars 316L powder, a low-carbon austenitic stainless steel (Courtesy The Steel Printers SL)

production time and prevents slow-downs due to the need for additional controls in the assembly stages.

Racing is another sector where the rapidity of AM represents a major benefit. While the industrial, 'mass' automotive market is mostly exploring technologies that are more focused on the production of parts at high volumes, such as Binder Jetting, the racing sector already makes wide use of Laser Beam Powder Bed Fusion (PBF-LB) AM for reasons of lightweight, compactness of design and quick response times. Applications mainly consist of single components with geometries that are customised to fit in with other components and improve the overall performance of the system. "An example," said Tarabiono, "is the design of certain parts of the exhaust pipe of racing cars. By changing the geometry of the exhaust pipe I can create counter-pressures that have an effect on the efficiency of the engine." Equally important is the possibility to order and replace spare parts in a matter of days, instead of weeks.

Finally, a sector that has shown exceptional promise is that of biomedical applications, thanks to the possibility of building custom prosthesis for the patient, on-demand. "The irregularity of surfaces typical of AM, that in some sectors may be considered a problem," explained Bonfanti, "is in this case an advantage. Combined with the possibility to make complex designs, the prosthesis can be customised to adjust to the patient's body, providing a partially empty reticular structure where human tissue can have the space to grow. The interaction between the 3D printed component and the patient is especially strong and efficient. This is an excellent case of an AM application that is already widely recognised and put into practice."

Promising markets

Recently, the topic of spare parts has been an especially hot one in the AM landscape – one of the main reasons being the potential to manufacture parts in AM that, rather than being redesigned for additive, are simply a copy of the original piece. This means that a company might take advantage of the speed of production of Additive Manufacturing machines to produce spare parts when needed, at the expense of lightweight and optimised design. "Of course," Tarabiono specified, "this does not preclude the possibility of producing spare parts that are completely redesigned for additive and, therefore, benefit from the whole range of improved features of AM components. But this, as we at Mimete know well, would necessitate a restructuring from the ground up of the company and the methods of production – and this is not always the easiest course of action."

Similarly, in the wider sector of general engineering, and especially with regards to the production of moulds, the adoption of AM technologies is often hindered by the prospect of having to revolutionise an already-established production process. Nonetheless, the implementation of additive designs in this sector has the massive potential to overcome the many stages and long production times of making complex pieces with standard technologies. "To rethink the moulds themselves in terms of additive technology," said Tarabiono,

Fig. 10 Multiple additively manufactured Mimete Mars 316L parts on the build plate (Courtesy The Steel Printers SL)

"would mean to introduce AM in the phase of engineering. This would be a crucial step in the passage from a specialised, selective use to a use at an industrial scale."

Current projects and future challenges

Although Mimete is a small company – just over twenty people – it is part of a huge international family. While having the speed of a young and nimble company, it also benefits from the structural soundness of a large group, with the related quality and safety procedures, financial stability, and accumulated knowledge of years of successful metallurgical practices that come with it. It is into this pre-existing framework of strengths that Mimete adds its newly acquired knowledge of metal powder production for the world of Additive Manufacturing, enabling it to provide both standard powders and custom powders for special projects. For this reason, customers are likely to find in Mimete an interesting partner, especially in such a new and relatively unstable industry. In the unpredictable world of AM technologies, Mimete represents a rare marriage between a small company's reactivity and a long-standing giant's business experience and reliability.

Mimete is aware of the importance of promoting AM technologies and is currently involved in different initiatives both at the European and national level. "Except for being part of unions that cover the entire supply chain, of which Mimete represents the first link, we have projects devoted to the training of new talent and the development of new alloys," Bonfanti shared. "We are, for example, participating in an initiative that has the goal to train young scientists who possess a highly specialised knowledge of additive technology by exposing them to the work of European companies. Another project is FIAM, coordinated by top Italian AM player BEAMIT, which brings together AM-oriented Italian companies and aims to develop a new alloy in copper for special applications in the aerospace industry."

While it looks ahead with hope for the future, Mimete's team knows that the road ahead for what is still a relatively unacknowledged technology, in a still-recovering

Fig. 11 Additively manufactured parts with complex internal structures produced from Mimete's Mars M300 powder, a maraging steel (Courtesy Texer Design SRL)

global market, is going to be tough, and will require a collective effort. "Every AM company right now is trying to increase productivity," said Tarabiono. "Most of our investments, too, are currently directed towards expanding our product portfolio and equipment." But the real game-changer, Conti suggested, would be a shift in mentality radical enough to drive more significant investments into the technology. "I think the real challenge is the perception of the enormous added value of AM. Once the top players begin to seriously invest – and we are glad to see that this process is already in motion – that's when AM will have a real chance at becoming a fully industrial-ised process."

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The creation of a Powder Metallurgy market leader: China's NBTM New Materials Group Co., Ltd.

When NBTM New Materials Group announced its acquisition of Shanghai Future High-tech in January 2020, the already-vibrant Chinese PM industry shifted up a gear, accelerating the development of the country's press and sinter PM market and helping to shape the future of its Metal Injection Moulding industry. For this article, Dr Q introduces NBTM, a Chinese industry leader, and speaks to Zhu Zhirong, CEO, and Mao Zengguang, CTO, about the technical approach and management style that has allowed this company to take the lead in this competitive national market.

In January 2020, NBTM New Materials Group Co., Ltd., a major producer of press and sinter structural PM parts and soft magnetic composites, headquartered in Zhejiang, China, announced its acquisition of Shanghai Future High-tech Co., Ltd, a leading producer of parts by Metal Injection Moulding. This acquisition, combining two of China's major metal powder technology companies into one entity, ushered a new giant into the Chinese Powder Metallurgy industry, and allowed NBTM to become a major player in the global sintered parts market.

The acquisition also had a profound impact on the development of China's Metal Injection Moulding industry. Originally, Shanghai Future High-tech's focus was on the use of MIM, Ceramic Injection Moulding (CIM) and bulk metallic glasses (BMGs) to cost effectively produce small, three-dimensional, complex high-performance structural parts, including products which are widely used in smartphones, communications systems, power tools, selected automotive applications and medical devices.

Since becoming a subsidiary of NBTM, Shanghai Future has further developed its capabilities and market penetration as a manufacturer of parts for internal combustion engines (ICEs) and electric and hybrid vehicles thanks to its new parent company's expertise in the world of PM automotive parts.

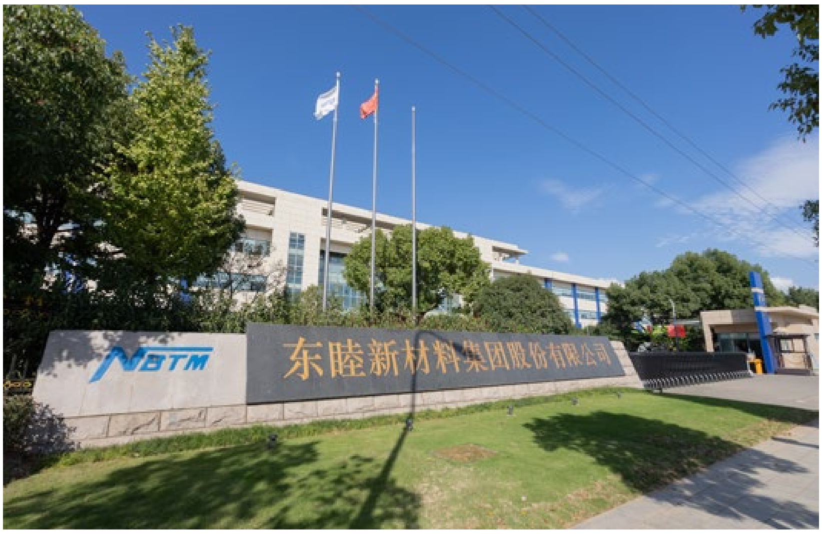

Fig. 1 NBTM's headquarters in Zhejiang, China (Courtesy NBTM New Materials Group Co., Ltd.)

Name	Location	Shareholdings	Identity
Shanghai Future High-tech Co., Ltd.	Shanghai	75% NBTM	Produces small, complex, high-performance structural components. Specialises in the MIM, CIM, and bulk metallic glass products.
Dongguan Huajing Powder Metallurgy Co., Ltd.	Guangdong	100% Shanghai Future	Produces MIM products for China
Lianyungang Future Intelligent Manufacturing Tech Co., Ltd.	Jiangsu	100% Shanghai Future	Produces MIM products servicing the Pearl River Delta.
Zhejiang NBTM Keda Magnetoelectricity Co., Ltd.	Zhejiang	60% NBTM	Produces iron cores, alloy magnetic powder cores, and other soft magnetic composite (SMC) materials production. Acts as a magnetic material scale production and technology research base. The most important production base for soft magnetic composites for NBTM.
Lianyungang NBTM New Materials Co., Ltd.	Jiangsu	100% NBTM	Produces PM parts for automotive, motorcycle, air conditioning and refrigerator compressor parts. An important low-cost, high-quality production base of NBTM.
Shanxi NBTM Huasheng Powder Metallurgy Co., Ltd.	Shanxi	75% NBTM	Produces air-conditioning compressor and automotive PM parts. It is an important production, research and development base and marketing window onto north and northwest China.
NBTM (Tianjing) Powder Metallurgy Co., Ltd.	Tianjin	100% NBTM	Produces medium and high-end air conditioning, refrigerator compressor, automotive, and motorcycle PM parts. An important regional marketing window onto the Bohai Economic Rim.
Guangdong NBTM New Materials Co., Ltd.	Guangdong	60% NBTM	Produces PM parts for air conditioning compressors and automotive, as well as copper-based PM parts. Also a large-scale PM production and technology R&D enterprise.
Changchun NBTM Fawer New Materials Co., Ltd.	Jilin	70% NBTM	Produces PM parts and automotive PM parts. Production base and marketing window of PM auto parts in Northeast China.
Nanjing NBTM Powder Metallurgy Co., Ltd.	Jiangsu	100% NBTM	Produces compressor powder metallurgical and automotive PM parts. This is the production base and marketing window in Jiangsu.

Table 1 Subsidiaries of the NBTM group

NBTM New Materials Group

Formerly known as Ningbo Powder Metallurgy Co., Ltd., NBTM was primarily engaged in press and sinter PM parts production. In January 1994, the company expanded an existing joint venture with Mutsumi Special Alloy Industry Co., Ltd., Japan, and Tongming Products Co., Ltd., China, and successively acquired Powder Metallurgy plants across China to become a large group company. At present, the group has eight subsidiaries – with the recent acquisition of Shanghai Future having added two.

Listed on the Chinese stock market, the group is considered by many to be the leader of the Chinese PM industry, and enjoys a global reputation in the Powder Metallurgy industry and relevant markets. Its portfolio of production technologies - PM, MIM, CIM and BMGs – enable it to offer parts to a diversified range of markets. Through continuous innovation, development, and research into new materials and processing technologies, the company hopes to lead the way in taking market share from traditional industrial processes, as well as replacing imports with Chinese-made products and supporting the development of emerging application areas.

Among the new application areas targeted by NBTM's press and sinter operations are the ICE vehicles, new energy vehicles, high-efficiency and energy-saving household appliances, and power tools. The company is also exploring further applications for its soft magnetic composites, including new energy vehicles, photovoltaic systems, power management systems, filters, communications products, motors, etc.

The company's PIM and BMG parts are used in applications including automotive, consumer electronics, smart wearables, medical devices, and communications products, Some advanced CIM parts are also used in medical and electronic applications. Fig. 2 shows a breakdown of NBTM's full-year turnover for 2020.

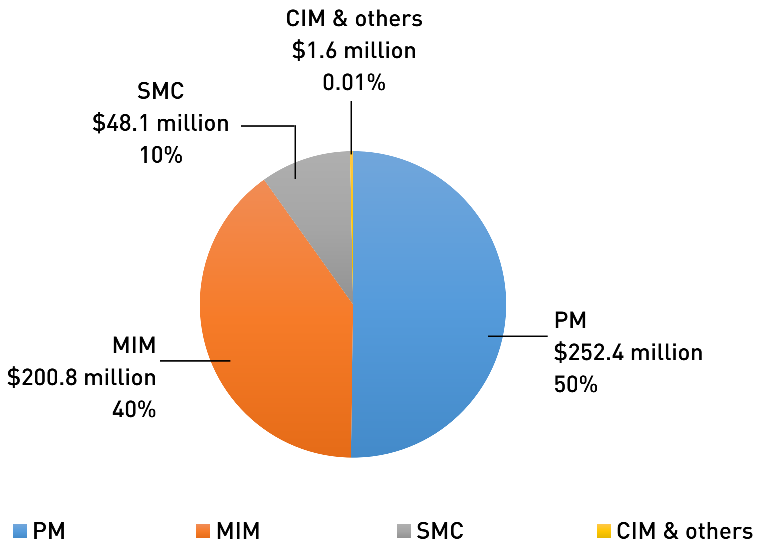

Fig. 2 Sales in 2020 of NBTM in millions of US$

A history embedded in research and innovation

NBTM has sixty years' experience in Powder Metallurgy production. As of June 2021, the company holds 168 invention patents, 430 utility patents, and thirty-four design patents, all of which are active. The company has established a National Enterprise Technical Center, with China National Laboratory accreditation, that undertakes post-doctoral research. The Zhejiang NBTM New Materials Powder Metal Research Institute is also a key regional institute.

Many employees have worked for NBTM for a lifetime – sometimes over two or three generations of a family – and one can often see the old and young work and learn together, as young talents are brought into the company to help improve its production technology and collaborate with older staff who have dedicated their careers to growing NBTM.

Fig. 3 Employees of NBTM, pictured next to a Dorst hydraulic press installed in the company's facility

"Many employees have worked for NBTM for a lifetime – sometimes over two or three generations of a family – and one can often see the old and young work and learn together..."

Fig 4. The automated sintering plant at NBTM (Courtesy NBTM New Materials Group Co., Ltd.)

Production lines and advanced products

Conventional press and sinter Powder Metallurgy is the foundation of production at NBTM. Over the decades, the company has sought to upgrade its PM production lines to include the newest and most advanced production equipment, in order to continually produce high-grade products. As shown in Figs. 4 and 5, it has what it states is the largest overall PM factory in China, capable of producing large, complex planetary gear parts, fuel cell plates, and advanced SMC bases for use in the automotive industry. A selection of the company's parts are shown in Figs. 6 and 7.

Although NBTM can be considered a traditional business, the mindset of its leadership might be considered as forward thinking and ambitious. In acquiring Shanghai Future as a subsidiary, the pace of its advanced equipment expansion and innovation technology continued: for example, the company now operates what are believed to be the most advanced six-zone temperature control vacuum debinding and sintering furnaces in China; increased production line automation and inspection have replaced a large number of manual jobs; and it is integrating its PM and MIM businesses and technologies in an attempt to improve its offerings to the 3C industry, the future automotive industry, and the medical equipment industry, as well as the manufacture and assembly of other small metal parts.

The company also continues to invest in new technologies for advanced materials processing – including BMGs and technical ceramics – to complement its PM and MIM offerings, overcome limitations in material selection and extend its service offering to customers.

"Technological competitiveness and innovation are the momentum we use to maintain NBTM's excellence. If a customer is looking for strength, detail, expansion, and attention to detail, we are always the first choice..."

Looking forward

On an Autumn afternoon in 2021, I went to NBTM's headquarters to visit Zhu Zhirong, NBTM's CEO, and Mao Zengguang, NBTM's CTO (Fig. 8). Over the course of the two-hour meeting, Zhu told me of the company's future plans, not only using its existing manufacturing technology, but also while it begins to explore Additive Manufacturing as a new method for the development of automotive components for vehicles including ICE, battery electric, hybrid and new energy vehicles.

The company's Powder Metallurgy technology is also being developed to manufacture fuel cell plates for a new generation of hydrogen energy storage solutions, posing a potential solution to China's decentralised energy storage strategy.

"Technological competitiveness and innovation are the momentum we use to maintain NBTM's excellence. If a customer is looking for strength, accuracy, expansion, and attention to detail, we are always the first choice," stated Zhu Zhirong. "In order to keep pace with our high-end customers,

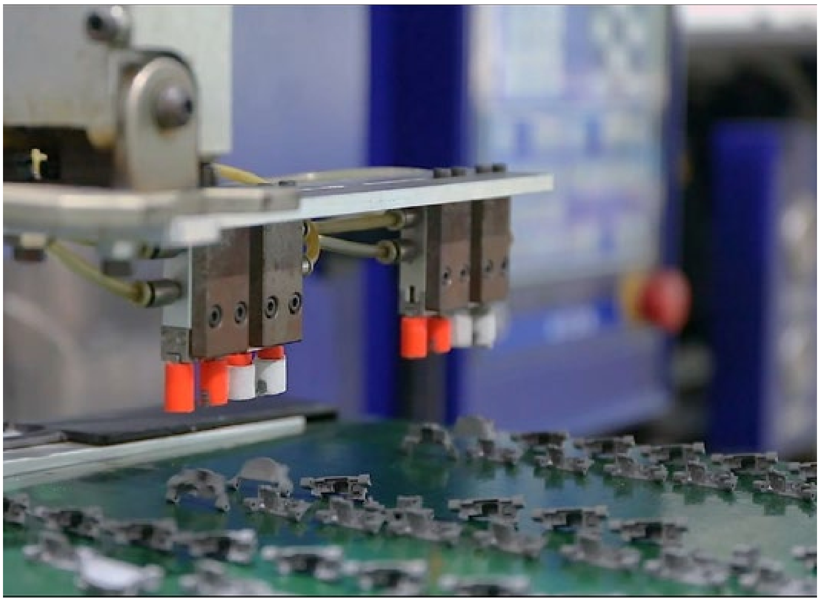

Fig 5. NBTM has adopted automation for MIM part processing in Shanghai Future High-tech's plant (Courtesy NBTM New Materials Group Co., Ltd.)

Fig 6. Ceramic injection moulded (CIM) assembly for the shell of a smart watch

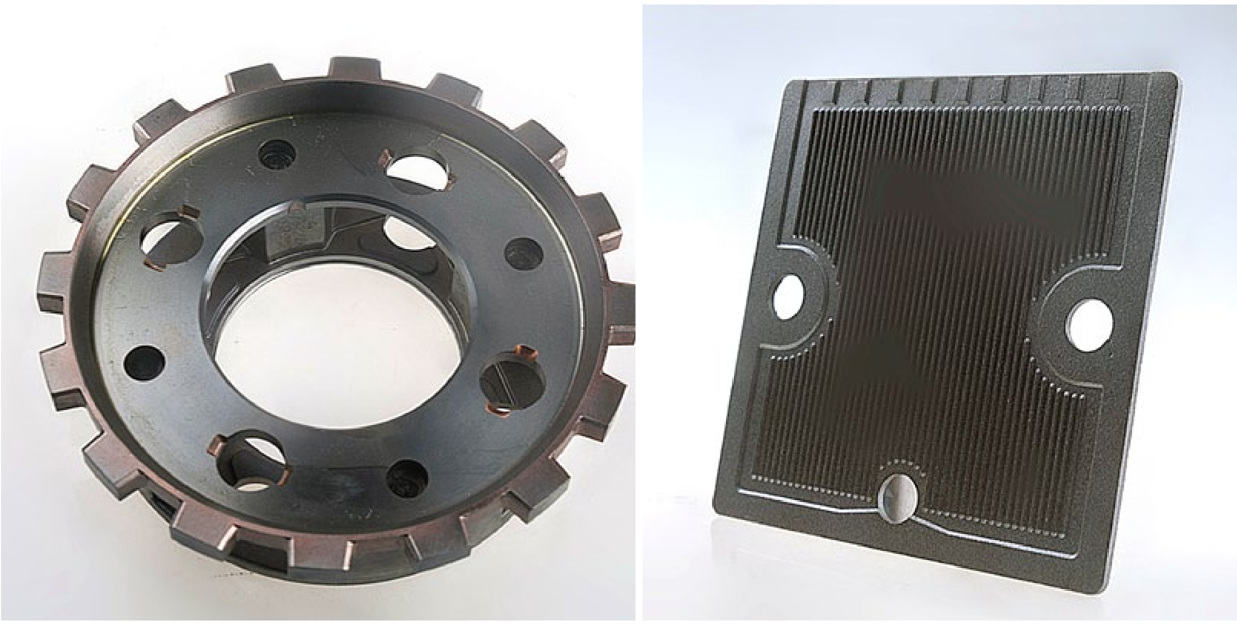

Fig. 7 Left; Large planetary gear produced by PM, Right; PM fuel cell pole-plate

Fig. 8 Top; Zhu Zhirong, NBTM CEO, talks with an employee, Bottom; Zhirong and CTO, Mao, pictured with article author Dr Q

research and development cannot stop for a moment, as the well of this technology runs deep. We do not believe in using outdated technologies and management styles here; we do what others can't do, and make the best of what they require, so that customers can't live without us. NBTM aims to make it to a hundred years of enterprise, not be a flash in the pan!"

NBTM is, by some metrics, the benchmark PM enterprise for China. Best known in the automotive domain as a parts supplier, each product produced is intended to be the greatest iteration yet. NBTM considers itself to be like a vehicle in its own right; carrying the ambitions of its staff, customers and the wider Chinese industry to explore a vast horizon.

The company's mission statement, it was explained, is "Leading through technology and innovation, providing material solutions; building a historic brand by professional and proficient craftsman spirit; realising sustainable development by sharing win-win green concepts."

www.pm-china.com

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POWDER METALLURGY REVIEW

FROM OUR ARCHIVE

JSJW NEW MATERIALS: BRINGING HIGH-QUALITY, HIGH-VOLUME SPHERICAL METAL POWDER PRODUCTION TO THE CHINESE MARKET

Based at the Powder Metallurgy Industrial Park of Taizhou City, Jiangsu Province, JiangSu JinWu (JSJW) New Materials Co., Ltd. has leveraged thirty years of research at Beijing University of Science and Technology to produce industrial volumes of high-quality spherical titanium, nickel superalloy and aluminium powders, as well as high-entropy powders, for applications including MIM, AM and PM. Dr Chiou Yau Hung (Dr Q) visited the company on behalf of PM Review and here offers an overview of how the management at JSJW has used its research expertise to advance the production and processing of challenging PM materials.

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Tungsten heavy alloys: An exploration of how key property combinations enable better mechanical performance

Applications for PM tungsten heavy alloys span from components for wristwatches and nuclear fusion plasma systems to parts for X-ray systems and eccentric vibrators. Given the huge range of applications, it stands to reason that an equally large variety of compositions, processing cycles and microstructures are used to deliver target combinations of density, strength, hardness, stiffness and conductivity in PM tungsten alloy parts. In this article, Prof Randall German reviews the relationships between key material properties used to achieve these combinations.

Tungsten heavy alloys were first produced nearly a century ago. The early high-density compositions provided radiation protection in a machinable tungsten-based material. From that start arose an array of applications combining tungsten's density and stiffness with the formability afforded by transition metal (iron, copper, nickel, cobalt) alloy matrix. Applications for tungsten heavy alloys are highly diverse; as well as those applications listed in the introduction to this article, the materials' thermal-electrical properties match the needs for semiconductor heat sinks, electro-discharge machining tools, and plasma containment structures. Still other uses arise in electrical arc erosion resistance and die casting tools and, for the past half century, a significant use has been in penetrators, munitions, projectiles, and perforation tools that require high density and high strength.

Accordingly, a large variety of compositions, processing cycles, and microstructures are used to deliver target combinations of density, strength, hardness, stiffness, and conductivity. Some of the key property combinations are introduced in this article.

What are tungsten heavy alloys?

It is common to abbreviate tungsten heavy alloys as WHA – where W is the chemical symbol for tungsten. With respect to properties, there is considerable sensitivity to the processing

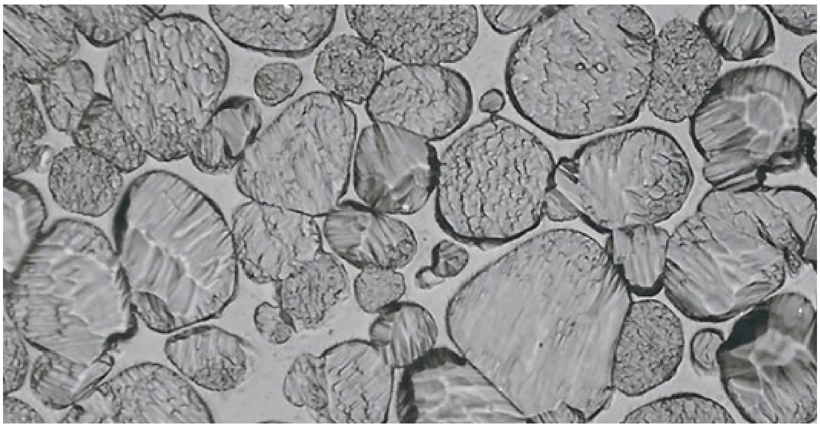

Fig. 1 Cross-section micrograph of a 95W-4Ni-1Fe tungsten heavy alloy after sintering. The rounded body-centred cubic tungsten grains are etched while the solidified matrix phase is seen in the gaps between the grains. The average tungsten grain is 30 μm in diameter. The tungsten grains are surrounded by a face-centred cubic matrix alloy consisting of nominally 54Ni-23Fe-23W

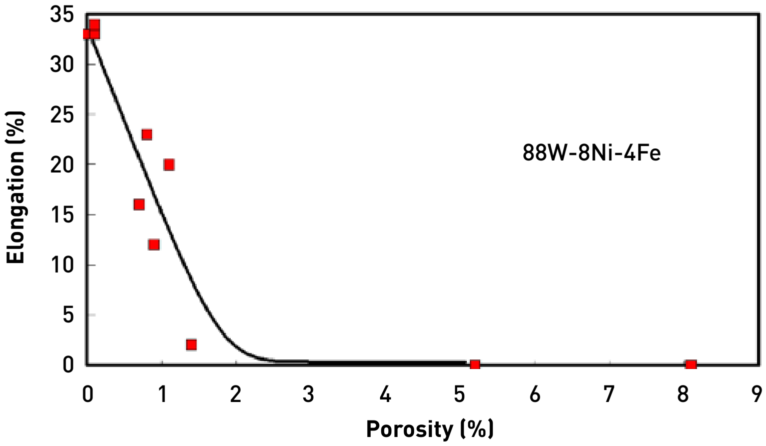

Fig. 2 Ductility data versus residual porosity for an 88W alloy heated to 1500°C and held at that sintering temperature during densification. Samples were quenched during sintering densification to monitor mechanical properties versus porosity

variables. In short, essentially everything is important. Impurities in the powder interact with sintering variables to change the microstructure. In turn, microstructure along with impurity segregation dramatically change mechanical properties. Heat treatments are employed to modify impurity segregation, while deformation and strain ageing trade ductility for strength. The resulting processing-microstructure-property links are well recognised. This knowledge allows for balancing property combinations to optimise component performance, including concerns ranging from toxicity, fracture toughness, notch sensitivity, hydrogen embrittlement, elastic modulus, conductivity, and hardening response.

Currently, WHA samples are being liquid phase sintered under microgravity conditions to quantify high temperature viscous flow models needed to understand distortion during sintering. As part of this research on the International Space Station, issues associated with pore stability and resistance to densification in microgravity are most evident.

Hold time (min)	Strength (MPa)	Elongation (%)
0	725	0
1	861	5
3	904	7
5	990	16
10	954	16
15	961	19
30	954	27
45	946	26
60	933	17
90	769	7
120	774	0

Table 1 Tensile strength and elongation for 90W-7Ni-3Fe sintered at various hold times at 1475°C in hydrogen

Background

Tungsten heavy alloys are two-phase metallic composites. They are fabricated by liquid phase sintering tungsten using molten matrix alloys. Sintering forms a three-dimensional skeleton of bonded tungsten grains (body-centred cubic) surrounded by a face-centred cubic transition metal matrix alloy. Several matrix alloy options are possible, including nickel-iron, nickel-copper, nickel-cobalt-iron, nickel-copper-manganese, and copper-cobalt.

Most of the composition reports cite the starting powder composition, but processing often loses some of the ingredients. For example, 5 wt.% nickel in the powder mixture results in 4.5 wt.% nickel in the sintered composite. For this reason, caution is needed as formulations tend to shift during sintering, especially for volatile alloying ingredients such as copper and manganese; in turn, the tungsten content in the final product tends to be higher than the starting formulation. Some of the composition change is due to segregation in handling loose powders. Tungsten powder is significantly different from the matrix powders; segregation occurs due to differences in particle density, particle size, and particle shape. Separation and stratification are especially problems in powder transfer, discharge, and loading into forming moulds.

The unique property combinations associated with WHA systems derive from the characteristic microstructure consisting of single-crystal grains bonded to one another to form a skeletal structure. The matrix alloy is interlaced around the tungsten grains. Fig. 1 shows the microstructure of a 95W-4Ni-1Fe alloy after sintering. Considerable grain growth occurs so each of these approximately 30 μm single crystal tungsten grains represents about 8000 starting tungsten particles.

The matrix between the tungsten grains is a face-centred cubic nickel-iron alloy containing dissolved tungsten. Both phases are continuous. This is important to both thermal and electrical conduction. The tungsten skeleton provides rigidity, stiffness, and arc erosion resistance. The matrix phase provides toughness and load transfer during deformation to enable ductility.

Cycle	Atmosphere	Elongation [%]
As-sintered	Hydrogen	5
Reheat and furnace cool	Hydrogen	5
Reheat and water quench	Hydrogen	20
Reheat and furnace cool	Argon	9
Reheat and water quench	Argon	26

Table 2 Comparative processing cycles and atmospheres with respect to tensile elongation for 95W-3Ni-2Fe

Processing

The WHA structure is formed by heating mixed elemental powders to a temperature where a liquid phase appears. This liquid might form as low as 1200°C for copper-containing alloys, and reaches to 1500°C for nickel-iron-cobalt alloys. Considerable sintering densification occurs in the solid state during heating. This is known as activated sintering. However, full density and high mechanical properties come from a final densification burst that occurs on liquid formation, usually within minutes after the liquid forms. During liquid phase sintering, the mass transport rate in the liquid is much faster, typically a hundred-fold, versus solid state diffusion. Thus, as long as there is tungsten solubility in the liquid matrix, final densification is rapid.

Similar ideas of fast liquid phase sintering are used throughout Powder Metallurgy – for example, in the fabrication of automotive components from iron-copper-carbon mixtures, oilless bearings from copper-tin mixtures, wear components from titanium carbide and tool steel composites, permanent magnets from slightly off-stoichiometry $Fe_{14}Nd_2B$ powders, and metal cutting tools formed using tungsten carbide and cobalt (WC-Co).

Besides composition variations, microstructure is adjustable by processing changes. In turn, those microstructure and composition changes are accompanied by processing variations that allow for considerable manipulation of final sintered properties. For high mechanical properties, most tungsten heavy alloys are subjected to post-sintering treatments, including deformation by swaging, rolling, extrusion, or forging. These efforts result in elongated tungsten grains, leading to anisotropic properties. However, deformation-induced strength gains are accompanied by a ductility loss, so post-sintering deformation is followed by a heat treatment to tailor the strength-ductility-toughness combination. In effect, WHA processing schedules are similar to steel schedules, where various attributes are optimised by prescribed heating, hold, and cooling cycles.

For inertial applications, the as-sintered condition is suitable, such as in wristwatch weights and golf club weights. In spite of tungsten being brittle at room temperature, the tungsten heavy alloys are able to deliver surprisingly high levels of ductility and toughness. Much more detail on the properties and processing-composition-microstructure links are given in a new publication. The Metal Powder Industries Federation recently published the *Tungsten Heavy Alloy Handbook*, written by this author. It is 458 pages, and based on nearly a thousand research reports. That compilation offers considerable detail on the powders, alloys, shaping and consolidation options (including injection moulding and Additive Manufacturing), binder and lubricant removal, sintering, post-sintering deformation, heat treatment and strain ageing treatments, and considerable detail on the microstructure and the findings from quantitative microscopy. Here, a portion of that structural (mechanical property) information is reviewed.

Properties

When sintered to full density, tungsten heavy alloys are high in both strength and ductility. Depending on the processing details, optimal properties might require post-sintering treatments to manipulate impurity segregation away from the tungsten-matrix interface. Repeated studies report more than 20% tensile elongation at fracture (slow strain rate, room temperature) for tungsten contents up to 95 wt.%; even at 97 wt.% tungsten, an elongation of 18% is attainable. Lower ductility arises with work hardening or embrittlement from one of several factors.

Sintering to full density is the necessary first criterion for good properties, but full density is not sufficient for optimal ductility, toughness, or strength. One factor is intermetallic precipitation during slow cooling from the sintering temperature. Also, impurities, and even hydrogen, segregate to interfaces during slow cooling, leading to reduced ductility and strength. A special problem derives from the starting powder, since most tungsten carries oxygen that is released during dissolution into the matrix as part of sintering (note the considerable grain growth occurs due to a solvation and reprecipitation cycle) and, if not properly removed, it can react or segregate to degrade properties.

Porosity

Porosity is a significant factor. Residual pores arise from incomplete densification and fill with carbon-oxygen or hydrogen-oxygen vapour

Composition	Time [min]	Temperature [°C]	Atmosphere	Cooling
90W-5Ni-5Fe	60,000	750-850	Argon	Quench
90W-5Ni-5Fe	60	1350	Vacuum	Quench
90W-6Ni-2Fe-2Co	120	1150	Vacuum	Quench
90W-7N-3Fe	11	600	Vacuum	≈3°C/min
90W-7Ni-2Fe-1Co	30	1100	Argon	Quench
90W-7Ni-3Fe	180	1100	Wet hydrogen	≈3°C/min
90W-7Ni-3Fe	60	1200	Argon	Rapid cool
92W-8Ni-0.1Fe	432,000	850	Vacuum	Slow cool
93W-5Ni-2Fe	480	1150	Nitrogen	Quench
93W-5Ni-2Fe	60	1150	Nitrogen	Quench
93W-6Ni-1Fe	60	1150	Nitrogen	Quench
93W-6Ni-1Fe	20 x 3 min cycles	1150	Nitrogen	Quench
95W-4Ni-1Fe	60	1000	Argon	Quench
95W-4Ni-1Fe	30	1350	Vacuum	Quench
96W-3Ni-1Fe	15	800	Vacuum	40°C/min

Table 3 Example post-sintering treatments applied to WHA systems

species (CO, CO_2, H_2O) to become stable, causing premature fracture. Just 0.5% porosity is sufficient to significantly lower ductility. This is illustrated by the data from an 88 wt.% tungsten alloy in Fig. 2: tensile elongation is plotted versus residual porosity after sintering a 88W-8Ni-4Fe alloy. At full density (16.67 g/cm^3), this alloy delivers almost 35% elongation and a tensile strength near 885 MPa.

Even when sintered to full density, rapid cooling prior to matrix solidification produces liquid-to-solid volume contraction on solidification. The resulting matrix phase solidification pores degrade properties. Thus, fast cooling from the sintering temperature is detrimental to as-sintered properties. On the other hand, slow cooling allows liquid migration along thermal gradients to avoid pore formation. But with slow cooling, the impurity segregation to the tungsten-matrix interface becomes a problem.

A related difficulty to under-sintering, and failure to remove all pores, is over-sintering. This is a problem where pores nucleate after reaching near full density. With moderate sintering times, the strength and ductility improve, but then fall with longer sintering times or higher sintering temperatures. Table 1 gives tensile results for a 90W-7Ni-3Fe heavy alloy versus hold time when sintering at 1475°C, illustrating the embrittlement associated with a long sintering time.

Oxygen content

Besides residual pores, other factors cause low ductility. Accordingly, various treatments are employed to avoid or offset embrittlement. For example, oxygen is in the starting powders and if this oxygen is retained to high temperatures it leads to embrittlement. Oxygen is removed via slow heating in hydrogen with intermediate temperature holds prior to pore closure. The final oxygen level is measured infrequently, but reaches up to nearly 200 ppm for 92W-6Ni-2Fe after sintering at 1480°C for 90 min in dry hydrogen. When reacted with hydrogen to form in-situ steam vapour, that 200 ppm oxygen level is sufficient to blister the component. Slow heating in a dry hydrogen atmosphere with a shift at peak temperatures to a wet hydrogen atmosphere is one of the processing tricks used to minimise detrimental oxygen effects.

Matrix alloy composition

Matrix alloy composition is another factor. This includes too little matrix phase or a matrix devoid of nickel; nominally, at least 35% nickel in the matrix is recommended. Ductility versus tungsten content shows a nominal effect of tungsten content. Here are the upper elongation levels for several tungsten contents (the alloying here consists of 7 parts nickel to 3 parts iron; 7Ni:3Fe):

- 35% elongation at 70W
- 35% elongation at 83W
- 37% elongation at 88W
- 35% elongation at 90W
- 36% elongation at 93W
- 35% elongation at 95W
- 19% elongation at 96 W
- 23% elongation at 97W
- 0% elongation at 99.5W

Composition	Deformation area reduction [%]	Ageing [°C, min]	Hardness [HRC]	Tensile strength [MPa]	Elongation [%]
86W-4Mo-7Ni-3Fe	18	500, 180	45	1440	1
90W-6Ni-2Fe-2Co	40	none	51	1430	9
90W-6Ni-2Fe-2Co	75	none	56	1646	6
90W-7Ni-3Fe	18	500. 180	45	1420	2
90W-7Ni-3Fe	30	none	45	1150	9
90W-7Ni-3Fe	50	400, 60	54	1580	1
91W-6Ni-3Fe	30	none	41	1211	12
92W-5Ni-3Fe	30	none	50	1400	1
93W-5Ni-2Fe	15	600, 60	51	1310	5
93W-5Ni-2Fe	18	none	41	1205	10
93W-5Ni-2Fe	20	none	40	1174	10
93W-5Ni-2Fe	25	500, 60	44	1400	7
93W-5Ni-2Fe	80	none	48	1570	7
96W-3Ni-1Fe	---	1000, 60	45	1454	15
96W-3Ni-1Fe	10	none	38	991	10
96W-3Ni-1Fe	18	none	40	1103	6
96W-3Ni-1Fe	95	1000, 60	45	1454	15

Table 4 Examples of deformation and ageing response for several WHA compositions

The top entries show elongation near 35–37% for compositions with less than 96 wt.% tungsten. Tungsten contents in the 96% range and higher are inherently less ductile and sintered pure tungsten is brittle at room temperature. Likewise, alloys lacking nickel are brittle – such as WCuCo alloys.

Impurity segregation

Impurity segregation is another factor. After sintering, reheating to 1000 to 1100°C followed by water quenching freezes impurities into solution. Dramatic ductility and impact toughness gains are associated with rapid cooling from near 1000°C. Indeed, even rapid cooling in hydrogen improves ductility. This is demonstrated in experiments using 95% tungsten as summarised in Table 2. Contrary to folklore, 'hydrogen embrittlement' does not result in brittle behaviour.

Likewise, data on a 90W-7Ni-3Cu alloy also illustrate the hydrogen role and its reversibility via the post-sintering heating atmosphere:

- The elongation after hydrogen sintering at 1460°C is 5%
- Heat treating at 1000°C in hydrogen decreases elongation to 4%
- Heat treating at 1000°C in vacuum increases elongation to 21%
- Reheating in hydrogen reverts elongation to 3%

Such observations are often interpreted as evidence of hydrogen embrittlement. This is wrong, since the studies fail to gather data on impurity level and cooling rates. Without such analysis, it is not possible to separate impurity segregation from hydrogen embrittlement. Such confounded results are typical in WHA studies. It is common to assign low ductility to hydrogen effects without confirmation data; for example, low ductility in a 90W-7Ni-3Co composition is simply assigned to hydrogen embrittlement. However, the underlying processing relied on a slow cooling rate that allowed for segregation and intermetallic precipitation which embrittled the alloy, independent of the hydrogen role.

Impurities go into solution in the matrix during a high-temperature anneal. Quenching in oil or water freezes the impurities in solution and avoids interface segregation. The removal of hydrogen also provides property gains, but the largest ductility gain comes from avoiding impurity segregation. Maximum properties arise from specific combinations of composition, sintering cycles, deformation, and heat treatment. In this context, some of the empirical post-sintering heat treatment cycles are compared in Table 3.

Although there is no consensus as to which heat treatment is optimal, some generalisations are possible:

- The heat treat atmosphere should be inert – vacuum, argon, or nitrogen

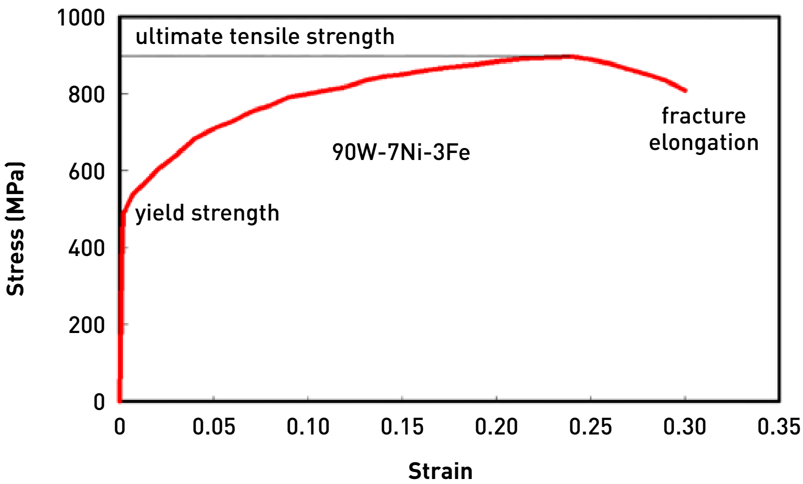

Fig. 3 Room temperature tensile stress-strain curve for a 90W-7Ni-3Fe composition, tested at a low strain rate at room temperature

- The peak temperatures range from 600 to 1350°C, with 1100 to 1200°C being most common
- Hold times at the peak temperature range from 15 min to 1000 hours or more, but a hold of about 60 min seems sufficient (but longer times might be required for thick sections)
- Slow cooling is required from the sintering temperature to below the matrix solidus to avoid solidification pores
- Quenching is typical as the last step in the cycle, usually from about 1100°C

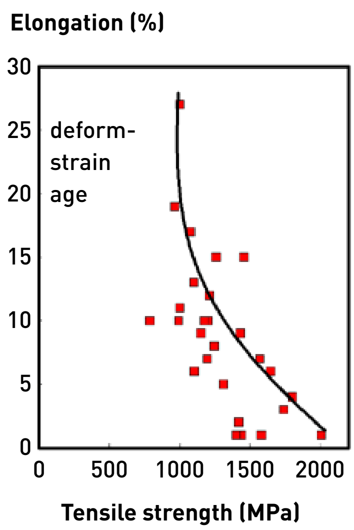

Fig. 4 Scatter plot of strength-ductility results from several studies

Sintering temperature [°C]	Hardness [HV]
1450	379
1475	390
1500	377
1525	378
1550	393

Table 5 Sintering temperature has a small effect on hardness for 93W-6Ni-1Co; the average hardness is 383 HV and typical scatter is ± 10 HV

Ductility range	Cases	Tensile strength [MPa]
Below 12% elongation	28	850
12 to 24% elongation	60	945
Over 24% elongation	47	946

Table 6 Summary on how elongation to fracture impacts the average reported ultimate tensile strength

In turn, some example mechanical properties from post-sintering deformation and heat treatment cycles are offered in Table 4.

Mechanical properties

It is clear that mechanical properties provide the most important assessment of proper processing. Tensile properties are most important. Over a range of compositions, the typical as-sintered WHA microhardness is 325 HV, corresponding to an average yield strength of 620 MPa. A typical ratio of yield strength (in MPa) to microhardness (in HV) is 1.9. When several tensile samples are tested under the same conditions, the strength repeatability is ± 20 MPa (about 2 to 3% of reported value), ductility is ± 5% (3 to 10% of the reported value), and hardness is about ± 0.5 HRC or ± 5 HV.

Fig. 3 is a stress-strain curve for 90W-7Ni-3Fe. In this case the yield strength is near 500 MPa at 0.34% strain, tensile strength is near 900 MPa at 24% strain, and elongation to fracture is more than 30%. From the onset of necking (24% elongation), the tensile bar experiences a reduction in cross section area, giving another ductility parameter calculated from the change in cross-section area normalised to the initial cross-section area. This area reduction parameter is not useful in design calculations. On the other hand, the yield strength is useful in setting an upper limit design stress.

Although correlations between strength and ductility are proposed for some WHA alloys, the overall behaviour is scattered and lacks statistical significance. Over a broad range of WHA compositions, the maximum elongation is about 35–37%, and the corresponding tensile strength is 900–1000 MPa, about where Fig. 4 shows asymptotic behaviour. The peak reported strength is near 2000 MPa, with essentially no ductility.

Trials with 93W-6Ni-1Co illustrate how hardness has a low sensitivity to sintering temperature (as long a liquid phase sintering induces full density). This is summarised in Table 5 for 30 min hold. This alloy delivers a higher hardness versus the typical 325 HV. Deformation increases hardness so higher values come from combinations of alloying, deformation, and heat treatment.

If there is low ductility, then the ultimate tensile strength suffers and corresponds to the stress at fracture. With high ductility, fracture occurs after passing through the ultimate tensile strength. Thus, once the elongation reaches 12 to 24%, further ductility gains have no impact on tensile strength. Out of several reports on as-sintered mechanical properties, Table 6 summarises a few representative tensile strength and elongation reports for alloys ranging from 70-98 wt.% tungsten. The overall average from 135 reports is 645 MPa yield strength, 925 MPa tensile strength, and 20% elongation.

Most mechanical property reports are after a hydrogen removal treatment. The treatment can be integrated into the cooling portion of the sintering cycle, but, in many cases, a separate annealing cycle is performed. With hydrogen removal the WHA compositions are high in strength and ductility. Table 7 gathers tensile properties for a range of ductile compositions. Most of these determinations are from net-shaped test bars. Only a few cases reflect machined samples taken from large blocks. In the latter case, the attainable mechanical properties are lower due to poor control of the cooling cycle to minimise impurity segregation.

The most important compositions are near 93 wt.% tungsten, where yield strength averages 650 MPa, tensile strength averages 947 MPa, and elongation averages 22%. Test results span a much larger composition range, from 70 to 98 wt.% tungsten. Over that extended composition range, the summary statistics are shown in Table 8. For hardness, the reports were all converted to the Vickers scale (HV).

Composition	Yield strength [MPa]	Tensile strength [MPa]	Elongation [%]	Hardness
18W-53Ni-29Fe*	184	417	63	124 HV
23W-54Ni-23Fe*	230	500	58	---
70W-20Ni-10Co	586	1123	35	30 HRC
70W-21Ni-9Fe	560	970	25	30 HRC
70W-21Ni-9Fe	565	983	30	30 HRC
74W-16Mo-7Ni-3Fe	892	1145	7	69 HRA
74W-16Mo-8Ni-2Fe	843	1150	10	68 HRA
78W-12Mo-8Ni-2Fe	773	1119	14	67 HRA
82W-8Mo-7Ni-3Fe	715	1030	20	66 HRA
82W-8Mo-8Ni-2Fe	688	1067	27	64 HRA
82W-8Mo-8Ni-2Fe	775	1144	8	68 HRA
82W-8Re-7Ni-3Fe	1530	1560	0	507 HV
83W-12Ni-5Fe	674	987	35	62 HRA
84W-7Ni-6Re-3Fe	815	1180	14	69 HRA
85W-7Ni-5Ta-3Fe	740	1025	3	62 HRA
86W-7Ni-4Mo-3Fe	625	987	24	64 HRA
86W-8Ni-4Re-2Fe	775	1115	14	68 HRA
86W-8Ni-4Re-2Fe	780	1125	13	68 HRA
88W-7Ni-3Fe-2Mo	570	945	28	63 HRA
88W-8Ni-4Fe	560	885	33	63 HRA
88W-8Ni-4Fe	565	908	37	63 HRA
90W-4Ni-4Fe-2Co	708	930	7	29 HRC
90W-5Ni-5Fe	717	925	13	27 HRC
90W-6Ni-4Cu	620	758	8	24 HRC
90W-6Ni-4Mn	800	920	6	---
90W-7Ni-2Fe-1Co	560	885	22	320 HV
90W-7Ni-3Fe	530	920	30	62 HRA
90W-7Ni-3Fe	540	800	5	280 HV
90W-7Ni-3Fe	575	927	30	64 HRA
90W-7Ni-3Fe	577	881	29	63 HRA
90W-7Ni-3Fe	586	938	35	31 HRC
90W-7Ni-3Fe	593	914	31	63 HRA
90W-7Ni-3Fe	593	914	31	63 HRA
90W-7Ni-3Fe	621	891	21	310 HV
90W-7Ni-3Fe	650	910	25	25 HRC
90W-8Ni-2Cu	600	850	6	300 HV
90W-8Ni-2Fe	551	918	36	64 HRA
91W-6Ni-3Co	820	1160	33	32 HRC
91W-6Ni-3Fe	600	870	22	285 HV
91W-6Ni-3Fe	619	896	37	27 HRC

Table 7 Compilation of room temperature, slow strain rate mechanical properties for sintered and annealed WHA compositions, continued overleaf

Composition	Yield strength [MPa]	Tensile strength [MPa]	Elongation [%]	Hardness
92W-3Mo-3Ni-2Fe	-	979	17	64 HRA
92W-4Ni-2Mo-2Fe	620	888	12	64 HRA
92W-4Ni-4Fe	753	1026	8	27 HRC
92W-6Ni-2Fe	631	911	24	314 HV
93W-3Ni-3Fe-1Al	567	908	16	34 HRC
93W-3Re-3Ni-1Fe	844	886	1	400 HV
93W-4Ni-2Fe-1Co	650	920	34	28 HRC
93W-4Ni-2Mo-1Fe	620	888	12	64 HRA
93W-5Ni-2Fe	590	903	31	64 HRA
93W-5Ni-2Fe	593	914	31	63 HRA
93W-5Ni-2Fe	596	983	21	64 HRA
93W-5Ni-2Fe	603	856	25	64 HRA
93W-5Ni-2Fe	616	886	16	335 HV
93W-5Ni-2Fe	620	758	12	26 HRC
93W-5Ni-2Fe	649	923	29	28 HRC
93W-6Ni-1Co	780	1035	20	380 HV
93W-6Ni-1Fe	600	965	35	31 HRC
95W-3Ni-1Fe-1Co	630	916	27	30 HRC
95W-3Ni-1Fe-1Pd	626	908	27	30 HRC
95W-3Ni-2Fe	600	850	12	300 HV
95W-3Ni-2Fe	642	924	26	29 HRC
95W-4Ni-1Cu	585	861	7	27 HRC
95W-4Ni-1Fe	575	845	17	64 HRA
95W-4Ni-1Fe	600	818	8	350 HV
95W-4Ni-1Fe	602	919	19	65 HRA
95W-4Ni-1Fe	620	900	23	365 HV
96W-3Ni-1Fe	600	972	26	32 HRC
96W-3Ni-1Fe	640	930	26	29 HRC
97W-2Ni-1Cu	600	660	3	64 HRA
97W-2Ni-1Fe	594	701	4	340 HV
97W-2Ni-1Fe	612	889	15	65 HRA
97W-2Ni-1Fe	620	750	8	310 HV
97W-2Ni-1Fe	620	883	10	28 HRC
97W-2Ni-1Fe	640	836	13	305 HV
97W-2Ni-1Fe	649	929	18	30 HRC
97W-2Ni-1Fe	700	735	4	30 HRC
98W-1Ni-1Fe	509	510	1	63 HRA
*intended to be pure matrix alloy				

Table 7 Compilation of room temperature, slow strain rate mechanical properties for sintered and annealed WHA compositions

Excluding the matrix alloy tests, the ultimate tensile strength is over 1000 MPa in about 20% of the studies. Efforts to correlate the tensile strength with elongation found no correlation; the correlation coefficient is just 0.06.

To sense the uniformity of these properties, consider the 93W-5Ni-2Fe composition. The average yield strength is 649 MPa (ranging from 593 to 814 MPa), average tensile strength is 974 MPa (ranging from 758 to 1185 MPa), and elongation averages 23% (ranging from 13 to 37%).

The tabulation shows 30% or more elongation is reported for more than 20% of the cases, mostly for compositions up to 95 wt.% tungsten. Above 75 wt.% tungsten, the average is 20% elongation, and this includes the low values at 97 and 98 wt.% tungsten.

For compositions with more than 75 wt.% tungsten, the yield strength averages 645 MPa and the ultimate tensile strength averages 919 MPa. The maximum yield strength occurs in the 90 to 95 wt.% tungsten alloys, with a few reports near 800 MPa in the absence of deformation treatments.

For the ultimate tensile strength, values over 1100 MPa are reported for compositions from 70 to 91 wt.% tungsten. Fracture prior to achieving the uniform elongation limits the ultimate tensile strength, resulting in lower strength at 97 to 98 wt.% tungsten.

The data do not support a strength-ductility correlation. The overall regression gives 0.00 correlation between ultimate strength and elongation and 0.07 correlation for yield strength and elongation. For some alloys there is a negative correlation between yield strength or tensile strength and elongation; higher yields strengths correspond to lower ductility. Likewise, a nickel to iron ratio near 4 gives the highest strength (not 2.3, as commonly presumed). For the popular W-Ni-Fe compositions, the sintered and annealed tensile strength is typically in the 1000 MPa range.

Efforts to adjust mechanical properties rely on alloying and precipitation hardening. In some cases, solution softening is reported, although typically strengthening is sought. Alloying with molybdenum or cobalt is a common approach to increase strength. However, the gain is minor. For example, 1 wt.% added cobalt is inconsistent in improving tensile strength. For 95W-3Ni-2Fe, the yield strength is 642 MPa and tensile strength is 924 MPa. Adding 1% Co decreases yield strength to 630 MPa and tensile strength to 916 MPa. Considering the natural variations in strength testing, that 8 to 12 MPa difference is not significant.

Microstructure models rationalise the mechanical properties to factors such as the contiguity, tungsten volume fraction, grain size, and mean free path between tungsten grains. The models are restricted to narrow composition ranges. For the W-Ni-Fe alloys, ductility declines at the high tungsten contents, especially more than 94 wt.%. This traces to the tungsten-tungsten contiguity, causing a fall to zero elongation when the contiguity reaches 0.8.

Some compositions are brittle and strength determination relies on compression or bending tests. Table 9 summarises strength and hardness for example brittle cases. Caution is necessary in comparing results, since test conditions are a large factor in determining brittle material strength. The transverse rupture strength is measured in bending for brittle compositions, giving a higher strength versus the tensile strength, typically 60% higher.

Crush test results tend to range even higher compared to bending test results. In some cases, the ratio of crush strength to tensile strength is near 10. Such high values are suspect, since some of the samples were not fully densified.

As mentioned already, it is common to subject tungsten heavy alloys to various post-sintering deformation and hardening treatments. Strain hardening involves deformation (extrusion, rolling, or swaging), followed by ageing. Defor-

	Mean	Median	Maximum
Yield strength [MPa]	645	620	1020
Tensile strength [MPa]	925	920	1200
Elongation [%]	20	20	37
Hardness [HV]	297	295	435

Table 8 Summary of mechanical properties for alloys from 70 to 98% tungsten

Composition	Strength [MPa]	Hardness
65W-35Cu	954	101 HRB
65W-35Cu	1126	107 HRB
70Cu-30Cu	1450	250 HV
70W-30Cu	450	203 HRB
70W-39Ag-1Ni	580	165 HV
75W-25Cu	415	341 HV
75W-25Cu	894	272 HV
75W-25Cu	1400	240 HV
79W-14Cu-7Zn	960	362 HV
80W-20Ag-1Ni	662	253 HV
80W-20Cu	400	230 HV
80W-20Cu	1350	250 HV
82W-17Ag-1Ni	586	226 HV
85W-15Cu	151	320 HV
85W-15Cu	1126	107 HRB
85W-15Cu	1348	350 HV
89W-10Cu-1Co	1000	500 HV
90W-6Mn-4Ni	1700	69 HRA
90W-7Ni-2Fe-1Co	992	320 HV
91W-5Ni-2Co-2TiO_2	2005	386 HV
91W-5Ni-2Fe-2ZrO_2	2053	341 HV
93W-5Ni-1Fe-1Co	695	475 HV
94W-6Ni_3Al	2000	512 HV
96W-3Cu-1Ni	1537	320 HV
99.7W-0.3Ni	890	75 HRA
99W-1Pd	620	300 HV

Table 9 Bending or compression strength for brittle WHA compositions

"Alloying with molybdenum or cobalt is a common approach to increase strength. However, the gain is minor."

Composition	Deformation, ageing	Yield strength [MPa]	Tensile strength [MPa]	Elongation [%]	Hardness
80W-14Ni-6Fe	75% roll, anneal 1000°C	930	1180	25	37 HRC
82W-8Mo-7Ni-3Fe	18% swage, age 500°C, 180 min	1390	1510	1	73 HRA
86W-7Ni-4Mo-3Fe	18% swage, age 500°C, 180 min	1345	1440	1	73 HRA
90W-6Ni-2Fe-2Co	Vacuum anneal, quench, 40% swage	961	1375	10	528 HV
90W-7Ni-3Fe	18% swage, age 500°C, 180 min	1315	1420	2	73 HRA
90W-7Ni-3Fe	24% swage, age 1090°C	1185	1261	5	42 HRC
90W-7Ni-3Fe	30% extrude, anneal, WQ	---	1150	9	45 HRC
90W-7Ni-3Fe	46% roll, anneal 1000°C	930	1117	11	35 HRC
91W-6Ni-3Co-1Fe	3x swage 10% Anneal 1100°c	1477	1514	12	518 HV
92W-6Ni-2Fe	50% swage, Anneal, quench	1382	1392	6	568 HV
93W-5Ni-2Co	Anneal 1000°C, WQ, age 800°C	634	1006	36	32 HRC
93W-5Ni-2Fe	36% extrusion	---	1387	14	48 HRC
93W-5Ni-2Fe	59% extrusion	---	1592	8	50 HRC
93W-5Ni-2Fe	75% extrusion	---	1542	9	48 HRC
93W-5Ni-2Fe	Heat 1150°C, 1100°C, 1200°C, quench, 18% swage	1505	1554	10	48 HRC
93W-5Ni-2Fe	Hot extrude	935	1390	21	28 HRC
93W-5Ni-2Fe	Swaged	1100	1200	13	71 HRA
95W-3Ni-1Fe-1Co	10% swage	1063	1064	12	40 HRC
95W-3Ni-2Fe	10% swage	1055	1060	12	39 HRC
96W-3Ni-1Fe	Swage, age 1000°C	1399	1454	15	45 HRC

Table 10 Example mechanical properties for WHA compositions after deformation and ageing thermal treatments

mation drives the properties to higher strength and lower ductility. Some examples of the mechanical property combinations attained with various post-sintering cycles are given in Table 10. Peak hardness occurs with 20–30% area reduction, followed by ageing at 500°C or higher, delivering strengths in excess of 1400 MPa, with reduced ductility. A typical ultimate tensile strength is 1200 to 1500 MPa with 10% elongation.

Research recommendations

Sintered tungsten heavy alloys are nearing a century of attention. The findings show a range of compositions and processing cycles able to deliver excellent properties. In his 1980 book *Powder Metallurgy Principles and Applications*, Prof Fritz Lenel identified tungsten heavy alloys as the model system for liquid phase sintering. He was quite correct, and today these compositions are leading the way in space-based liquid phase sintering research.

Some WHA applications only seek a high density. For these applications, polymers filled with graded sizes of tungsten powder would be sufficient. Such ideas first gained traction in the production of practice (frangible) ammunition. A polymer bond combined with compaction offers good strength without sintering. Early compositions relied on nylon as the binder, but water adsorption proved a problem. More attractive are active chemicals (for example, cyanoacrylates) that offer a low-cost means for the fabrication of wristwatch weights, fishing sinkers, bullets, and radiation shields. At least 60 vol.% (96.6 wt.%) tungsten is possible, giving densities in the 11.3 g/cm^3 range, similar to lead without the high cost of sintering. Multimodal powder distributions further increase the density to 16.5 g/cm^3.

Tungsten powders are usually selected for particle size and cost, with little attention paid to impurities. Attention has been given to intentional impurity additions, but experiments are missing with high purity powders. Such trials would help determine specifications with respect to powder purity. Some impurities can be removed during heating, but process cycle design for impurity removal is empirical. A few efforts have installed analytical devices, such as mass spectrometers, on the furnace to track impurity removal. More is needed. For example, studies should include partial pressure hydrogen sintering and oscillating gas pressure cycles to push-pull reactants in and out of the pores. The goal is to remove oxygen, carbon, and other impurities prior to pore closure during sintering densification. Since only selective impurities might respond, identification of those that are removed and the time-temperature-atmosphere conditions for removal would set rational powder specifications.

The ideal heating process involves an empirical set of heat and hold steps, especially when high mechanical properties are desired. Research is needed to integrate the various cycles into a rational plan for attaining high strength and high ductility in larger components. Some of the aspects include the following questions:

- Is the use of mixed powder sufficient versus milled or mechanically alloyed powder?
- What is the optimal time-temperature combination to remove oxygen while heating in dry hydrogen?
- A typical green density is about 60% of theoretical, leaving open pores for hydrogen reduction during heating. Higher green densities improve sintering, but might trap oxygen. What is the best green density for oxide reduction and sintering densification?
- Active polymers are known to improve sintering, such as polyvinyl chloride. Are there species useful for WHA sintering?
- How do sintering time and temperature vary with component section thickness? How is distortion to be controlled during large component sintering?
- There is considerable variation in the hydrogen removal step after sintering. Instrumented trials are needed to identify the proper atmosphere, temperature, time, and adjustments for section thickness. It is unclear which atmosphere is optimal - vacuum, argon, or nitrogen?
- Heat treatment schedules are highly variable. Rationalisation of the cycles to properties is missing. What are the factors determining final properties? What is the most efficient cycle?
- Tungsten heavy alloys need time-temperature-transformation diagrams focused on strength, hardness, or ductility. Are such ideas useful for examining tradeoffs to achieve desired hardening?

The WHA mechanical properties depend on microstructure. Ductility requires the grain rounding that only occurs with liquid formation during sintering. In turn, tungsten solubility helps form a strong and ductile microstructure that responds to heat treatments to control intermetallic precipitation. Is there a tungsten contiguity threshold above which high ductility is not possible? Below the threshold, the maximum attainable strength and ductility are seemingly independent of alloying. This is seen in Fig. 5, where yield strengths from several studies are plotted versus tungsten content. The peak attainable strength (indicated by the sideways 'J' curve) is similar for many compositions up to about 95 wt.%.

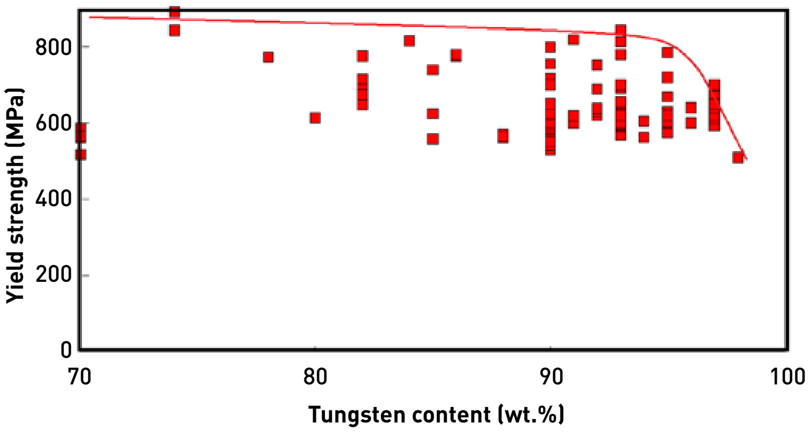

Fig. 5 Yield strength after sintering, and some cases after post-sintering heat treatment, for 100 reports. The data indicate the maximum attainable yield strength is about 800 MPa for most compositions up to about 95 wt.% tungsten

Tungsten [wt.%]	Yield strength [MPa]	Tensile strength [MPa]	Elongation [%]
23*	230	500	58
93	655	951	36
95	550	800	33
95	720	1030	28
97	675	980	23
100	550	560	0

*Table 11 Tensile property comparison between 100% tungsten and matrix phase (23% W) including a few high tungsten content alloys with properties far beyond those expected from a rule of mixtures conceptualisation (*matrix alloy)*

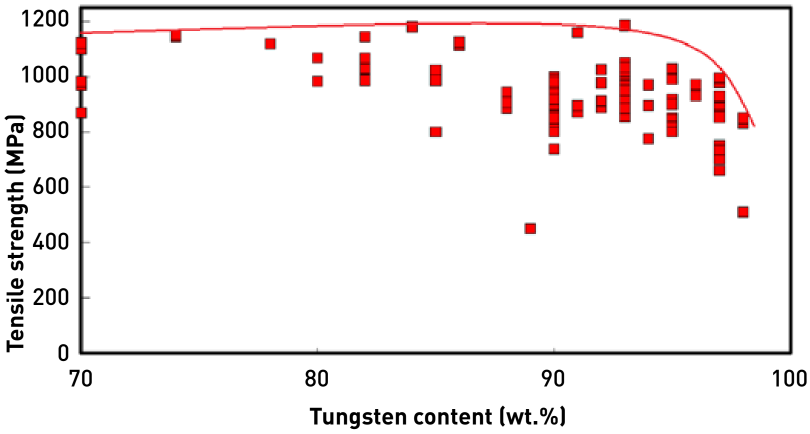

Fig. 6 Scatter plot of ultimate tensile strength versus tungsten content for 123 reports. For most of the compositions the possible maximum strength is at least 1100 MPa independent of composition

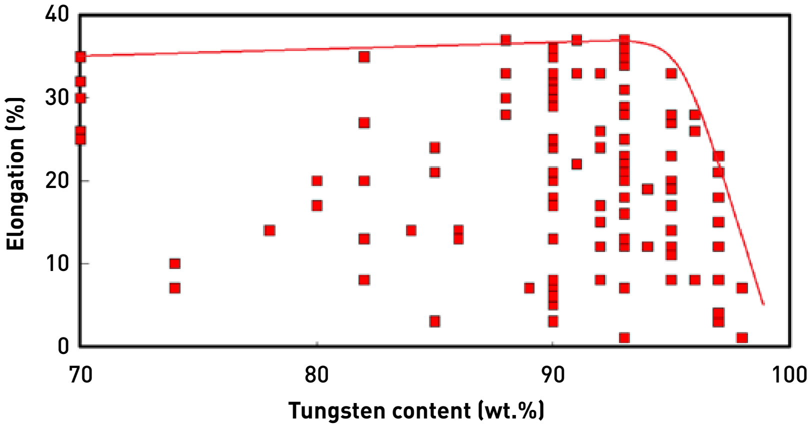

Fig. 7 Elongation scatter plot versus tungsten content, showing the maximum ductility (≈ 35-37%) is nearly independent of the tungsten content up to about 95 wt.% W

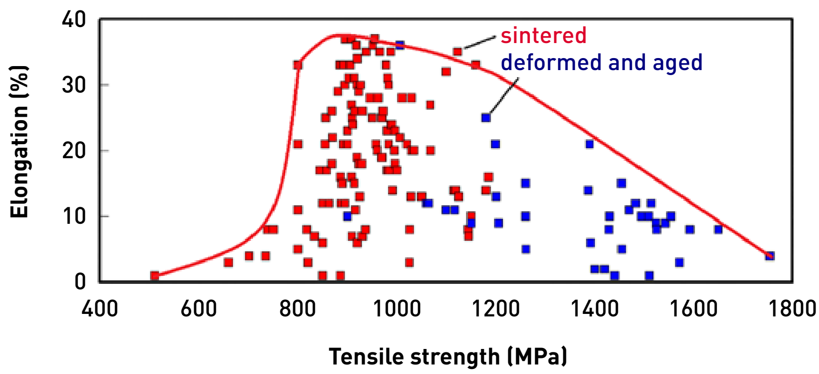

Fig. 8 A scatter plot of elongation versus tensile strength for both sintered (red) and deformed and aged (blue) WHA materials, consisting of approximately 160 reports. The line provides a sense of the maximum property combinations possible

Various microstructure models are available for prediction of strength. It is unclear if these models are effective. This point is emphasized using a few reports in Table 11. It is difficult to explain the properties based on any rule of mixtures concept where the matrix properties plus tungsten properties are prorated to volume fraction. For example, 93 wt.% W corresponds to approximately 85 vol.% tungsten. A rule of mixtures using the matrix tensile strength of 500 MPa and the pure tungsten tensile strength of 560 MPa gives 551 MPa for 85 vol.% tungsten. By comparison, the measured value is 951 MPa. The additional 400 MPa strength for the WHA occurs because of significant stress transfer and work hardening in the tungsten-matrix combination. This works if the interfacial strength is not degraded by impurities or precipitates. When properly fabricated, the matrix phase toughening during deformation provides a synergistic benefit. The combination is worthy of modelling using microstructure finite element analysis. Such a model would provide direction to microstructure manipulations to improve properties. These models were first developed for multiple phase microstructures, such as casting alloys.

Likewise, maximum tensile strength versus tungsten content shows little composition effect up to 95 wt.% tungsten, as plotted in Fig. 6. The peak tensile strength is about 1100 to 1200 MPa from 70 to almost 95 wt.% W.

A substantial strength sensitivity occurs as the tungsten content increases. This is exacerbated in larger structures, where a precipitous decline in tensile strength occurs. Small changes in tungsten content produce large property changes. Most of the tensile data are generated using net-shape tensile samples, so they lack machining damage. When a large body, say 25 kg, is sintered and sectioned for tensile samples, the resulting properties are dramatically lower, especially ductility. Attention to this problem seems to be lacking, so it is unclear if the problem is from machining, segregation of impurities, poor oxide reduction, or slow cooling in thick sections. Chemical analysis versus depth from the surface might help isolate the controlling parameter.

The maximum elongation is not sensitive to tungsten content for less than 95 wt.%. Fig. 7 plots the elongation from 123 reports, showing little change in maximum ductility until up to 95 wt.% tungsten. Mechanical properties decline at the very high tungsten contents, reflecting a critical shift in the microstructure. Other than contiguity manipulations, no other critical microstructure factor seems to enable consistent ductility gains.

At each tungsten level, the data are scattered. It is likely that differences in test factors, as well as microstructure and surface finish, contribute to the scatter. Testing specification are needed to avoid such scatter. What explains the lack of sensitivity up to about 95 wt.% tungsten?

Fig. 8 is a plot of elongation and tensile strength combining data from sintered and deformed and aged materials. Approximately 160 reports are involved in this plot. A few reports claiming 2000 to 2200 MPa after deformation and ageing are excluded due to missing ductility data. The expectation is almost no ductility at those strength levels.

When viewed this way, the WHA alloys seem to maximise ductility near 1000 MPa tensile strength. Strengths over about 1100 MPa come from deformation and ageing treatments, trading ductility for strength. Curiously, the results reinforce the conjecture that penetrator performance remains largely the product kinetic energy (velocity and mass or 1/2 M V^2), with little impact from mechanical properties. Accordingly, it seems 96–97 wt.% tungsten is the best choice for penetration.

Alloy development has been without guiding principle. Tungsten solubility in the Ni-containing matrix is necessary, but not sufficient for sintering densification. Strong oxide formers, such as chromium, aluminium, titanium, and manganese cause a loss of ductility. Additions such as Ni_3Al enable the formation of Al_2O_3 dispersions due to oxygen transfer from the tungsten to aluminium, resulting in incomplete densification and brittle fracture. Systematic experiments within the Ni-Fe-Co ternary matrix compositions are needed. If 6Ni-1Fe is a good matrix, then 6Ni-2Co merits examination, since it should have similar properties. Further, alloy testing needs to be in the context of the envisioned application; high strain rate tests are required for some applications.

The WHA variants are recognised as models for understanding liquid phase sintering. Gravity acts to induce pore migration (due to buoyancy forces), while compressing the solid grains to form a rigid solid skeleton. Current research is focused on removing gravity using WHA liquid phase sintering on the International Space Station. The results challenge current concepts of space-based manufacturing. The findings show compositions with high dihedral angles and high solid contents are the best choices for low gravity environments. Densification is not possible if gravity is removed, since the pores simply agglomerate and remain stable. Further, we lack full understanding of microstructure evolution during reduced gravity liquid phase sintering. Consider the image in Fig. 9, corresponding to 97W-3Ni sintered at 1550°C for 180 min in microgravity.

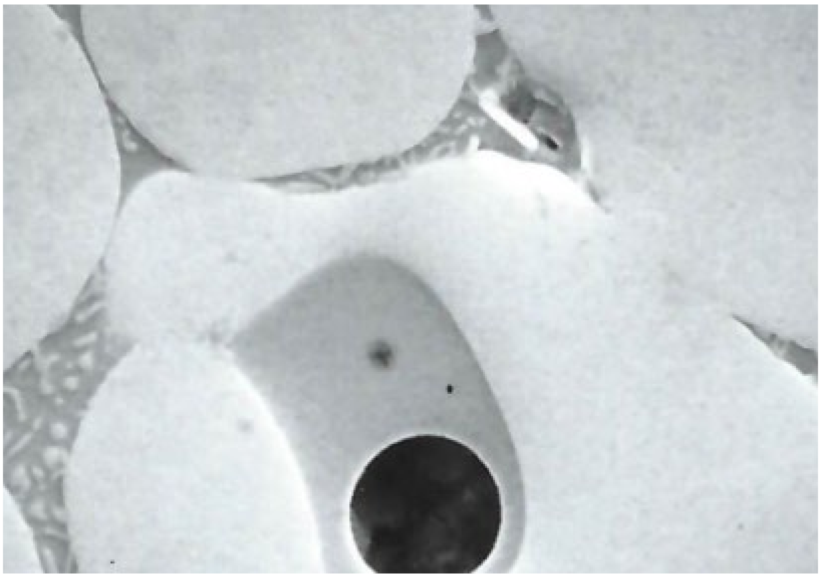

Fig. 9 An anomalous gas filled pore surrounded by liquid with an outer ring of coalescing tungsten grains, 97W-3Ni after 180 min at 1550°C

"Densification is not possible if gravity is removed, since the pores simply agglomerate and remain stable. Further, we lack full understanding of microstructure evolution during reduced gravity liquid phase sintering..."

Step	Key aspect	Parameters
Powder	Homogeneity	Aggressive mixing or milling, up to 24 h
Binder addition	Agglomeration	Add paraffin wax or other binder to the powder, possibly spray dry
Shaping	Oversize tooling anticipating densification	Select tooling and forming process for target geometric attributes
Binder removal	Progressive extraction	Use solvent and heat to remove binder, typically below 600°C in protective atmosphere
Green density	About 60% density	Forming pressure up to 200 MPa
Oxygen removal	Remove impurity	Heat in dry hydrogen, include intermediate 900 to 1200°C holds, long holds for thicker section
Activated sinter	Onset densification	Heat at 10°C/min or less to allow solid-state sintering in dry hydrogen
Liquid phase sintering	Full density sintering	Heat to 30°C over matrix melt temperature, hold for 30 to 60 min in dry hydrogen
Swelling prevention	Offset internal gas generation	Switch to wet hydrogen after reaching peak temperature
Controlled cooling	Avoid solidification pores	Slow cool to matrix solidus at 3°C/min
Hydrogen removal	Switch to inert conditions	Remove hydrogen in vacuum or inert gas, near 1000°C
Impurity segregation	Freeze impurities into solution	Reheating necessary, water or oil quench from about 1000°C
Deformation hardening	Small 10% area reduction	Strengthen as desired using swaging, rolling, or forging steps, intermediate anneals
Strain ageing	Controlled precipitation	Hold at approximate 500°C for desired hardness, strength
Finishing	Avoid surface scratches	Machine final size, polish as last step
Coating	Paint or electroplate	Coat to provide corrosion protection

Table 12 Summary of best practices for tungsten heavy alloy fabrication

The central spherical pore is filled with gas. It sits inside a liquid pool that, in turn, is surrounded by coalescing tungsten grains. No theory predicts such a structure, but it probably is the lowest energy configuration when buoyancy forces are absent. Since residual pores significantly impact mechanical properties, the expectation is degraded properties for space-based Additive Manufacturing.

Summary comments

Summarised in Table 12 are the processing steps associated with optimal properties in tungsten heavy alloys. Research insights will add to this outline. Individuals involved in commercial WHA production advise one of the critical needs is to find processing rules geared to thick components, effectively determining how to adapt the production cycle to accommodate section sizes variations.

Acknowledgements

Current research support on WHA sintering distortion and densification is provided by the National Aeronautics and Space Administration, most recently under grant 80NSSC19K0231. The project manager from the Marshall Space Flight Center is Fernando Reyes Tirado. The San Diego State University experiments are in collaboration with Elisa Torresani and Eugene Olevsky.

Considerable details on tungsten heavy alloys is given in the new book *Tungsten Heavy Alloy Handbook* available from Metal Powder Industries Federation, Princeton, NJ. That book contains more extensive data and nearly 1,000 references used to construct this shortened version.

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Pharmaceuticals and PM are closer than you think: A new approach to understanding powder compaction and tablet characterisation

While the pharmaceutical and Powder Metallurgy industries both work with the compaction of expensive, specially formulated powders, beyond this basic similarity they are not typically seen as having a great deal of overlap. However, a recent study by Chris Freemantle, Pilot Tools (Pty) Ltd, and Henry Kafeman, HDK Solutions Ltd, found that the use of pharmaceutical tablet characterisation methods could benefit the Powder Metallurgy industry. In this case study, the authors share how their use of a Gamlen powder compaction analyser, initially designed for pharmaceutical application, helped them to better measure and understand metal powder compaction for cemented carbide tool manufacture.

The Powder Metallurgy industry has a great deal in common with the pharmaceutical industry, in that both industries work with specialised and expensive powders, which are precisely formulated for their specific application. Powders can be notoriously difficult materials to handle, due to their complexity, and are frequently compacted into tablet form in both these industries. In the case of pharmaceutical applications, of course, tablets are frequently packaged and sold in the compacted, tableted state, while, in Powder Metallurgy, compressed powder 'tablets', aka green compacts, undergo further processing to form dense, metallic or ceramic final products.

Regardless of the material, it is easy to appreciate how the nature of a powder can directly impact its compaction behaviour. Particle size, shape, morphology, hardness, density, porosity and the presence of entrapped air in the mixture, to name but a few, can all affect the way in which the powders form a tablet. The topic of powder compaction is a very important one for both industries and has been the subject of a great many scientific publications. In this article, we will describe a case study using a relatively new technique for measuring and characterising tablet formation, namely the Gamlen powder compaction analyser.

Could pharmaceutical tablet characterisation methods benefit PM?

A chance encounter during a powder rheology webinar led to the suggestion by Henry Kafeman (the co-author of this article) that pharmaceutical tablet characterisation methods could perhaps help the Powder Metallurgy industry. This suggestion

Fig. 1 The Gamlen powder compaction analyser, used to characterise tablet manufacture and properties

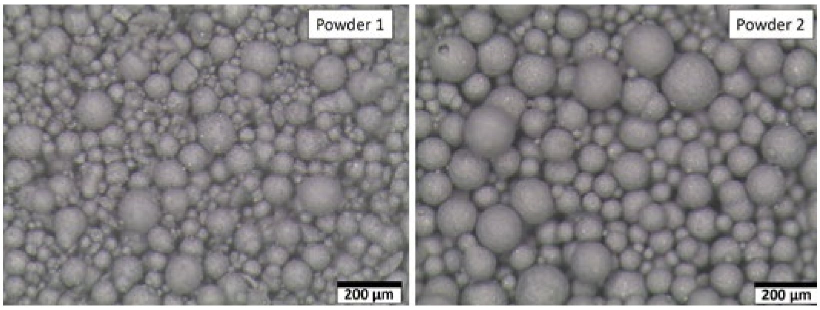

Fig. 2 Spray dried cemented carbide powders showing Powder 1 (left) and Powder 2 (right) spray dried using different spray pressures

> *"The Gamlen device was initially aimed at applications in the pharmaceutical industry, but shows great potential use in the Powder Metallurgy industry."*

led to an interesting collaboration, one that has resulted in a deeper understanding of the connection between pharmaceutical powders and Powder Metallurgy. The Gamlen device (Fig. 1) was initially aimed at applications in the pharmaceutical industry, but shows great potential use in the Powder Metallurgy industry. In this case, we will look at the use of the Gamlen device to benefit the manufacture of cemented carbide cutting tools and how it has assisted Pilot Tools (Pty) Ltd, a cemented carbide manufacturer based in South Africa, to better understand the fundamental differences between the metal powders it uses.

Powder Metallurgy manufacturing techniques are used to produce cemented carbide materials because of the very high melting points of tungsten carbide and related materials, which make other manufacturing methods prohibitive. Cemented carbides make use of the hard tungsten carbide phase (WC) bonded together with a binder metal (usually cobalt). The manufacturing process begins with the milling of the raw material powders, along with a waxy lubricant mixture, into a slurry, followed by spray drying into granulated spheres, allowing the powder to flow more easily. Having a free-flowing powder is important to allow it to fill a die cavity prior to compaction. The process is similar to tablet compaction in pharmaceutical companies, except that the dimensional tolerances are very strict – to within even a few microns for some tool cutting edge designs. Metal powders are not as compressible as many pharmaceutical powders, yet are still required to produce complex geometries. The compacted shapes (green compacts) are then sintered, typically at around 1400°C, into a dense part ready for inspection, coating if required, and finally sold to clients, who will use the tools in metal cutting, machining, mining and wear parts.

Producing good spray dried metallic powders is a very technical business. Many manufacturing parameters can change the properties of the powder particles; for example, spray drying temperatures, the viscosity and yield stress of the feedstock slurries, pressures, the type of spray dryer used, etc. Improving powders and their compaction behaviour is important to continuously improve productivity and quality. Many useful techniques, such as powder rheology (flow measurements), porosimetry and pycnometry (density measurements) can be used to characterise powder properties in the hope of producing better compacted tablets. However, the industry has to date lacked a machine capable of testing various critical parameters of the tablet compaction process.

Some important factors here are, for example, loading and unloading curves during compaction, die wall friction, the adhesive force between the punch and the powder which can lead to 'picking' or 'pull-off' of the powder from the tablet, the fracture strength of the tablets and many more. A very limited way for a manufacturer to conveniently measure these things is on the press itself, which takes time away from manufacturing and is limited by the fact that such presses are usually not equipped to measure all of the necessary parameters, requiring other, sometimes very complex, techniques to be used. Presses are, after all, aimed at mass production and not material characterisation.

Case study

Material selection

In this case study, two cemented carbide tool materials were milled and then spray dried into powders. The metallurgical composition was WC-10 wt.% Co, which is commonly used in the manufacture of cemented carbide cutting tools, especially those aimed at milling applications in metal cutting. The polymer lubricant used to bind the powder was a polyethylene glycol-based polymer blend (2.0 wt.% of the powder mass) in both powders, which helps to hold the granules together and, most importantly, provides lubrication and strength to the compacted tablets.

The slurries were milled and their slurry grain sizes measured using a Malvern particle size analyser. Both powders possessed material of very similar milled grain (crystal) sizes, with Powder 1 slightly finer than Powder 2, having an average slurry particle size of around 0.65 µm, compared to 0.7 µm for Powder 2.

Regardless of this difference, both powders sintered to virtually identical metallurgical properties, such as hardness and grain size. They were therefore metallurgically sound and thus approved by quality control for the manufacture of cutting tools.

The reason slurry grain size is important in a study such as this is due to the 'shrinkage' of the compacted tablet during sintering, in which the cobalt binder melts, particle rearrangement and grain growth occurs and the product achieves > 99% density. The grain size of the slurry influences the pressure required to compact the powders into a tablet of sufficient quality (i.e. without cracks or defects such as 'picking'), that possesses sufficient strength and that shrinks correctly during the sintering process. It is well known that finer grain sizes require higher pressing forces in order to compact them to the required density, but, in this case, the powders were very similar.

After milling, the slurries were spray dried (using a Niro commercial spray dryer) to produce the spherical powders shown in Fig. 2. Powder 1 was spray dried at higher pressure than Powder 2 to intentionally produce a finer granule (spray dried sphere) size distribution than Powder 2, in order to facilitate manufacturing tests on these powders. The powder granule size distribution was measured using a Microtrac dry particle size analyser; with the results being shown in Fig. 3.

Another factor in cutting tool production is the final surface finish of the product. Finer spray-dried powders tend to produce very good surface finishes when tableted compared to coarser powders, but can be prone to flow problems and compaction issues. The surface roughness profile of the sintered part tends to be smoother when finer powders are used, which is very attractive if surface quality is a priority.

A debate arose within the company as to which of the powders was better and which should be used for production of the cutting tool products. Of course, the ideal solution would be a powder that tablets easily, has a perfectly smooth surface and sinters into shape perfectly; however, this is not realistic, and a compromise has to be struck between powder properties, ease of manufacturing, the required metallurgical properties and the product quality. Hence, these two powders were of particular interest for this case study.

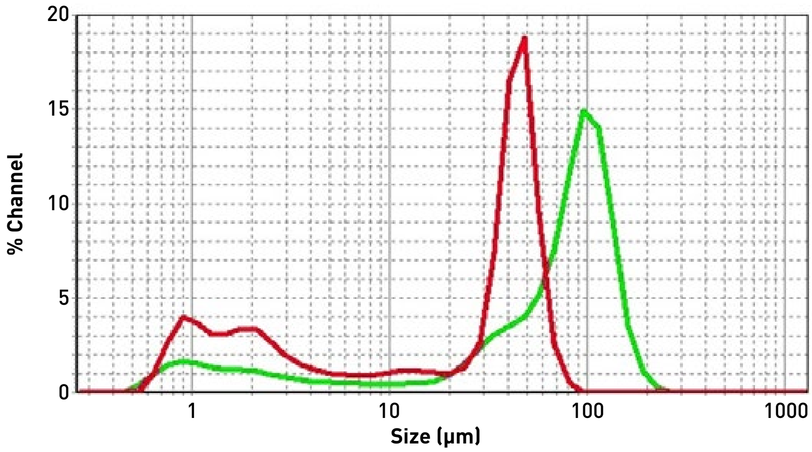

Fig. 3 The particle size distribution of Powder 1 (in red) and Powder 2 (in green), showing that Powder 1 had a finer particle size distribution than Powder 2

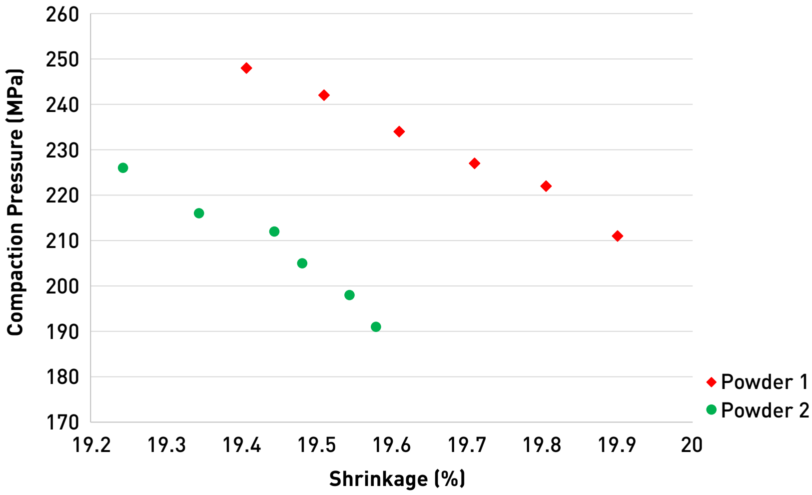

Fig. 4 Compaction pressure of Powder 1 and Powder 2 as a function of the shrinkage experienced by the powders during sintering. Powder 1 required higher pressure to compact the powders to the same extent as Powder 2 and experienced cracking and weight fluctuations

Compaction and sintering

Powders 1 and 2 were compacted using Fette hydraulic presses. It has been found that these 'submicron' powders usually require a pressure of 180–200 MPa to form tablets correctly. The green compacts were inspected for dimensional tolerances, any defects such as cracks, and were then sintered. Although both powders could produce parts with the same metallurgical properties, the press operators complained that Powder 1 was more sensitive and experienced weight fluctuations and flow rate problems. The powder produced fine cracks in some of the components, leading to scrapping of these parts after inspection. A graph showing the compaction behaviour of the powders, and the shrinkage

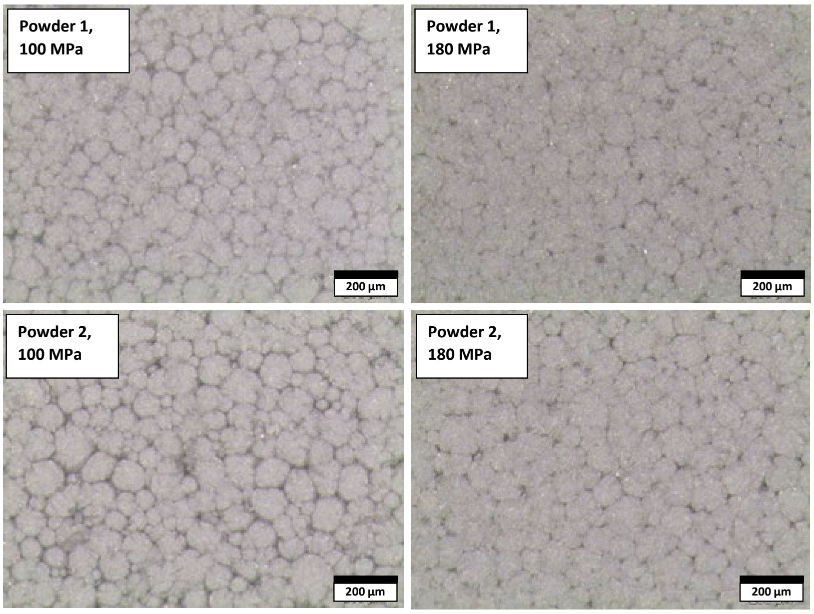

Fig. 5 Optical micrographs of the surfaces of the compacts of Powder 1 and 2. Powder 1 produced a superior surface finish

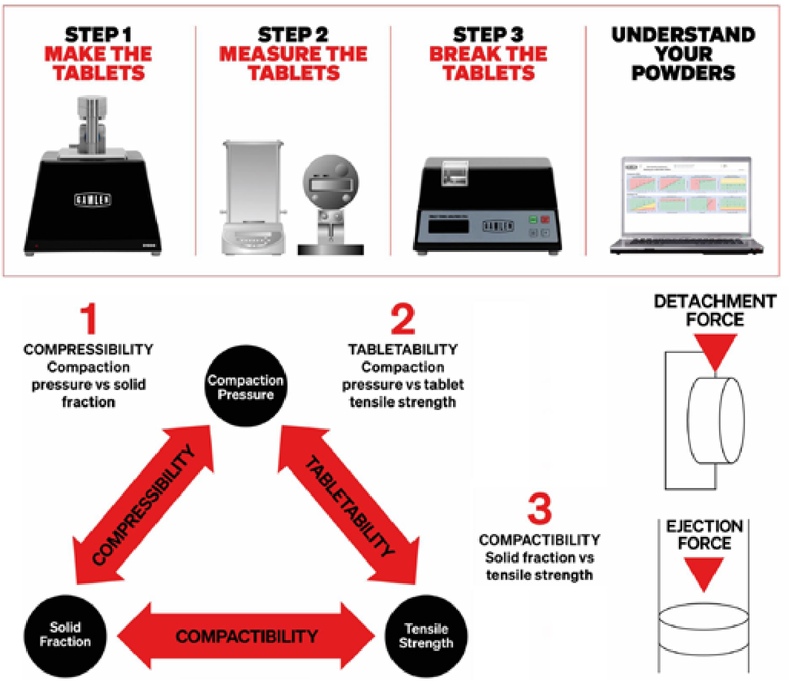

Fig. 6 The Gamlen tablet testing method. The tablet is first produced, measured and then broken after which compressibility, tabletability and compactibility and other useful results are determined. The detachment force and ejection force are also measured.

experienced during sintering by each component pressed at various pressures, is shown in Fig. 4.

The full batch of Powder 1 was manufactured into cutting tools despite the difficulties, but productivity was greatly reduced and the scrap rate was high. Nevertheless, some of the tools were still of acceptable dimensional and metallurgical quality, possessing an excellent surface finish, better than that of Powder 2. Examples of the surface quality can be seen in Fig. 5, showing the compacted surface at a lower compaction pressure (100 MPa), performed for demonstration purposes, and at a typical compaction pressure of 180 MPa.

Testing and analysis

In order to better understand and characterise these powders, both powders were tested in the Gamlen powder compaction analyser, a portable laboratory instrument which follows the basic process shown in Fig. 6. The powders were first compacted into tablets at a range of controlled compaction pressures, then dimensioned and weighed, and finally fractured using the diametral compression test. Compact fracture has been shown by numerous studies to be a valuable and sensitive technique for differentiating very similar powder systems. During the compaction event, the powder analyser also measures the lubrication properties of the compacted material (tablet ejection and tablet detachment stresses), which provide valuable insight into the expected compaction behaviour. A number of studies have shown that the properties determined on the Gamlen instrument are reliable predictors of production behaviour for most pharmaceutical materials. This is the first report on its use in the compaction of tungsten carbide materials.

The Gamlen instrument has been designed to compact powders in the laboratory under carefully controlled conditions and with monitoring of all key compaction parameters. These include punch position, punch force, compaction, detachment and ejection profiles. Using the data collected, the complete range of compaction properties specified in the document 'US Pharmacopoeia <1062> Tablet Compaction (Compactibility, Compressibility and Tabletability)' can be determined. Taken together, these parameters completely characterise the compaction process.

In addition, the Gamlen instrument quantifies lubrication effects, in particular the detachment or take-off force needed to detach the tablet from the punch and the ejection force needed to eject the tablet from the die. These parameters have been shown to be directly related to the incidence of compaction faults, particularly 'picking' or 'pull-off' resulting from powder sticking to the punch.

Results

The results for Powder 1 and Powder 2, tested using the Gamlen instrument, are shown in Figs. 7 to 13. Two separate series of tests were performed for each of the powders, on powder samples taken from different stages in the spray drying process, in order to provide a more batch-representative result; hence we display two sets of results for each powder on the graphs. Each data point represents an average of five tests; therefore, each powder was tested ten times in total for each parameter. For each data point, the average value is shown, with 1 standard deviation also indicated by error bars (though, in many cases, 1 standard deviation is very small and not visible). The background colours in the figures represent commonly accepted guidelines in the pharmaceutical industry for 'good', 'borderline' and 'poor' values.

Fig. 7 shows the detachment stress profile of the cemented carbide powders. Although the detachment stress of the tungsten carbide powders was considered generally 'good' by pharmaceutical standards, Powder 1 exhibited a higher detachment stress than Powder 2 in the first test series, with similar results to Powder 1 in the second test series. We are not yet sure why this difference occurred, but we speculate that the state of the powder may have affected the second test series. We are continuing to investigate the parameters affecting detachment stress, which may be the subject of a future article.

In the manufacturing process, Powder 1 displayed 'pull-off' after only a few components were pressed, while Powder 2 performed much better, requiring punch cleaning at less frequent intervals. Furthermore, Powder 2 compacted more easily than Powder 1, as shown in the Fette press results in Fig. 3, leading to a well-compacted tablet in which the force of adhesion between the powder particles within the tablet was greater than the force of adhesion between the tablet material and the punch, thus the material experienced less 'pull-off' or 'picking'. The detachment stress results in Fig. 7 appear sensitive enough to detect such differences, thus offering a promising technique for measuring this phenomenon.

The ejection stresses (Fig. 8) were all very similar, with Powder 2 experiencing slightly higher ejection stress than Powder 1, but both

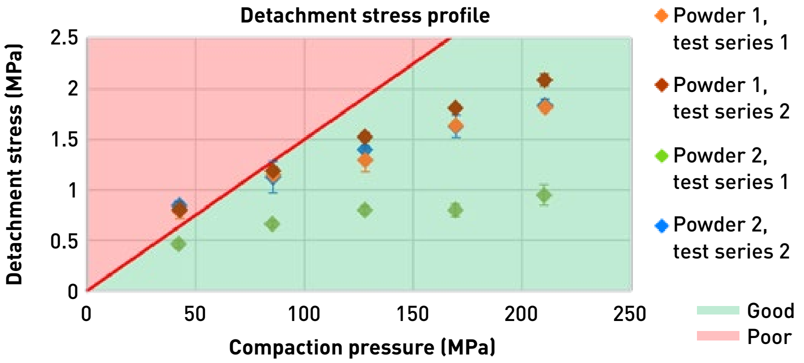

Fig. 7 Detachment stress profile showing the detachment stress of the tablets as a function of compaction pressure. Powder 2 series 1 required a lower detachment stress

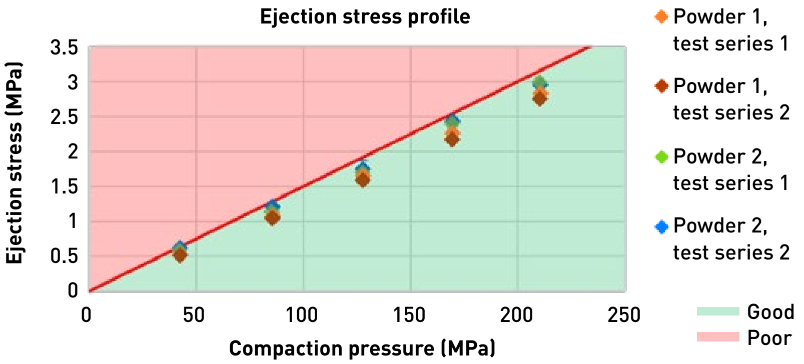

Fig. 8 Ejection stress profile showing ejection stress as a function of compaction pressure. Both powders showed similar ejection stress behaviour, with Powder 2 only slightly higher than Powder 1

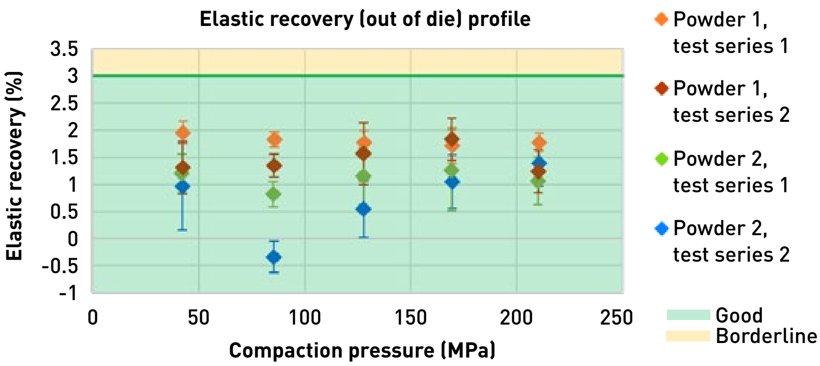

Fig. 9 The percentage elastic recovery as a function of compaction pressure for Powder 1 and Powder 2. Powder 2 displayed consistently better elastic recovery i.e., less springback, than Powder 1

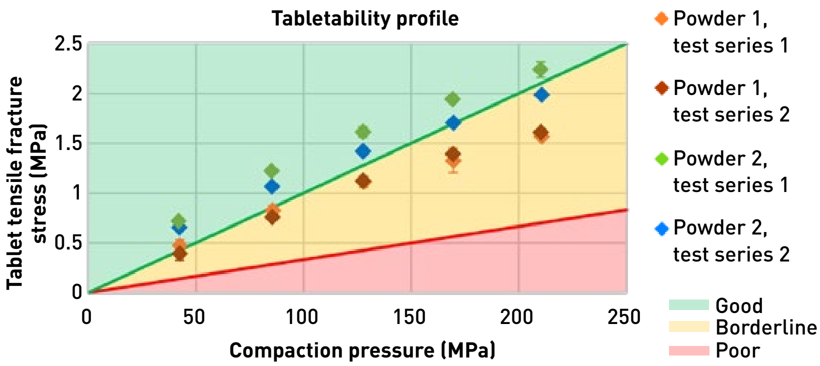

Fig. 10 Tabletability profile of Powder 1 and Powder 2, showing the tensile fracture stress (TFS) as a function of compaction pressure. Powder 2 produced stronger tablets than Powder 1

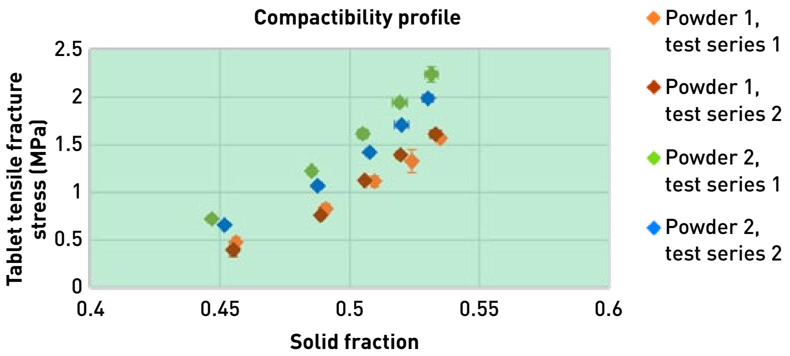

Fig. 11 Compactibility profile of the powders showing that Powder 2 was clearly and consistently more compactible than Powder 1

powders ejected well according to pharmaceutical standards.

The elastic recovery behaviour of the two powders is shown in Fig. 9. Although both powders displayed 'good' elastic recovery compared to pharmaceutical standards, Powder 2 experienced less elastic recovery (also referred to as springback) than Powder 1 in both test series performed. We speculate that, because Powder 2 had a coarser powder granule size, entrained air within the powder was able to evacuate the tablet quickly during compaction, rather than becoming trapped and compressed, thereby leading to a lower elastic recovery than Powder 1. Furthermore, since Powder 1 required higher pressure to compact, it follows that the compacted tablets, produced from Powder 1, were under higher stress, thereby experiencing more springback. Regardless of the causes, this test demonstrated that the Gamlen device can distinguish the elastic recovery of the two powders clearly and so is a sensitive device.

The international standards described by the primary USP<1062> measurements relate to tabletability and compactibility. An important characteristic of a compact is its tensile fracture stress (TFS). This was identified by Fell and Newton in 1968 as being a sensitive measure of compact properties and can therefore differentiate between small differences in compacts. TFS can be measured in a number of different ways, including diametral compression, three and four-point bend tests, and compression. The simplest test is the diametral compression test, also known as the Brazilian disk test. Measurements of TFS as a function of compaction are largely independent of tablet size and provide an important insight into material properties. In this case, Powder 2 produced significantly stronger tablets than Powder 1 when tabletability was tested (Fig. 10). The tablet's tensile fracture stress for Powder 2 was always higher than that of Powder 1. Put another way, to achieve a given strength value, the compression force needed for Powder 1 is approximately 50% higher than for Powder 2. This has an impact on machine wear and also other tablet properties. Importantly, these measurements again agree with what was determined in manufacturing when these powders were used to produce cutting tools, in which Powder 1 was difficult to press, compared to Powder 2.

Compactibility results are shown in Fig. 11. Compactibility under USP<1062> is defined as the relationship between solid fraction, or density, and TFS. It tells you the density needed to achieve a particular tablet tensile fracture stress. In the pharmaceutical world, this controls the speed at which water can penetrate the tablet and allow it to dissolve. In the case of tungsten carbide, the density needed to achieve a particular strength has an impact on the properties of the final sintered product. Powder 2 clearly achieved higher tablet density than Powder 1. The advantages of a denser compact prior to sintering are clear; less volumetric contraction (shrinkage) generally corresponds with less variation in the sintered dimensions. In other words, a dense compact can be expected to sinter more uniformly than a less dense one.

The ejection stress versus tensile fracture stress profile is shown in Fig. 12. The green region shows good tablet strength in pharmaceutical applications, where the tablet is deemed sufficiently strong to survive manufacturing and handling processes. Powder 2 was the only one of the two powders to achieve this, with Powder 1 significantly far behind.

A useful calculated value from the Gamlen device is the so-called

G-ratio, which is defined as the quotient of the tensile strength with compaction pressure, plotted against the compaction pressure. The advantage of plotting the results of the G-ratio in this way is that it restates the tabletability in a clearer way, simplifying compaction data to allow for a quick evaluation of different materials and formulations, as shown in Fig. 13. A G-ratio greater than 1 indicates good compaction behaviour, while a value less than 1 indicates poor compaction. If the G-ratios remain reasonably consistent with compaction pressure, this is considered preferable, as this indicates (in the case of the pharmaceutical industry) that the material is less likely to over-compact or become weaker at higher pressures. In our case, Powder 2 displayed a G-ratio greater than Powder 1 for most compaction pressures, indicating good compaction behaviour. Powder 1 was generally inferior and presented a G-ratio of 1 or less across the entire compaction range. The strength of the tablet falls off as the tablet approaches a maximum achievable density in both cases, which indicates that cemented carbide powders would be considered 'problematic' by pharmaceutical standards, which is, in itself, not surprising.

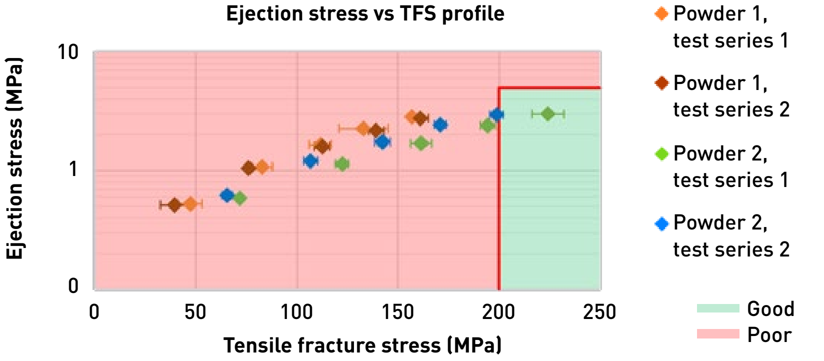

Fig. 12 Ejection stress as a function of tensile fracture stress (TFS) indicating weak tablets in the red region, and strong tablets in the green region, as per pharmaceutical standards

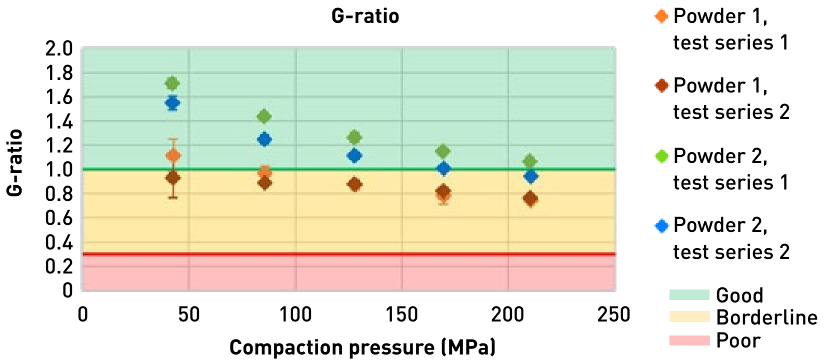

Fig. 13 G-ratio of Powder 1 and Powder 2. A G-ratio > 1 indicates good compaction, while a G-ratio < 1 indicates poor compaction. Powder 2 displayed better compaction behaviour than Powder 1

Powder 1 and Powder 2 had similar grain (crystal) sizes – which affect shrinkage and compaction pressures. Nevertheless, we do not believe that the small grain size difference itself was the leading cause of the powder compaction differences between Powder 1 and Powder 2. Both materials were milled in the same way and sintered to the same metallurgical properties to within a very tight tolerance of each other, therefore, although grain size was likely a contributing factor, we believe that it was not the dominant factor in the differences observed in tableting these powders. The powder particle size (granule) distribution was very different, with each powder spray dried at different spray pressures, resulting in Powder 1 having a significantly finer granule size distribution than Powder 2, as shown in Figs. 1 and 2. Although Powder 1 produced a very good surface finish, that, unfortunately, turned out to be its only redeeming quality.

Conclusion

The Gamlen powder compaction analyser produced values and predictions which corresponded very well with the behaviours of Powder 1 and Powder 2 observed in the manufacturing process. Recall that Powder 1 presented the press operators with great difficulties, such as high pressing forces, weight fluctuations, cracking, 'picking' (or 'pull-off') earlier in the process, and resulted in scrap generation. Conversely, Powder 2 performed very well in manufacturing and was able to be fully utilised with minimal wastage and was easy to press into tablets by comparison.

Michel Gamlen, the Chief Scientific Officer of Gamlen Tableting Ltd., commented on the results of the characterisation of WC-10 wt.% Co powder undertaken in this work, "I was surprised to see that, even for the tungsten carbide powder samples, guidelines very similar to those commonly accepted in the pharmaceutical industry for USP<1062> compressibility, tabletability and compactibility are valid despite the very different nature of the materials."

The machine performed very sensitive tests, able to clearly resolve small differences between the powders. Differences in detachment stress were detected, which can have implications for productivity, indicating which powders can produce more components before 'pull-off' is experienced. The ejection stress data provided very useful information that we expect could be used to predict tool and die wear and gives us insight into the durability of the manufactured tablets themselves. The compactibility and tabletability profiles were clearly able to distinguish the density and strength behaviour of the different powders, leading to a greater understanding of our powder compaction process and the impact a process change – such as powder granule size distribution (resulting from different spray pressures) – can have on our manufacturing process.

We realise that, while the USP<1062> properties in the pharmaceutical industry have internationally accepted standards for compaction behaviour – and there are also accepted values for the lubrication behaviour – these will not necessarily apply to the compaction of tungsten carbide. However, the compaction of tungsten carbide is done on tablet machines very similar to those used in pharmaceutical applications (such as the Fette presses used in this work) and the established values we have obtained in this study certainly provide a good starting point on acceptability of the values generated by the Gamlen powder compaction analyser. It will take more research and development by cemented carbide powder manufacturers to determine the exact values required for ideal tablet production in their factories, but our results show a close relationship between the principles of cemented carbide tableting and pharmaceutical tableting.

Using the Gamlen instrument is simple and reasonably quick; a single point determination of powder compressibility takes only a few minutes and full evaluation of a powder can be completed in forty minutes or less. Therefore, it is our belief that this machine has yet to reach its full potential in the broader Powder Metallurgy and ceramics industries, which both make use of powder tableting and compaction. The experience gained by complementing the powder manufacturing process at Pilot Tools with data from the Gamlen powder compaction analyser has greatly enhanced our powder characterisation capabilities. This case study has demonstrated that the device is sensitive and can clearly distinguish between different powders even of the same composition. By applying some useful knowledge from the pharmaceutical industry, and equipped with a device like this, we envision that the tableting process and characterisation of powders in Powder Metallurgy could be greatly improved in the future.

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Henry Kafeman has an MA in Engineering from Queens' College of the University of Cambridge (UK) and many years of experience working in R&D, support, etc. He combines creative thinking with engineering excellence across many disciplines and technologies. As an independent consultant via his own company HDK Solutions Ltd. (formed in 2008), he has worked on projects for Gamlen Tableting Ltd. contributing to product developments, including: the unique patented rotating die, 'Dashboard' in Excel for basic data analysis & visualisation and using the MathWorks Matlab toolboxes combined with a SQL Server Database to provide advanced & unique insights.

References

[1] Proposed new USP general information chapter, 'Tablet Compression Characterization <1062>', G E Amidon, I Akseli, D Goldfarb and X He, Pharmacopeial Forum 40(4), January 2014

[2] https://gamlentableting.com/compaction-science, accessed October 2021

[3] Technical discussions with Michael Gamlen, CSO of Gamlen Tableting, August – November 2021

[4] Technical discussions with Thomas Steenkamp, Press-shop Manager, Pilot Tools, Pty (Ltd), October 2021

Advertisers' index & buyer's guide

Our advertisers' index and buyer's guide serves as a convenient guide to suppliers across the PM supply chain. In the digital edition of *PM Review* magazine, available at www.pm-review.com, simply click on a company name to view its advert, or on the company's weblink to go directly to its website.

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EVENTS

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Industry events

Powder Metallurgy Review is dedicated to driving awareness and development of Powder Metallurgy and its related technologies. Key to this aim is our support of a range of international partner conferences. View our complete events listing on www.pm-review.com

2022

MIM2022
February 21–23, 2022
West Palm Beach, FL, USA
www.mim2022.org

Asiamold
March 3–5, 2022
Guangzhou, China
www.asiamold-china.cn.messefrankfurt.com

Hannover Messe 2022
April 25–29, 2022
Hannover, Germany
www.hannovermesse.de

PM China 2022
May 23–25, 2022
Shanghai, China
www.pmexchina.com

RAPID + TCT 2022
May 17–19, 2022
Detroit, MI, USA
www.rapid3devent.com

20th Plansee Seminar
May 30–June 3, 2022
Plansee Group, Reutte, Austria
www.plansee-seminar.com

Rosmould
June 7–9, 2022
Moscow, Russia
www.rosmould.ru.messefrankfurt.com

PowderMet2022 / AMPM2022
June 12–15, 2022
Portland, OR, USA
www.powdermet2022.org / www.ampm2022.org

EPMA Powder Metallurgy Summer School
June 20–24, 2022
Ciudad Real, Spain
www.summerschool.epma.com

Dritev – International VDI Congress
July 6–7, 2022
Baden, Germany
www.vdiconference.com/dritev

PMTi2022
August 29–31, 2022
Montréal, QC, Canada
www.pmti2022.org

Formnext + PM South China 2022
September 14–16, 2022
Shenzhen, China
www.formnext-pm.hk.messefrankfurt.com

13th International Conference on Hot Isostatic Pressing
September 11-14, 2022
Columbus, OH, USA
www.hip2022.com

World PM2022
October 9–13, 2022
Lyon, France
www.worldpm2022.com

Event listings and media partners

If you would like to see your Powder Metallurgy related event listed in this magazine and on our websites, please contact Kim Hayes,
email: kim@inovar-communications.com