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POWDER METALLURGY REVIEW

HOEGANAES INNOVATION CENTRE

THE MASTER ALLOY ROUTE

POWDERMET2016: REPORT & AWARDS

www.pm-review.com

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We welcome contributions from both industry and academia and are always interested to hear about company news, innovative applications for PM, technology developments, research and more.

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www.pm-review.com

POWDER METALLURGY REVIEW

Acquisitions take centre stage as the PM industry prepares for Hamburg

As the international Powder Metallurgy Community prepares to meet at the PM2016 World Congress and Exhibition in Hamburg, Germany, (October 9-13, 2016), recent mergers and acquisitions are without doubt going to be one of the key talking points.

Tuesday September 6th saw two announcements that were a surprise to many in the industry. The first announcement, concerning Sumitomo Electric Industries Ltd's (SEI) acquisition of one of the longest established and largest US PM parts producers - Keystone Powdered Metal Company - marks a significant international expansion for the Japanese firm. Keystone, based in St Marys, Pennsylvania., is a leading supplier to the US automotive industry, and has a strong track record in the development of innovative, high performance PM parts. The acquisition adds to SEI's existing interest in US and will position SEI as one of the largest global PM parts producers.

The second announcement of that day will go down in history as a key marker in the rapidly evolving metal Additive Manufacturing industry. GE's acquisition of two leading metal AM machine manufacturers, Germany's SLM Solutions and Sweden's Arcam for $1.4 billion, took the industry by surprise and made the headlines in the mainstream media around the world. The move is undoubtedly a huge vote of confidence in the metal AM industry, a sector in which GE had already positioned itself as a leading player. The acquisition, of course, also secures a leading source of metal powder and MIM feedstock for GE through Arcam's ownership of Canada's AP&C.

Delegates in Hamburg will no doubt be sharing a wide range of opinions on the status of the various sectors making up the global PM industry. If you're attending the event please come and visit the PM Review team on booth 199 in the exhibition hall. We look forward to hearing your views!

Paul Whittaker
Editor, *Powder Metallurgy Review*

Cover image
GKN Sinter Metals received an MPIF Award of Distinction for this driven pulley for use in an electric power steering system (Courtesy MPIF)

Autumn/Fall 2016

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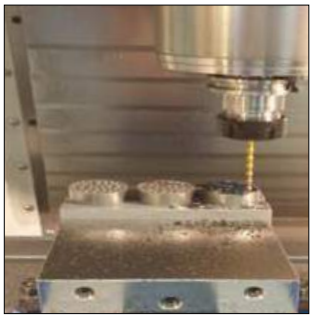
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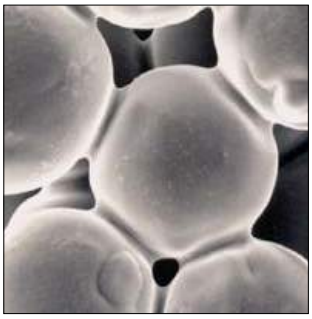
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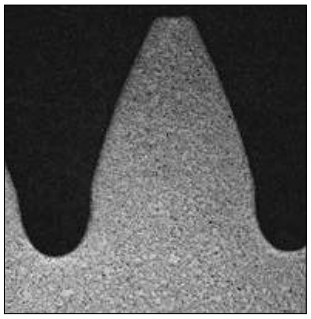
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To submit news for inclusion in *Powder Metallurgy Review* contact Paul Whittaker, paul@inovar-communications.com

Sumitomo Electric to acquire Keystone Powdered Metal Company

Sumitomo Electric U.S.A. Holdings, Inc., a wholly owned subsidiary of Sumitomo Electric Industries Ltd., has announced it will acquire Keystone Powdered Metal Company, a privately held company. The two companies executed an acquisition agreement on August 5, 2016, which, along with the Plan of Merger, was approved by Keystone's shareholders on September 2, 2016.

Sumitomo Electric Industries, Ltd., is a global company with many different production groups including powdered metal which operates under name of Sumitomo Electric Sintered Alloy, Ltd. The merger with Keystone provides the group with growth and adds synergies in products, technologies, markets and customers.

Keystone is a leading designer and manufacturer of highly engineered powdered metal and powder forged automotive powertrain and driveline solutions. For Keystone, the move allows access to expanded resources and offers the ability to provide their technologies to customers on a global basis.

Keystone has been a leader in the North American powder metal industry since its founding in 1927. The company services the automotive (OEM's and major Tier 1 companies), appliance, outdoor power equipment, electrical motor and industrial markets offering the full spectrum of ferrous PM materials and processes, ranging from conventional material systems to full density Powder Forged parts.

With over 58,000 m^2 of manufacturing floor space across three facilities located in St. Mary, PA, Lewis Run, PA and Cherryville, NC, Keystone has approximately 600 employees, sales in excess of $120 million and is one of North America's largest PM companies.

Keystone manufactures PM components used in the new 10-speed automatic transmission developed for Ford and GM

Once the acquisition is finalised, Keystone will continue to operate under the Keystone brand. The current Keystone management team will remain with the company, providing continuity to all stakeholders of the business.

www.keystonepm.com
www.global-sei.com

GKN reports growth and announces expansion of Indiana facility

GKN PLC, has reported a further period of growth for the group during the six months ended June 30, 2016. Sales for the first half year were up 17% at £4,518 million. "This is a good set of first half results with GKN continuing to make underlying progress in line with our expectations. Each division has continued to deliver against our strategy. GKN is in good shape with excellent technology and strong positions in the aerospace and automotive markets," stated Nigel Stein, Chief Executive of GKN.

GKN Powder Metallurgy, comprising GKN Sinter Metals and Hoeganaes, reported sales in the first half 2016 of £499 million, up from £474 million in 2015. Trading profit was reported to be £63 million in the period, up from £56 million in 2015. Underlying sales growth was achieved in all regions with the strongest performance being in Asia.

It was added that during the period, GKN Powder Metallurgy achieved a number of important milestones, which included winning, in just six months, around £120 million of annualised sales in new and replacement business. The company commenced production of automotive grade powders in China for the Asian market and received three design awards from the MPIF.

Indiana facility expansion

It was also reported that GKN Sinter Metals is expanding its operations in Salem, Indiana, USA. The company plans to invest over $6.9 million to update equipment and renovate its facility, creating up to 24 new jobs by 2020. GKN Sinter Metals stated that the new equipment will allow increased production of eight-speed and ten-speed automotive transmission components.

The first round of the new enhanced equipment was installed this year, with the second phase scheduled to begin in 2017. In addition, the company plans to make both interior and exterior enhancements to its existing building, which includes a new innovation room to showcase current advanced manufacturing technologies.

"In order to continue increasing our sales, it's important for us to expand our product offering as customer demands change," stated Jai Perumal, Plant Manager at GKN Sinter Metals. "In order to exceed our customers' expectations, we want to continue investing in equipment and technology that results in quality products."

GKN Sinter Metals' facility in Salem mainly produces automotive engine and transmission parts for customers who include Ford, General Motors, Allison Transmissions, Toyota, Honda, Mazda and Chrysler.

www.gkn.com

Schunk Sintermetal celebrates 50 years in Mexico and announces major investment

Schunk Sintermetal recently marked 50 years of Powder Metallurgy component production in Mexico during a celebration at its facility in Ocoyoacac, Estado de Mexico. The company also announced an initial investment of more than US $10 million in the business, with the aim of tripling sales in the next five years.

The company was established in Mexico City in 1966, before relocating to Ocoyoacac in 1985. Purchased by Schunk Group in 1995, Schunk Sintermetal manufactures a range of sintered parts mainly for the automotive industry and household appliances in Mexico.

Schunk Sintermetal has focused on fulfilling the requirements of the NAFTA region and has worked closely with Mexico's automotive industry. Following investment in the region by many of the main automotive OEMs, the area is offering huge potential for suppliers to this sector. "Years ago we established as our vision in Mexico to be a global leader in the manufacturing of sintered parts. Today we can confirm. This expansion will create more than 300 jobs in the different phases," stated Daniel Alfonso, Schunk Sintermetal Director.

The investment represents only the first stage of future strategic investments that have been planned for Mexico. It was stated that the goal for the Schunk Group in the Sinter Metals division is to become one of the few global players in this technology. "This is the biggest investment that has been made in the history of the company since it became part of the Schunk Group; the target is to integrate our factories around the world as a 'One Firm' company to fulfil the requirements of our global customers with the same products, same machinery and of course the same quality," stated Dr Arno Roth, CEO, Schunk Group.

Schunk Sintermetal held a celebration with the top management of the Schunk Group, customers and representatives of Mexico's automotive industry

Schunk Group has four plants in Mexico, two of them belonging to the Sinter Metals division and two belonging to the Schunk Carbon Technology division.

www.schunk.com.mx

Hoeganaes to form joint venture to produce titanium powder in North America

GKN Hoeganaes has agreed to enter into a joint venture agreement with TLS Technik to manufacture titanium powders in North America for Additive Manufacturing applications. It was stated that the new facility is planned to open in 2017.

TLS is located in Bitterfeld, Germany and has 20 years of experience manufacturing titanium powder for the AM market. The new joint venture complements GKN's previously announced powder R&D efforts in Cinnaminson, New Jersey and provides its customers with a North American source for titanium powders especially for the growing aerospace and medical markets.

GKN Hoeganaes, a subsidiary of GKN Powder Metallurgy, is a producer of metal powders for structural components with metal powder manufacturing facilities in the United States, Europe and Asia.

www.hoeganaes.com

Alpha Sintered Metals acquires Precision Made Products

Private equity firm O2 Investment Partners has announced that its portfolio company, Alpha Sintered Metals, headquartered in Ridgway, Pennsylvania, USA, has acquired Precision Made Products (PMP) based in Brunswick, Ohio, USA. Founded in 2002, PMP is an established Metal Injection Moulding business with CNC machining capability serving the medical, aerospace and firearms markets. Due to certain proprietary elements of its MIM manufacturing process, PMP claims to have significantly shortened the de-binding and sintering cycles which results in low shrinkage rates, better shape stability and very tight tolerances.

Alpha Sintered Metals, LLC manufactures Powder Metallurgy components and assemblies for the automotive, small engine, recreational vehicle, commercial vehicle and agricultural equipment industries. "I was seeking a strategic partner that could help us take PMP to the next level. Alpha's experience in powder metal manufacturing coupled with our MIM technology will create exciting opportunities for the future," stated Majid Daneshvar, founder and CEO of PMP.

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

www.alphasintered.com

SHW AG reports profit within target despite lower sales forecast

Germany's SHW AG has published figures for the first six months of the fiscal year 2016. In the period from January to June 2016, the company reported group sales of €215.3 million (previous year €240.1 million). As well as the expected decline in sales in the Pumps and Engine Components business segment, sales in the Brake Discs business segment were also lower than expected.

"We further improved our production and business processes in the Pumps and Engine Components business segment and therefore also improved our margins. However, to reflect the reticence of individual customers, we are adjusting our sales forecast for 2016 and 2017. Nevertheless, our confidence that we will return to profitable growth from 2018 onwards following these two years of consolidation strengthened. We have landed a number of major new orders both for engine oil and transmission oil pumps over the past few months," stated Dr Frank Boshoff, CEO of SHW.

SHW announced it is adjusting its sales forecast for 2016 and 2017 by around €30 million each. The Company now expects Group sales of between €410 million and €430 million for 2016 and 2017 (previously €440 million to €460 million each). It is forecasting sales for 2016 of between €320 million and €340 million in the Pumps and Engine Components business segment (previously €340 million to €360 million) and sales of around €90 million in the Brake Discs business segment (previous year €98 million), taking into account the lower material surcharges. Despite the reduced sales forecast, the Company continues to expect a year-on-year improvement in the operating profit margin.

www.shw.de

PM Review website re-design enhances user experience

PM Review's website has been re-launched with a number of significant upgrades as well as a domain name change that now reflects the magazine title. The new website, www.pm-review.com, has been designed around a user-friendly interface, allowing it to fully adapt to the different screen sizes found in mobile and desktop devises.

As well as featuring the latest industry news, a complete archive of back issues of *PM Review* magazine can be downloaded in PDF format free of charge. There is a section of the site dedicated to providing an introduction to PM technology, as well as an industry events listing. The site also features more flexible advertising banner options, allowing companies to reach their market with a much clearer and more visual campaign.

www.pm-review.com

Miba reports stable revenue and celebrates 25 years of PM production in Slovakia

Miba AG, headquartered in Laakirchen, Austria, has reported that revenue in the first half of 2016-2017 (February to July) was €376.5 million, compared with €375.2 million in the previous year. "Last year's picture continues. Strong demand from the automotive sector is offset by a further weakening of the capital goods industry," stated F. Peter Mitterbauer, Miba's Chairman of the Management Board.

Miba benefited from positive developments in the automotive industry across all regions. However, demand for construction and mining equipment, tractors, compressors, ships and locomotives declined in all regions except for the truck markets in Europe and China.

"Irrespective of the flat growth in one sector, we are well equipped for the future and are therefore continuing to focus on jobs and training," stated Mitterbauer. As of the July 2016 reporting date, Miba Group had 5,583 employees worldwide, corresponding to an increase of just under 200 employees compared to the previous year.

"Over the short and mid-term, we expect stable growth in the automotive industry in almost all regions. For the capital goods markets, however, we do not see any improvement in the situation until 2017. We are actually afraid that the situation in these markets could again deteriorate slightly," stated Mitterbauer.

Miba celebrates 25 years of PM parts production in Slovakia

Miba also announced that it recently celebrated the 25th anniversary of its Powder Metallurgy component plant in Dolny Kubin, Slovakia. Miba Sinter Slovakia, with over 1,000 employees, is now the largest Miba facility in the world following almost €100 million investment during the last 25 years.

Miba Sinter Slovakia began as a joint venture with the state enterprise ZVL. Established in 1991 as Miba-ZVL, it was one of the first joint ventures to be built with foreign capital in the former Czechoslovakia. Today the facility is one of the major employers in the Orava region.

The plant manufactures a wide range of PM products for the automotive industry including synchroniser rings, friction rings, belt pulleys and chain sprockets, as well as components for body and chassis applications.

www.miba.com

Miba Sinter Slovakia was established in 1991

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Federal-Mogul enters into merger agreement with Icahn Enterprises

Federal-Mogul Holdings Corporation and Icahn Enterprises L.P. have announced that Federal-Mogul has entered into an Agreement and Plan of Merger with a subsidiary of Icahn Enterprises, Federal-Mogul's majority shareholder. The move will see Icahn Enterprises offer to purchase all of the outstanding shares of Federal-Mogul common stock not owned by Icahn Enterprises or its affiliates.

The all-cash offer represents a premium of 86% above Federal-Mogul's closing share price of $4.98 on February 26, 2016, the business day prior to Icahn Enterprises' original proposal. The merger agreement has been unanimously approved by the Boards of Directors of both companies, the Audit Committee of Icahn Enterprises and the Special Committee of independent directors previously established by Federal-Mogul's Board of Directors to review and evaluate Icahn Enterprises' proposal. Upon completion, Federal-Mogul will be an indirect wholly-owned subsidiary of Icahn Enterprises, becoming a privately held company with its common shares no longer listed on the NASDAQ or any public market.

Federal-Mogul was founded in Detroit in 1899 and maintains its worldwide headquarters in Southfield, Michigan. The company has more than 53,000 employees globally.

www.federalmogul.com

Bodycote acquires Nitrex Metal Technologies

Bodycote, the world's largest thermal processing services provider, has announced that it has acquired Nitrex Metal Technologies headquartered in Burlington, Ontario, Canada. Nitrex Metal Technologies serves the North American market with precision gas nitriding and ferritic nitrocarburising in both batch and continuous forms.

Continuous gas nitriding and ferritic nitrocarburising are unique in the industry and are particularly suited to high-volume automotive work. The addition of Nitrex Metal Technologies to the Bodycote Group broadens the range of thermal processing services that Bodycote offers, which range from conventional atmosphere heat treatments to more exotic specialty technologies.

"Nitrex Metal Technologies is a great addition to the Bodycote Group. Along with the rest of Bodycote's existing service offerings, this acquisition really cements our position as the go-to expert source for all things nitriding," stated Dan McCurdy, President of Bodycote Automotive and General Industrial Heat Treating in North America and Asia.

www.nitrexmetaltech.com
www.bodycote.com

Plansee reports sales of €1.8 billion

Plansee, based in Reutte, Austria, has reported that in its fiscal year 2015/2016 the company achieved consolidated sales of €1.18 billion. Dr Michael Schwarzkopf, Chairman of the Executive Board, stated at a recent press conference that despite a dramatic fall of up to 42% in raw materials prices, Plansee was generally able to maintain sales volumes and sales at a stable level and that the lower sales prices resulting from the raw materials situation were largely balanced out by favourable exchange rates.

More than half of the Plansee Group's sales were said to come from the mechanical engineering, automotive and consumer electronics sectors. Some 53% of sales were achieved in Europe, 23% in America and 24% in Asia.

During the last fiscal year, the Plansee Group made investments of almost €220 million. These included the construction of a new production site in India and expansions to production in Austria and Luxembourg. In addition, the Plansee Group acquired three companies. Ceratizit took over the German toolmaker Klenk GmbH & Co. KG in Balzheim. Ceratizit also signed a purchase agreement for a majority holding in the Indian tool manufacturer Cobra Carbide Pvt. Ltd. The tungsten powder producer GTP acquired the Finnish company Tikomet Oy.

"All these expansions and acquisitions underpin the Plansee Group's strategy in which the high-tech materials molybdenum and tungsten play a leading role, from the processing of the ore through to the custom-built component," added Schwarzkopf.

www.plansee.com

Arcast forms new company to focus on production of titanium powder

Arcast Inc., based in Oxford, Maine, USA, a specialist in arc and induction melting systems, has announced it is creating a new company, Arcast Materials, to focus on the bulk production of a number of challenging alloys including titanium alloy powders.

The company forecasts that production of clean titanium alloy powders will be in the order of 'tonnes per month' once the new plant is operating at its full potential. Arcast state that this will directly feed the growing PM market, especially in the areas of Additive Manufacturing and associated net shape production techniques.

www.arcastinc.com

Sino-Euro Materials receives aerospace certification for its PREP metal powders

Sino-Euro Materials Technologies (SMT) located in Xi'an, Shaanxi Province, China, a producer of spherical metal powders including titanium alloys, superalloys, cobalt-chromium alloys and stainless steel, has announced it has been awarded AS9100C certification. AS9100 is a widely adopted and standardised quality management system for the aerospace industry.

SMT was founded in 2013 by Northwest Institute for Non-ferrous Metal Research and the company states that it plans to complete a medical system audit later this year in order to obtain ISO 13485 certification. The company uses the Plasma Rotating Electrode Process (PREP) for metal powder manufacturing and has two production lines with the capacity to produce 500 tonnes of spherical metal powders annually.

In order to obtain the finer powders (<45 µm) necessary for some applications, engineers at SMT have improved the rotating mechanism to raise the speed from 15,000 rpm to 33,000 rpm. The Super-Speed PREP method has been used to produce Ti-64 and In718 powders, with the percentage of <45 µm powders above 20% and 50% respectively.

www.c-semt.com

China PM association reports slowdown of Powder Metallurgy production

Statistics published by the China Machine Powder Metallurgy Association (CMPMA) showed a slowing down of PM component production in 2015 albeit that the figures reflect the output and sales of 48 PM businesses as against 50 companies reporting in 2014.

Output in terms of sales value decreased by 1.1% to Yuan 624,621.8 million ($950.7 million) in 2015, but an increase of 7.4% was observed in sales of new PM products to Yuan 154,276.9 million ($234.8 million).

Exports of PM products increased by 12.1% in 2015. In terms of tonnage production of PM parts the CMPMA reports a decline of 6.2% to 181,214 tonnes in 2015, but this reduction compared with 2014 could also be a reflection of the two fewer reporting PM businesses.

For the first quarter of 2016 the CMPMA reports further declines in sales and tonnage production with sales down by 7.5% to Yuan 149,338.8 million. This could again be attributed to the fewer number of reporting companies which totalled 40 in the period.

Passenger car production and sales in China in the first 4 months was reported to be 7,537 million units and 7,448 million units respectively – increases of 6.6% and 6.7% compared with the same period in 2015.

www.cmpma.com.cn

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Sandvik achieves NORSOK approval for its Alloy 625 HIP products

Sweden's Sandvik AB has announced that it recently achieved NORSOK approval for its Alloy 625 Hot Isostatic Pressed (HIP) products. Sandvik is the only company to have achieved the NORSOK qualification for HIP products in this material.

"This is an important step towards providing customers with increased design flexibility and manufacturing advantages especially for subsea systems," stated Mats Petersson, Sandvik Product Manager, HIP products, Oil & Gas. In many oil and gas projects the NORSOK qualification is a prerequisite, "This qualification will drive product differentiation and means that customers in this sector will no longer have to seek other, less effective forms of manufacture. It opens up more opportunities where we can satisfy the complex nature of the products along with the exceptional corrosion resistance and inbuilt strength of the HIP process."

HIP facilitates the manufacture of products with irregular shapes and complex geometries such as subsea wye pieces, manifolds, tees, swivels, valve bodies etc., to near-net-shape. Costly operations such as machining and welding are greatly reduced, process safety improved and material properties enhanced.

Sandvik advanced metal powder technology is available in a full range of stainless steels, duplex and super-duplex material grades. These offer excellent resistance to corrosion and hydrogen induced stress cracking making them ideal for subsea offshore oil & gas operations.

www.sandvik.com

MPG to consolidate metal forming brands

Metaldyne Performance Group, Inc., has announced it is consolidating its metal-forming brands. The businesses, which include HHI, Grede, Cloyes, Metaldyne, Jernberg, Impact Forge, NovoCast and FormTech, will now fall under the MPG name.

"Our business was formed nearly two years ago through a combination of three metal-forming technology manufacturing companies," stated MPG's CEO George Thanopoulos. "Integration has gone exceptionally well and exactly as planned. As such, we can now take the next step to brand ourselves solely as MPG."

Headquartered in Southfield, Michigan, USA, MPG has a global footprint of around 12,000 employees at over 60 locations in 13 countries.

www.mpgdriven.com

Stackpole helps boost results for Johnson Electric

Johnson Electric Holdings Limited, Hong Kong, China, has reported the group's sales for the quarter ended 30 June 2016 were US$686 million up from US$526 million in the same quarter of 2015. The company stated that its acquisition of Stackpole International and AML Systems jointly added US$144 million to group sales.

Stackpole's sales for the quarter were US$126 million and AML's sales contribution since its acquisition on 18 May 2016 were reported to be US$18 million. In the company's Automotive Products Group (home to Stackpole and AML amongst others), sales, excluding currency effects and the acquisitions of Stackpole and AML, increased US$19 million compared to the same period last year. The Automotive Products Group's organic sales growth was largely driven by an increase in demand for products for powertrain cooling, engine air management, braking and engine coolant valve applications. This was slightly offset by lower sales of products for engine fuel management applications.

Including Stackpole and AML but excluding currency effects, the Automotive Products Group's sales increased by 44%.

"In the context of a sluggish global economy, Johnson Electric delivered a very solid sales performance in the first quarter of the 2016/17 financial year. The recently acquired Stackpole and AML businesses are performing as expected and we are excited by the new set of business opportunities that the combination with Johnson Electric has enabled," stated Dr Patrick Shui-Chung Wang, Chairman and Chief Executive.

www.johnsonelectric.com

Bodycote Ipswich facility earns MedAccred award

Bodycote's facility in Ipswich, Massachusetts, USA, has earned MedAccred accreditation in recognition of its quality control procedures. The Ipswich plant, in close proximity to Bodycote's Hot Isostatic Pressing (HIP) facility in Andover, offers a range of services for the region's medical device and implants market, offering heat treatment to process and strengthen medical implants, surgical and dental tools and other medical devices.

MedAccred, administered by Performance Review Institute, offers a managed approach to ensuring critical manufacturing process quality throughout the medical device supply chain. It establishes stringent consensus audit criteria based on industry requirements.

www.bodycote.com

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Linde introduces atmosphere control system for annealing and sintering

Linde LLC, located in Bridgewater, New Jersey, USA, a member of The Linde Group, has introduced Hydroflex, an advanced atmosphere control system that allows clean and bright oxide-free annealing of steel, stainless steel, copper, bronze or brass. The system can also be used in sintering and brazing applications.

"The Hydroflex advanced atmosphere control can use one or more carrier gases, nitrogen or argon, to maintain the furnace pressure while a controlled ratio of hydrogen helps prevent oxidation," stated Akin Malas, Head of Application Technology, Metals & Glass Market, Linde LLC.

"Uses go beyond annealing," added Grzegorz Moroz, Program Manager, Heat Treatment and Atmospheres, Linde LLC. "The Hydroflex control system can help optimise your process efficiency and enhance productivity of your process regardless of whether you are annealing, sintering or brazing copper, steel, stainless steel, bronze or brass. First, it contributes to repeatable parts quality. In addition, a bright oxide-free finish means less rework and a high reliability process means higher productivity."

Linde offers a variety of advanced gas control technologies and engineering services for heat treatment furnaces. In addition, engineers at Linde Application Technology Centres can develop new gas supply systems for heat treatment processes and improve the control systems of existing processes. Metallography laboratory services include material analyses, scanning electron micrography (SEM) and a variety of hardness tests.

www.lindeus.com

APMA 2017 conference scheduled for Taiwan

The 4th International conference on Powder Metallurgy in Asia (APMA 2017) will be held in Hsinchu, Taiwan, from April 9-11, 2017. The event will be organised by the Taiwan Powders and Powder Metallurgy Association.

The APMA 2017 conference will showcase the capabilities of the Asian PM industry through technical papers which will update R&D and recent industry PM developments and trends. There will also be an exhibition to demonstrate the latest developments of the Asia PM supply chain.

www.apma2017.conf.tw

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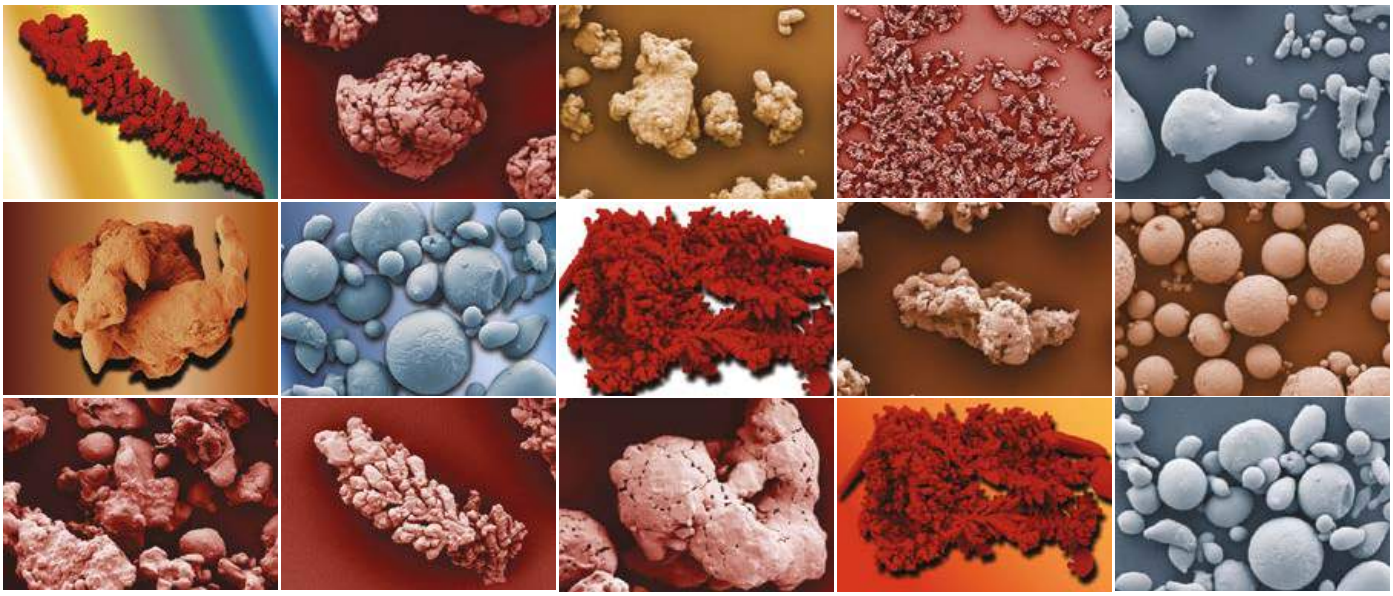

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Graphit Kropfmühl celebrates 100 year anniversary

Graphit Kropfmühl, a global producer of graphite for a range of industrial applications, is celebrating its 100th anniversary in September 2016. Formed as a public limited company in 1916, Graphit Kropfmühl is a specialist in the extraction, processing and refining of natural crystalline graphite with locations in Europe, Asia and Africa.

Graphite is used in Powder Metallurgy in a number of ways. It can be employed as an alloying element to increase the strength of sintered parts and it can also be used as a second phase material in metal bonded particulate composites. Another important application for graphite is in the lubrication and friction moderation in bearings.

"Innovation, market proximity and customer-focused approach have helped us to become a trend-setting graphite refiner. Our leading position as an international graphite specialist is both a motivation and obligation in equal measure," stated Thomas Junker, Managing Director and COO Graphite at Graphit Kropfmühl.

Different graphite is necessary for each application to comply with the demands of the specific process. "A strong focus on research and development work ensures that our product range is continuously optimised. Graphite Kropfmühl is committed to developing high-quality tailored products and solutions using cutting edge and quality-driven processes on the back of intensive dialogues with its customers and partners," added Junker.

www.gk-graphite.com

POWDERMET2017 Call for Papers

The Metal Powder Industries Federation (MPIF) has issued a Call for Papers for POWDERMET2017, the International Conference on Powder Metallurgy and Particulate Materials, taking place June 13-16, 2017 in Las Vegas, USA.

Both oral and poster presentations addressing recent advances in the full spectrum of PM technologies will be included in the technical programme. The MPIF has requested that all submissions should be original and unpublished work, with the deadline for submitting abstracts being given as November 4, 2016.

In addition to the conference, there will be an international exhibition focused on the PM, PIM and metal Additive Manufacturing industries.

www.powdermet2017.org

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Intelligent automation systems from Roboworker help speed up PM production process

Roboworker Automation GmbH, based in Weingarten, Germany, has introduced a range of intelligent automation systems aimed at improving workflow as well as increasing quality and efficiency in the Powder Metallurgy production process. The company offers a modular design of automation systems that provide the flexibility to be adapted to individual customer requirements.

Roboworker's pick and place devices combine speed, precision and reliability due to the use of high performance linear robots. Linear robots guarantee top productivity and accuracy, with precision being boosted further with direct measurement systems. This is the basis for gentle gripping and an attractive solution for placing products in trays with ridges, protrusions or other structures. Freely programmable placement patterns designed for high densities ensure optimum furnace loading.

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

Tray handling systems are available for the smallest right up to large batch sizes. Customers can choose between single belt systems or magazine and stacking solutions with a large tray store for high autonomy times and cost-saving potentials in plant operation.

Also crucial is component quality control and documentation of the inspection results to ensure traceability in the production process, especially for the automotive industry. A wide range of inline functions can be integrated in picking systems, such as part brushing, weighing, laser marking, optical geometry measurement and tactile height measurement.

Roboworker states that a brush and blow-off system integrated in the automation system, for example, removes the very last burrs or metal dust from the blank and helps improve its quality. Further, to support a fast handling process, up to two precision scales can be integrated allowing one part to be weighed while a second scale is loaded. Depending on the ambient conditions, precision levels of +/- 5 mg or better can be achieved in the process.

Laser marking is claimed to be an ideal way of ensuring traceability of the pressed parts and is another function that can be integrated in the company's automation systems. This integration dispenses with the need for a separate, time-consuming labelling process.

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

Components that do not match the specified tolerance are immediately identified and sorted out by corresponding devices, with feedback to the press triggering automatic correction. This interaction of press and automation system with programmable and saved movement sequences and process data is claimed to boost process stability.

Roboworker's pick and place devices combine speed, precision and reliability

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

www.roboworker.com

Höganäs to reduce environmental impact of metal powder production

Swedish metal powder producer Höganäs AB has announced collaboration with a local energy supplier and WA3RM AB to re-use residual heat and carbon dioxide from Höganäs' metal powder production plants in tomato cultivation, fish farming and as electricity. The cooperation will not just result in a reduced effect on the environment, it will also profit local business and create more jobs in the area, the company stated.

Höganäs' production of metal powder products generates residual heat and carbon dioxide. Today, some of that residual heat is used for district heating in cooperation with local energy supplier Höganäs Energi. However, not all waste heat can be re-used in this way. "It is difficult to use residual heat with a temperature under 70°C for district heating," stated Magnus Pettersson, Energy Coordinator at Höganäs. "But it can be used for other things, lowering our total environmental impact."

Höganäs AB and Höganäs Energi is therefore cooperating with WA3RM, a company whose goal is to develop new industries based on industrial residual heat, called Regenerative Industrial Development (RID). WA3RM will buy the heat and carbon dioxide from Höganäs that is not suitable for district heating and use it for greenhouse cultivation, fish farming and electricity.

"Höganäs, Sweden, is an interesting area for us to do business in. Höganäs is a successful industrial company generating residual heat, in combination with a surrounding local community with great experience from greenhouse and fish farming. We believe that the prerequisites for a successful establishment are great here," stated Michael Wiegert at WA3RM.

Magnus Pettersson, Energy Coordinator at Höganäs

"From our point of view, this is by far a question of being a sustainable business, utilising residual heat contributing to the surrounding community and the environmentally friendly production of food and energy," added Pettersson.

The facilities will be located as close to Höganäs' plants as possible, with planned production beginning within three years.

www.hoganas.com

Alicona introduces measurement technology for large components

Alicona, headquartered in Graz, Austria, has announced the development of measurement systems that incorporate universal robots and the company's optical metrology technology to provide flexible quality assurance in production processes. The measurement systems can be used either manually or automatically for the inspection of features on large components.

Systems can be built for quality assurance of round heavy components (see image) weighing up to 120 kg or horizontal systems for large flat objects on which detailed features need to be measured. Applications for this integrated measurement system, for example, include the control of sharp edges or break out on aircraft engine turbine disks and to detect chipping along the edge or to verify minimum radii, essential for safety and reliability in the engine. The systems can also be used to measure imperfections or scratches at discrete locations on the surfaces of these objects.

The wheeled design makes the robot portable and flexible to use in a variety of places. "Manufacturers have the option of taking the measurement to the product or taking the product to the measurement," the company started.

The handling of the new robot measuring systems is said to be very easy and user friendly in either automatic or manual mode. The automatic modes can be pre-programmed and the measurements made unattended. In manual mode the operator manipulates the robot arm and measuring sensor to the required position for measurement. By means of an app, a smartphone displays the live view for manual, precise positioning and measurement.

www.alicona.com

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Magna celebrates the supply of five million transfer cases to BMW Group

Magna International has now supplied five million Actimax transfer cases to BMW Group. The automotive supplier has been providing BMW with drive systems since 2003, including the Actimax transfer case, which powers the all-wheel-drive in nearly all BMW xDrive models. The transfer case is manufactured in Ilz and Lannach, Austria, as well as in Ramos Arizpe, Mexico.

"We are proud of the entire team's commitment as well as the trust that BMW Group has placed in us and our innovative powertrain solutions," stated Jake Hirsch, President of Magna Powertrain. "Milestones such as this demonstrate Magna's global leadership position in developing and producing all-wheel drive and four-wheel drive systems."

Through its powertrain operating unit, Magna is the largest independent 4WD/AWD supplier globally with 29% of an $8.2-billion consolidated market. All-wheel drive (AWD) technology, which was once limited to off-road vehicles, is now being used in almost all vehicle segments, including compact cars.

Magna has supplied five million Actimax transfer cases to BMW Group

www.magna.com

2017 Atomisation for Metal Powders short course

Atomising Systems Ltd and Perdac Ltd (now part of CPFResearch Ltd) have announced that the Atomisation for Metal Powders intensive short course will take place in Manchester, UK, February 23-24, 2017.

The popular course will consist of presentations from John Dunkley (Atomising Systems Ltd), Dirk Aderhold (Atomising Systems Ltd), Doug Millington Smith (Freeman Technology) and Andrew Yule (Manchester University).

Sessions will cover the main methods of atomising metals, the specific requirements for different classes of metal, the design, operation and economics of plant, AM, measurement methods and an overview of modelling and prediction techniques.

www.cpfresearch.com

Energy efficient chokes from SMP offer compact design and external mounting

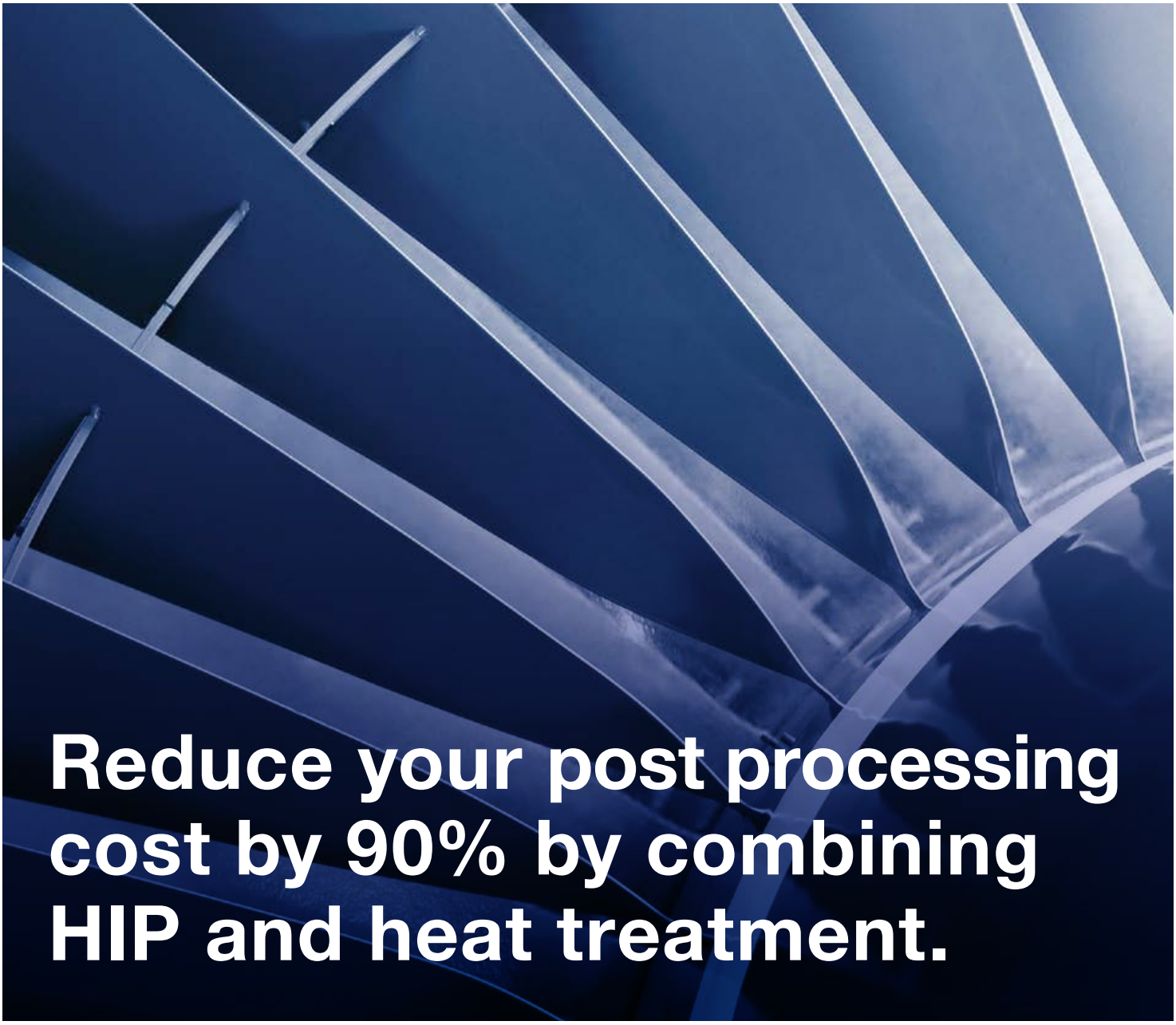
SMP Sintermetalle Prometheus GmbH & Co KG (SMP), Graben-Neudorf, Germany, will display its range of external inductive chokes at Electronica 2016, Munich, Germany, November 8 – 11. The chokes are manufactured from specifically engineered powder composites that are made in-house via a Powder Metallurgy processes. They incorporate a protective paint coating to IP66 specifications which protects from water and dust and is suited to inverters that are exposed to harsh ambient conditions, including rail vehicles or oil rig applications.

The IP66 protection rating enables the chokes to be mounted outside the inverters. The advantage of this kind of mounting is that the heat generated by the choke is outside the inverter, not inside it. A lower temperature inside the inverter eliminates the need to dissipate the heat using fans, which in turn saves energy. Another advantage of mounting them on the outside is that the inverter can be designed significantly smaller. External mounting is beneficial for the choke itself, because it can be adapted to the expected ambient temperature in its operating environment. For example, whereas temperatures inside the inverters in railway applications can reach 70 to 80°C, the temperature outside inverters in underfloor-mounted electronics is not expected to exceed about 40°C.

Almost all of SMP's products are custom-made for individual customers, with the required materials being developed and manufactured in-house. SMP's components are used in a wide array of applications, including power electronics, automation, signal processing, adjustable frequency drives, railway and maritime technology, electro-mobility, medical engineering, aerospace and renewable and conventional energies.

www.smp.de

A protective coating protects the PM chokes from water and dust



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NTN's high strength sintered alloy replaces steel machine parts

NTN Corporation, headquartered in Osaka, Japan, has developed a high-strength sintered alloy with a reported density of 7.6 g/cm^3 or more and an endurance strength of 660 MPa (maximum stress 1467 MPa) or higher. This, states NTN, allows machine parts that require cutting processes, such as gears and bushes to be replaced with sintered alloys.

NTN developed a high-density sintered alloy in 2012, and has conducted further research to optimise the base powder, moulding, heat treatment and other processes with the aim of achieving a higher density and strength.

The use of a proprietary heat treatment process has improved the fatigue strength of gear teeth to 660 MPa, which is almost double that of NTN's conventional sintered alloy products and similar to ordinary steel parts. NTN claims that this allows many types of machine parts to be replaced with this developed product, which was not possible with conventional sintered alloy products. A surface pressure strength, the index for surface stress on gears faces, of 2.3 GPa or more has been achieved.

NTN will not only apply this sintered alloy to machine parts, but also units and module products that feature combinations of resin parts and magnetic parts. The sintered alloy will also contribute to lower fuel consumption and electrification of automobiles, as well as enhance the reliability of industrial machinery components as part of efforts to achieve a reduction in environmental impact, states NTN.

www.ntnglobal.com

EPMA's key PM statistics now available online

The European Powder Metallurgy Association (EPMA) has announced that a number of its Key Powder Metallurgy Figures booklets are now available to download via the association's website. Whilst the latest figures are published exclusively for EPMA members, the association has made the 2011 and 2012 issues available to non-members.

The EPMA's Key Powder Metallurgy Figures booklets contain statistical data on the Powder Metallurgy industry, providing a global and regional view of material and component production. The booklets also include relevant economic data and information from end-user sectors.

www.epma.com

Daido Steel and Honda develop world's first heavy rare earth free hybrid motors

Japan's Daido Steel Co., Ltd. and Honda Motor Co., Ltd. have announced the development of heavy rare earth-free magnets that will now be used for the first time in the driving motors of hybrid electric vehicles. Hot deformed neodymium magnets, containing no heavy rare earths, are reported to offer the high heat resistance properties and high magnetic performance required for motor applications and will be used in Honda's new Freed vehicle.

Neodymium magnets are used for the drive motors of electric vehicles, including hybrid vehicles, due to their high magnetic properties. These magnets must have high heat resistance properties as they are used in a high temperature environment. Adding heavy rare earth (dysprosium and/or terbium) to the neodymium magnets has been a conventional method to secure such high heat resistance. However, due to regional restrictions on the production and supply of these heavy rare-earth elements, a reduction in their use has been one of the major challenges to using neodymium magnets for the drive motors of hybrid vehicles.

Daido Steel has produced neodymium magnets using the hot deformation method, which is different from the typical sintering production method for neodymium magnets. The hot deformation method is a technology that enables nanometre-scale crystal grains to be well-aligned in order to realise a fine crystal grain structure that is approximately ten times smaller than that of a sintered magnet, which makes it possible to produce magnets with greater heat resistance properties.

A rotor for the i-DCD drive motor containing neodymium magnets produced using the hot deformation method instead of the typical sintering production method for neodymium magnets

In addition to the shape of the magnet, Honda revised the shape of the rotor to optimise the flow of the magnetic flux of the magnet. As a result, the hot deformed neodymium magnet became usable for the drive motor, demonstrating torque, output and heat resistance performance equivalent to those of a motor that uses the conventional type of magnet.

www.world.honda.com
www.daido.co.jp

Japan Powder Metallurgy Association celebrates 60th Anniversary

The Japan Powder Metallurgy Association (JPMA) is celebrating its 60th Anniversary in 2016. The association was established in April 1956 and has actively represented Japan's Powder Metallurgy industry whilst promoting PM technology ever since.

At an event held earlier this year, a total of 213 people including representatives from Japan's Ministry of Economy, Trade and Industry (METI), Japan Society of Powder and Powder Metallurgy (JSPM), the related association members, JPMA OB members and JPMA members met to recognise this milestone. Speakers included Mamoru Moritani, JPMA President, Tsuyoshi Toyama, Director of METI and Jun Sakai, President of JSPM.

During his presentation, Mamoru Moritani described the history of the JPMA and gave an overview of the last ten years of the PM industry in Japan and the world. The importance of educating those who are entrusted with the future of PM was reiterated and a special commendation was awarded to Professor Ryuzo Watanabe, Adviser to JPMA and Honorary Professor of Tohoku University, for his long service and contribution to the PM industry.

www.jpma.gr.jp

Mamoru Moritani, JPMA President

A special commendation was awarded to Professor Ryuzo Watanabe, Adviser of JPMA and Honorary Professor of Tohoku University

Global automotive industry buoyed by strong growth in Western Europe and China in first half of 2016

The major international automotive markets were boosted by strong growth in the first half of 2016 in Western Europe, which posted a 9% gain in vehicle sales to reach 7.5 million units along with a 4% increase in light vehicle (LV) production to 9.860 million.

China reported production and sales of automobiles rising to 12.9 and 12.8 million units respectively, increases of 6.5% and 8.1% year-on-year. LV production in North America overall was up 2.6% to 8.99 million units with LV production in the USA up 2.4% to 6.1 million units, Canada up 13.3% to 1.24 million, however Mexico slipping by 3.6% to 1.66 million.

India's automobile market grew by a solid 4% to 1.4 million in the six months since the beginning of 2016. In Japan car production was down by 2.4% to 3.8 million in the first six months and domestic sales were 5.3% lower at 2.1 million units. South Korea also recorded a decline in production in the first half, dipping 5.5% to 2.2 million units.

Russia and Brazil remain problem markets with sales in Russia down by 14% to 672,140 units, the worst half-year result since 2003. Brazil's weak economy contributed to a 25% decline in new car sales, with 952,200 units sold in the first half of 2016.

Spain's 2017 PM Conference heads to Ciudad Real

The organiser of Spain's 6th National Conference on Powder Metallurgy has announced that the bi-annual event will be held in Ciudad Real, Castilla La Mancha, June 7-9, 2017. For the first time, the conference will be open to presentations from both PM and ceramic sectors and will include participation from Latin American countries by incorporating the 1st Congreso Iberoamericano de Pulvimetalurgia within the event.

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

A formal call for papers will be published soon; in the meantime those interested in presenting should forward an abstract to the organiser (trabajos@vicnp.es) before January 20, 2017.

www.vicnp.es

Kittyhawk appoints new President

Kittyhawk Products, a specialist Hot Isostatic Pressing (HIP) company based in Garden Grove, California, USA, has appointed Brandon Creason as its new President. The company's former President, Dennis Poor, will take the role of Director of Strategic Development.

Creason has been with Kittyhawk for twelve years, working primarily as the company's Sales Manager. "I am very excited about the future of Kittyhawk Products and our continued partnerships with such amazing companies in the casting, powder, automotive, Metal Injection Moulding and Additive Manufacturing industries," Creason told *PM Review*.

Kittyhawk Products provides a complete toll HIP service to a range of industries.

www.kittyhawkinc.com

China's largest PM exhibition continues to grow

PM China 2016, China's largest international Powder Metallurgy exhibition, took place at Shanghai's Everbright Convention and Exhibition Center from April 27-29. The event attracted more than 360 exhibitors from around the world, making it the largest event in the series to-date.

"The successful combination of a wide range of exhibition booths, expert tutorials and a parallel technical conference succeeded in attracting the attention of high numbers of international and local visitors," PM Expo's Maggie Song told *PM Review*.

Exhibitors from China included materials, equipment and parts suppliers covering technologies including conventional Powder Metallurgy, Hot Isostatic Pressing and Metal Injection Moulding. International industry suppliers present included leading companies from USA, UK, Germany, Italy, Sweden, Switzerland, India, Singapore and Japan. "We believe that many new business deals were done and a lot of new contacts were created through this effective networking platform. Visitors from home and abroad were satisfied with the wide range of display," stated Song.

As in previous years, *PM Review* magazine along with sister publications, *PIM International* and *Metal AM* magazine, was distributed from our booth in the exhibition. PM China 2017 will take place from April 26-28, 2017 at the Shanghai Everbright Convention and Exhibition Centre, with the organisers already reporting high demand for space.

www.cn-pmexpo.com

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MPIF announces POWDERMET2016 outstanding technical paper winner

The Metal Powder Industries Federation (MPIF) has announced that the 2016 Howard I. Sanderow Outstanding Technical Paper Award winner has now been selected from among the manuscripts presented at the POWDERMET2016 conference held in Boston, USA, June 5 – 8, 2016.

The MPIF Technical Board has selected 'Consolidation of Aerospace-Grade Aluminium 7055 Powder via Sinter-Forge Processing' by Neal P. Kraus, Dalhousie University; D. Paul Bishop, Dalhousie University; Richard L. Hexemer, Jr., GKN Sinter Metals, LLC; and Ian W. Donaldson, FAPMI, GKN Sinter Metals, LLC, as this year's winner.

The objective of the research published in the paper was to assess the response of gas atomised 7055 powder to a sinter-forge style of Powder Metallurgy processing. In meeting this objective the powder was processed through a three-stage sequence of cold isostatic pressing, liquid phase sintering and rotary forging. Core variables included average particle size, the effects of admixed sintering activators (Mg, Sn) and forging temperature.

The authors will receive their award plaques during POWDERMET2017, June 13–16, 2017, in Las Vegas, Nevada, USA. The paper is published in the conference proceedings, Advances in Powder Metallurgy & Particulate Materials – 2016. The paper is also available to read on the MPIF website's listing of Howard I. Sanderow Outstanding Technical Paper award winners.

www.mpif.org

Programme published for 36th Senafor PM conference

The organisers of Brazil's 36th Senafor, October 5 – 7, 2016, Porto Alegre, Rio Grande do Sul, have published the conference programme for the 12th National Meeting of Powder Metallurgy and 6th International Conference Powder Metallurgy – Brazil.

The three day event includes a wide selection of conference and poster presentations alongside an exhibition. A number of technical visits have also been arranged for delegates. Registration to the event is now open and a number of exhibition and sponsorship opportunities are available.

www.senafor.com

Ivor Jenkins Medal presented to Dr John Dunkley

The UK's Institute of Materials, Minerals and Mining (IOM[3]) has presented its 2016 Ivor Jenkins Medal to Dr John Dunkley CEng, FIMMM, Chairman of Atomising Systems Limited, UK. The prestigious award is presented 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.

Dr Dunkley has over 40 years experience in atomising plant technology, dating back to his early career when he started the Davy-McKee operation that supplied and installed such plant in 1974. When Davy-McKee decided to withdraw from this business in 1992 he founded his own company, Atomising Systems Limited (ASL). ASL has now built and supplied around 140 plants to customers in 34 countries. These range from major powder suppliers, of whom around half have dealt with ASL, to small in-house operations.

The company has developed many specialist powders, including water atomised stainless steel powders for filter applications, gas atomised Ag-28Cu powder for brazing and gas atomised special Cu alloys for diamond tool manufacture. Significant atomisation technology developments made have included technology for the production of satellite-free powders in gas atomisation, ultrasonic vibratory atomisation used for very narrow size range, perfectly spherical solder powder production for electronics and centrifugal (spinning cup) atomisation – which is also used in the latest electronic solder powder plants.

www.iom3.org | www.atomising.co.uk

Hagen PM Symposium to focus on 'Machining of and with Powder Metallurgy Materials'

The annual Hagen PM Symposium and Exhibition scheduled to be held in Hagen, Germany, November 24-25, 2016, will focus on recent advances in Powder Metallurgy materials such as hardmetals (cemented carbides) and PM high speed steels used for machining.

There will also be focus on the machining of PM and hard material components, the production of compacting tools made by PM, and the use of Additive Manufacturing for producing cutting tools. The symposium is organised on behalf of the German Ausschuss für Pulvermetallurgie.

www.pulvermetallurgie.com

Net shape HIP project targets large aerospace engine components

The Nesmonic project, formed under the Clean Sky Joint Undertaking with partners from CEIT in Spain, The University of Birmingham, UK, and the Manufacturing Technology Centre, UK, began in 2013 to look at the manufacturing of components from IN718 using Net Shape Hot Isostatic Pressing of powder (NSHIP). The project concluded this year and the results show significant advantages to using this method for the production of complex high performance aerospace parts.

To exploit this technology a number of challenges had to be addressed, including the difficulty in HIPing nickel super alloy powder, the high cost of sacrificial tooling, diffused surface layer on components due to interaction with the tool material and finally the lack of credible performance information for IN718 parts produced using the NSHIP process. Trials were performed to determine the best powder and HIPing conditions to use to produce parts with the desired microstructure and properties. Novel low cost tooling methods were developed and surface engineering techniques, to eliminate tool/component interaction, explored. A computation model of IN718 powder consolidation was used to calculate the correct tool geometry to enable "right-first-time" net shape parts to be produced.

On conclusion of the project the researchers reported that an 80% reduction in aerospace material consumption (nickel alloys) and the elimination of swarf disposal and recycling costs is achievable using NSHIP. Also, the manufacturing process allows for a 75% reduction in energy consumption as a result of reducing energy-intensive machining operations.

The process has the ability to manufacture complex components which will provide the essential high pressure and temperature capability critical to achieve the required reductions in fuel burn in large civil aero-engines.

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It was decided by the consortium that for the final full scale demonstrator, a large 1.5 m IN718 engine casing should be manufactured through the NSHIP process

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Powder Metallurgy EXPO

Hoeganaes Innovation Centre: Technical support and powder development for the next generation of PM applications

Hoeganaes Corporation is one of the world's largest manufacturers of metal powders, supplying an ever wider range of materials and grades to a growing customer base. Earlier this year the company invited *Powder Metallurgy Review* to visit its Innovation Centre in Cinnaminson, New Jersey. *PM Review's* Paul Whittaker reports on how the company not only develops powders for the next generation of PM processes, but also offers support to customers in the development of new PM applications and troubleshooting production issues.

Hoeganaes Corporation is one of the largest global producers of atomised iron and steel powders for the production of structural Powder Metallurgy components. Headquartered in Cinnaminson, New Jersey, USA, the company has manufacturing facilities in the United States, Europe and Asia. As part of the GKN Powder Metallurgy group, Hoeganaes supplies powders directly to more than thirty GKN Sinter Metals facilities as well as to a significant and growing number of external customers.

As a group, GKN Powder Metallurgy reported global sales of £906 million in 2015, of which Hoeganaes accounted for £143 million. In 2015, Hoeganaes produced a total of 285,000 tons of powder, making the company the second largest producer of ferrous-based metal powders in the world and accounting for around 25% of the global market.

Growth in North America

The history of Hoeganaes dates back long before the UK based engineering company GKN plc acquired the business in 1999. Founded in 1953, Hoeganaes Corporation was a wholly owned subsidiary of Swedish sponge iron powder producer Höganäs AB. In the same year the company began manufacturing sponge iron powder at its new plant in Cinnaminson, New Jersey, later expanding to include atomised stainless steels

Fig. 1 The Hoeganaes Innovation Centre in Cinnaminson, New Jersey

Fig. 2 The Gallatin plant began full operation in 1980

and Ni- and Co-alloys in 1962 and water atomised steel powder in 1969.

In 1968 Interlake Corporation purchased an 80% stake in Hoeganaes, coinciding with a strong period of growth in the Powder Metallurgy industry that saw increased demand for Hoeganaes' iron powder. During the 1970s, atomised steel powder production capacity in North America was unable to support the demand of new PM applications, so Hoeganaes took the decision to further increase capacity. As a result, Gallatin, Tennessee, was chosen as the green-field site for a new state-of-the-art water atomising facility.

The Gallatin plant began full operation in 1980 with one 45-ton electric arc furnace and three powder annealing furnaces (Fig. 2). The original facility had a capacity of 45,000 tons and only made three powder grades. In 2000, the plant completed a significant upgrade worth over $100 million and today the facility has a 60-ton electric arc furnace with a ladle refining furnace and twelve powder annealing furnaces. Gallatin is the worlds largest steel atomising plant with a capacity in excess of 300,000 tons. The company makes more than twenty grades of iron and steel powder at this site.

Fig. 3 Hoeganaes is the only metal powder producer with manufacturing facilities in the major markets of America, Europe and Asia

In 1988 Hoeganaes opened an additional facility in Milton, located close to a significant number of PM part producers in Pennsylvania. The Milton plant incorporates sophisticated automation and produces the company's ANCORBOND range of press-ready, binder-treated hybrid alloy systems. ANCORBOND is designed to offer uniform die fill, improved production rates, greater density control, more consistent weight distribution and increased dimensional stability.

ARC Metals was founded in Ridgway, Pennsylvania, in 1987 to service the growing number of PM part producers in the region by re-milling waste ferrous PM materials into a re-usable powder products. The company was acquired by Hoeganaes in 1996 and continues to produce re-milled iron powders for the local PM community, as well as providing blending services for Hoeganaes and its customers.

In 1999 the global engineering group GKN Plc, headquartered in Redditch, UK, acquired Interlake Corporation and in turn its stake in Hoeganaes. At the time Hoeganaes was the major metal powder supplier to GKN's Powder Metallurgy parts making business, GKN Sinter Metals. In 2001 GKN acquired the remaining shares in the company.

Expansion into Europe

The Hückeswagen facility, located in the heart of Germany, was opened by Hoeganaes in 2001. The company produces custom press ready regular premixes, ANCORBOND binder treated premixes and has the ability to re-process green scrap to customer specified premixes and standard materials. The site is close to major customers in the region.

To further expand the company's footprint in Europe, Hoeganaes acquired the Buzau facility in Romania in 2003. The water atomisation plant was established in 1995 by Ductil Company to produce iron powders for the manufacturer of its wire and wire products. Today, the facility manufactures iron and diffusion alloy powders and premixes mainly for the PM industry, but also services the welding industry as well as other industrial applications.

The Buzau plant is located in South-Eastern Romania and is the only manufacturer of metal powders in the South East region of Europe. After its acquisition by Hoeganaes, the facility was expanded and is today producing more than fifteen grades of iron powders.

Fig. 4 The Bazhou plant in China has produced powders since 2011

Fig. 5 AncorTi has been developed to meet the needs of the aerospace and medical Additive Manufacturing industry

Manufacturing metal powders in China

Hoeganaes has identified Asia as a key growth area for sales of its metal powders for conventional PM applications. In 2016 the company formed a joint venture with Chinese partner Bazhou Hongsheng Industrial Company Ltd that saw Hoeganaes take a majority share in a metal powder manufacturing facility located in Bazhou City, Hebei Province, China (Fig. 4). The plant has been in operation since 2009 and has expanded its product line to produce GKN Hoeganaes' international grade powders for use in automotive and industrial applications in the growing Asian markets. The move into China has made Hoeganaes the only atomised iron powder manufacturer with complete production facilities in all the world's three major automotive producing regions.

"This joint venture will allow us to better serve our customers in both China and the wider Asia Pacific area and is a reflection of our commitment to expanding our global footprint and meeting the needs of our customers. In addition, it provides a local manufacturing base for Hoeganaes' advanced metal powder technologies, enabling us to meet the increasing need for more technically enhanced powders in Asia," stated Tim Hale, the newly designated Director of Sales for Asia.

"As the Chinese market continues to grow and mature, demand for higher quality and advanced PM materials will increase," added Bruce Lindsley, Director of Advanced Engineering Materials at Hoeganaes Corporation.

Powders for metal Additive Manufacturing

Additive Manufacturing is seen by Hoeganaes as offering the highest growth potential for the supply of metal powders in North America and Europe. The company sees demand coming from both the aerospace and medical sectors.

To meet this demand, a move into the manufacturing of titanium powders suitable for Additive Manufacturing was announced in 2016. A joint venture agreement with TLS Technik will see a new facility open in 2017 to produce titanium powders in North America. TLS, located in Bitterfeld, Germany, has twenty years of experience manufacturing titanium powder for the AM market (Fig. 5).

Fig. 6 Tensile strength tests are one of the many testing procedures available at the innovation centre

Fig. 7 Many different microscopy techniques are used in metallographic analysis

Hoeganaes is actively developing gas atomised grades suited to the AM process and is also working on developing water atomised powders that question the notion that AM powder particles must be spherical in nature.

The Hoeganaes Innovation Centre

Located in Cinnaminson, New Jersey, the company's Innovation Centre is housed in a striking, recently modernised building on the former site of the sponge iron powder production plant. Research and development in metal powders has been undertaken at Hoeganaes since 1960 and the company completed a multi-million dollar investment in the Innovation Centre in 2015. This expanded the facilities and provided state-of-the-art equipment including a pilot gas atomiser for the development of a new generation of advanced metal powders.

The Innovation Centre is home to a range of services for Hoeganaes and its customers. Direct application development and testing services for customer powder launches and PM part failure analysis are teamed with in-house development of new powder products and support for Hoeganaes production plants. From within the Innovation Centre it is possible to study the entire Powder Metallurgy process, from powder to part to finishing.

Housed in the main building are a number of laboratories and workshops, as well as a large customer meeting room and administration offices. Behind this are a further three buildings making a total floorspace of some 5,100 m^2. The Innovation Centre's laboratories include apparatus capable of physical, mechanical, chemical and metallographic testing (Figs. 6-9). A range of powder compaction presses and sintering furnaces are complemented by pilot melting, annealing and mixing equipment. There are around thirty full time staff members employed at the site.

PM Review's visit to the Innovation Centre included a tour of the

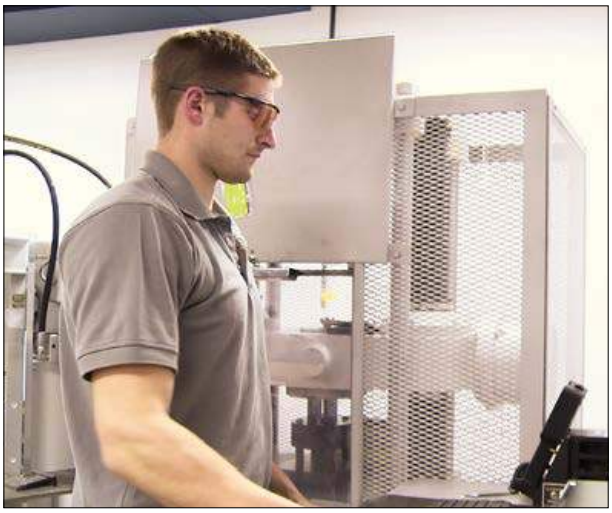

Fig. 8 Compaction testing can be used to determine green density and green strength

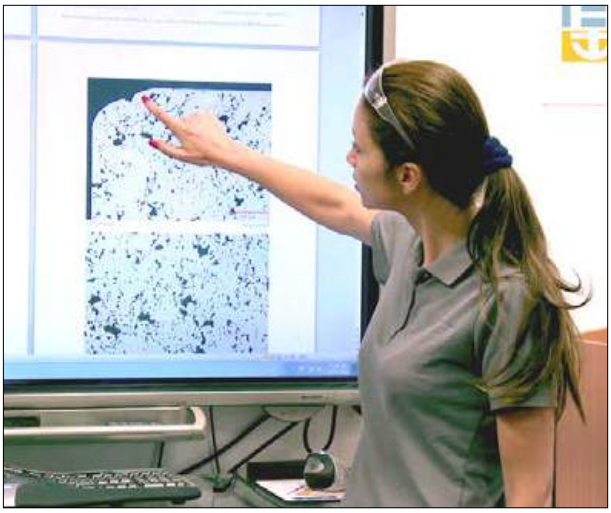

Fig. 9 A wide range of testing procedures are used to investigate and troubleshoot customers' production issues

impressive facility, which not only highlighted the wide range of equipment available to Hoeganaes and its customers, but also the significant wealth of experience and technical knowledge of its staff. From development of new powder grades to solving specific issues with a customer's production process or part, it is clear that the Innovation Centre is well equipped to provide answers to the vast majority of questions related to the production of structural PM components.

During the tour it became apparent that much of the work undertaken at the Innovation Centre is of benefit to the global PM industry as a whole. Improving the processing of parts, providing solutions to production problems and developing new materials, for example, all contribute to the wider adoption of the Powder Metallurgy process.

Machinability of PM components

One such area of work has been the improvement made to the machinability of PM components. Machinability is a challenging post-processing step for many PM components. "Although Powder Metallurgy has the advantage of creating near net-shape products, machining is often necessary as parts require increasingly tight tolerances, specific surface finish and features such as grooves and holes," commented Lindsley during the tour.

Finishing operations

The most common finishing operations for PM parts are hard turning and drilling. Near-net-shape turning only requires shallow cuts and a minimum number of steps, but machining accuracy and a precise holding of the work piece are essential for accurate dimensional tolerances and low surface roughness. Roughing operations and interrupted cuts place higher stresses on machining inserts and accelerate tool wear. In addition to this, the presence of porosity results in reduced tool life in machining of PM components as a PM part is heterogeneous on a microscopic scale, which creates an interrupted cut condition as the tool tip continuously moves from solid to pore. Small thermal and mechanical fatigue cracks and chipped tool edges develop from this phenomenon as well as from the presence of single hard particles. Oxides and carbides resulting from sintering and heat treating can also contribute to increasing the abrasion on the machining tool.

"Although Powder Metallurgy has the advantage of creating near net-shape products, machining is often necessary"

Machining additives to reduce wear

With production schedules requiring high machining throughput, wear connected to the intermittent-cut condition is increased. Ad-mixed machining additives are intended to alleviate such effects and the PM industry uses manganese sulphide as the preferred additive. MnS acts to improve machinability by providing lubrication between cutting tool and work piece, therefore reducing wear at the cutting edge of the tool. However, there are drawbacks deriving from the addition of MnS in PM components, the main one being enhanced oxidation in humid atmospheres and consequent accelerated corrosion especially when ad-mixed with Fe-Cu-C mixes.

Development of AncorCut

Manganese sulphide bears other processing disadvantages limited not only to Cu containing materials (FC-020X), such as high reactivity during storage and release of sulphur containing gas during sintering,

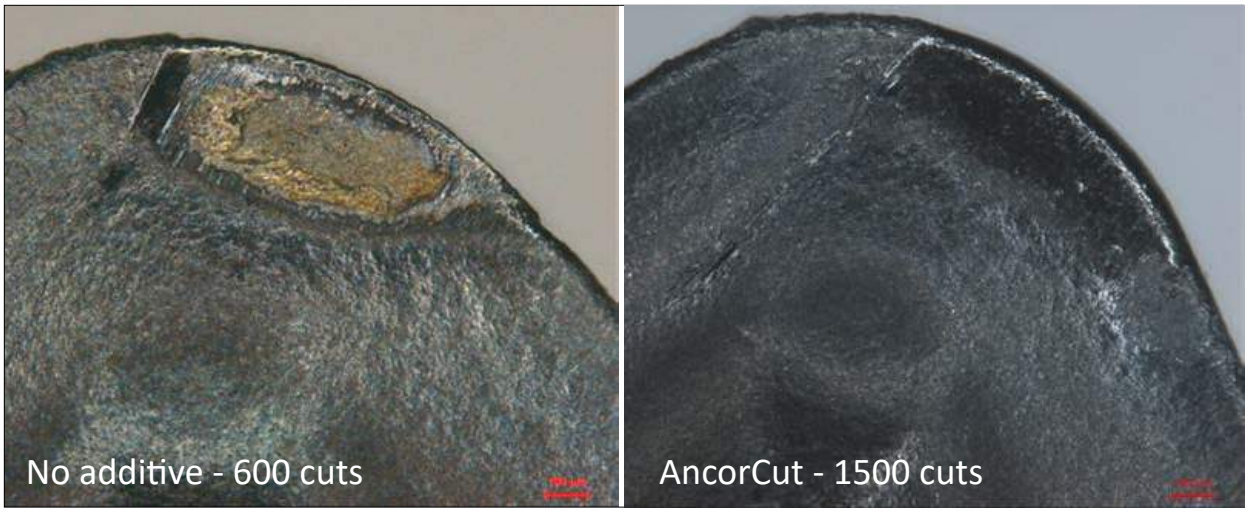

Fig. 10 Crater wear on the cutting tool at 1000 sfm with FC-0208. Imminent tool failure observed after 600 cuts without an additive, whereas extended life and predictable wear are observed with AncorCut

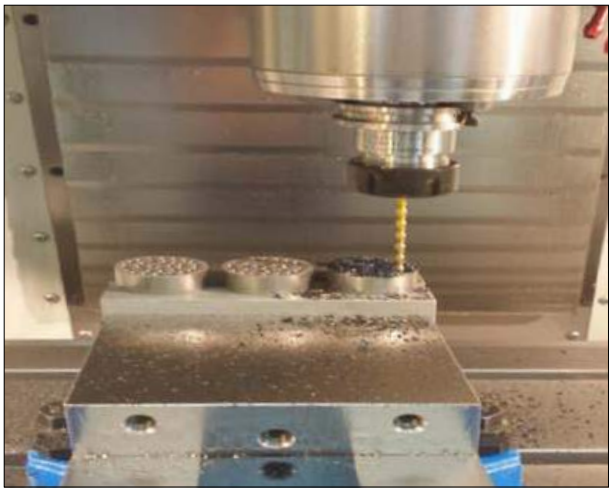

Fig. 11 Drilling setup on the HAAS VF-1

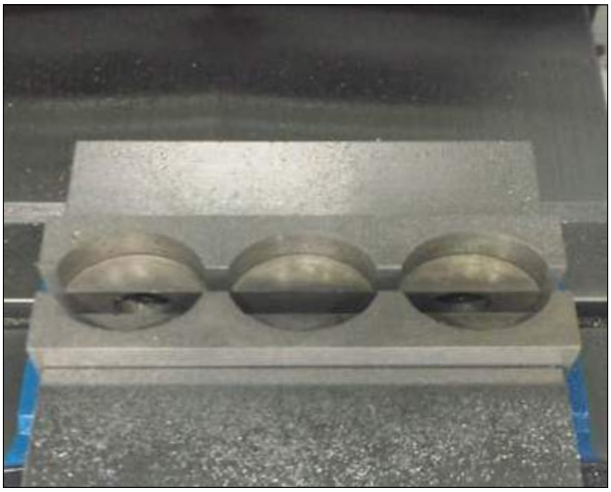

Fig. 12 This aluminium fixture holds the test samples

which can lead to detrimental deposits in the furnace itself. "There is the compelling need for an effective machining additive that can be manufactured in large quantities and characterised by chemical stability along the production chain," stated Lindsley. "Here at the Innovation Centre we have designed a novel machining compound we call AncorCut. This has been extensively tested in Fe-Cu-C and diffusion alloyed (FD-0405) mixes for both turning and drilling operations.

Turning studies have also been conducted on a variety of other alloys, including sinter-hardening grades and carbon free alloys, and improvements in tool life have been observed."

"Additional machining enhancer options provide our customers flexibility in the production process and another tool to manufacture components as efficiently as possible," added Lindsley.

Lindsley and his colleague Cecilia Borgonovo have worked on the development and further testing of this new machining compound. Turning tests were run using a Haas ST-10 CNC lathe equipped with a touch probe to accurately measure part diameter. A target of 1500 cuts on the outside diameter of test samples was typical. Examples of insert wear are shown in Fig. 10. Drilling tests have been carried out on a HAAS VF-1 vertical milling centre, capable of delivering up to 30 hp and 8100 rpm with a resolution of 0.0025 mm. A 2 mm tungsten carbide ball stylus that is 50 mm long was employed for measuring machined parts and hole diameter. The machining setup (Fig. 11) comprises three samples (pucks) held by an aluminium fixture (Fig. 12). 33 holes can be drilled per puck, resulting in a total of 99 holes drilled per cycle.

Two pivotal factors should be used to evaluate machinability in drilling operations, stated Lindsley. Firstly, the number of holes drilled as this provides insights on the life that the tool is expected to have. Long tool life, for example, translates into substantial cost savings in production. Secondly, dimensional tolerances, as larger dimensional variation can result in scrapping of the component during quality inspection. In drilling, hole diameter measurements as the tool wears out can be used to calculate dimensional tolerance.

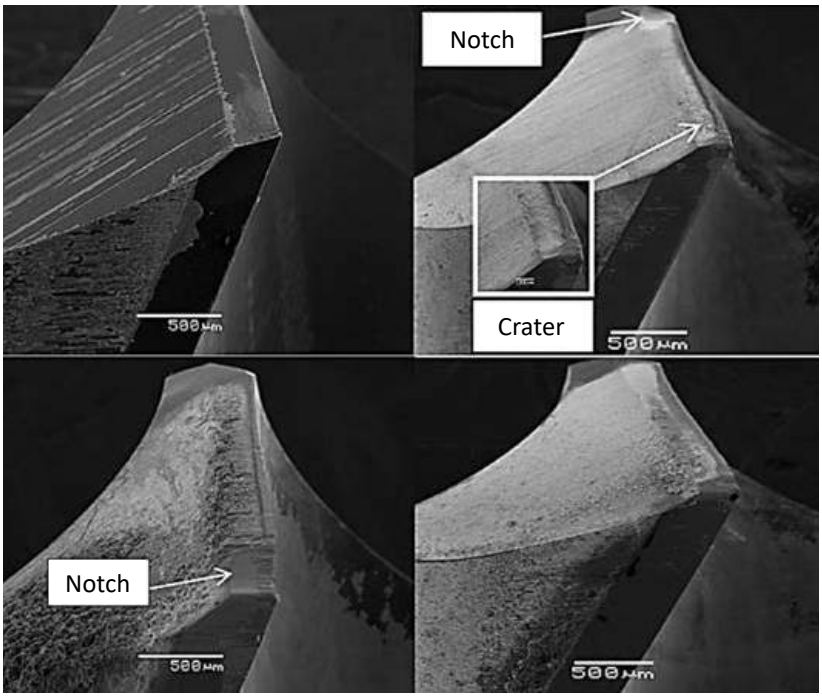

Fig. 13 Top left: New Carbide bit, Top right: FD-0405, Bottom left: +0.35% MnS, Bottom right: +0.2% AncorCut

Expert analysis of each stage

The advantage of undertaking work at the Innovation Centre is that expert analysis of each stage of the process is possible at any point. In the development of AncorCut, this involved the production of detailed micrographs that clearly show the effects of using AncorCut compared with using MnS or no compound. As can be seen in Fig. 13 the presence of grooves and notches on the cutting edge confirms the occurrence of abrasive flank wear when machining FD-0405. Plastic deformation is also present which manifests itself when the cutting temperature is too high for a specific tool-work piece material combination. This plastic deformation dulls the cutting edge, leading to a rapid increase in spindle torque, thereby resulting in short tool life.

Further tests for other drill bit materials have also been undertaken and all show similar results, demonstrating the effectiveness of using AncorCut during the machining operation.

Improving dimensional tolerances for critical PM applications

Working with Hoeganaes' customers in the development and understanding of component manufacture is a significant role of the Innovation Centre. One such example of this is the recent collaborative efforts between MPG Gear Technologies, a PM parts producer based in Subiaco, Arkansas, and Hoeganaes to understand a number of issues in the production of sintered VVT components.

"Iron-copper-carbon Powder Metallurgy steels are the most widely used materials in the PM industry because of their ease of processing, good mechanical properties and relatively low cost. These steels are the material of choice for automotive transmission carriers, main bearing caps, forged connecting rods and VVT components," stated Francis Hanejko, Manager, Customer Applications, at Hoeganaes. Each of these product families has unique mechanical property and dimensional control requirements. However, the VVT product family represents a part category that demands high sintered dimensional control, often exceeding the inherent control capability of the FC-0208 type steel and often requiring extensive secondary machining to meet the product specification.

Dimensional variations result in unacceptable level of rejected parts

Issues with high levels of part rejects due to dimensional variations had resulted in MPG Gear Technologies contacting Hoeganaes. The team at the Innovation Centre set about investigating variables that included density distribution within the part, sintering temperature, production rate, lot-to-lot variations in the apparent density and sintered dimensional control capability of the supplied premix. An optimisation study was performed that investigated each of these variables to minimise the impact on the final sintered part.

The VVT part investigated was a three-level part having a major sprocket diameter of ~134.6 mm with an inner diameter of 84 mm and an overall height of ~20 mm, see Fig. 14. Part mechanical requirements necessitated that the sprocket flange region maintain a sintered density of ~6.9 g/cm^3, while the specification of the major long hub was an overall green density of ~6.8 g/cm^3. The major short hub is formed by a fixed step in the upper punch.

Compaction was performed on a mechanical press and sintering was done nominally at 1120°C for ~25 minutes at temperature in a 95% nitrogen / 5% hydrogen atmosphere. The MPIF FC-0208 powder was premixed using Hoeganaes' proprietary ANCORBOND processing. Quality control testing of the premix evaluated each premix lot for sintered carbon, sintered copper, absolute DC, and DC as measured via difference from a standard lot sintered simultaneously with the production lot. All dimensional change data was measured using MPIF standard

Fig. 14 The VVT part showing major short hub OD on left and major long hub on right

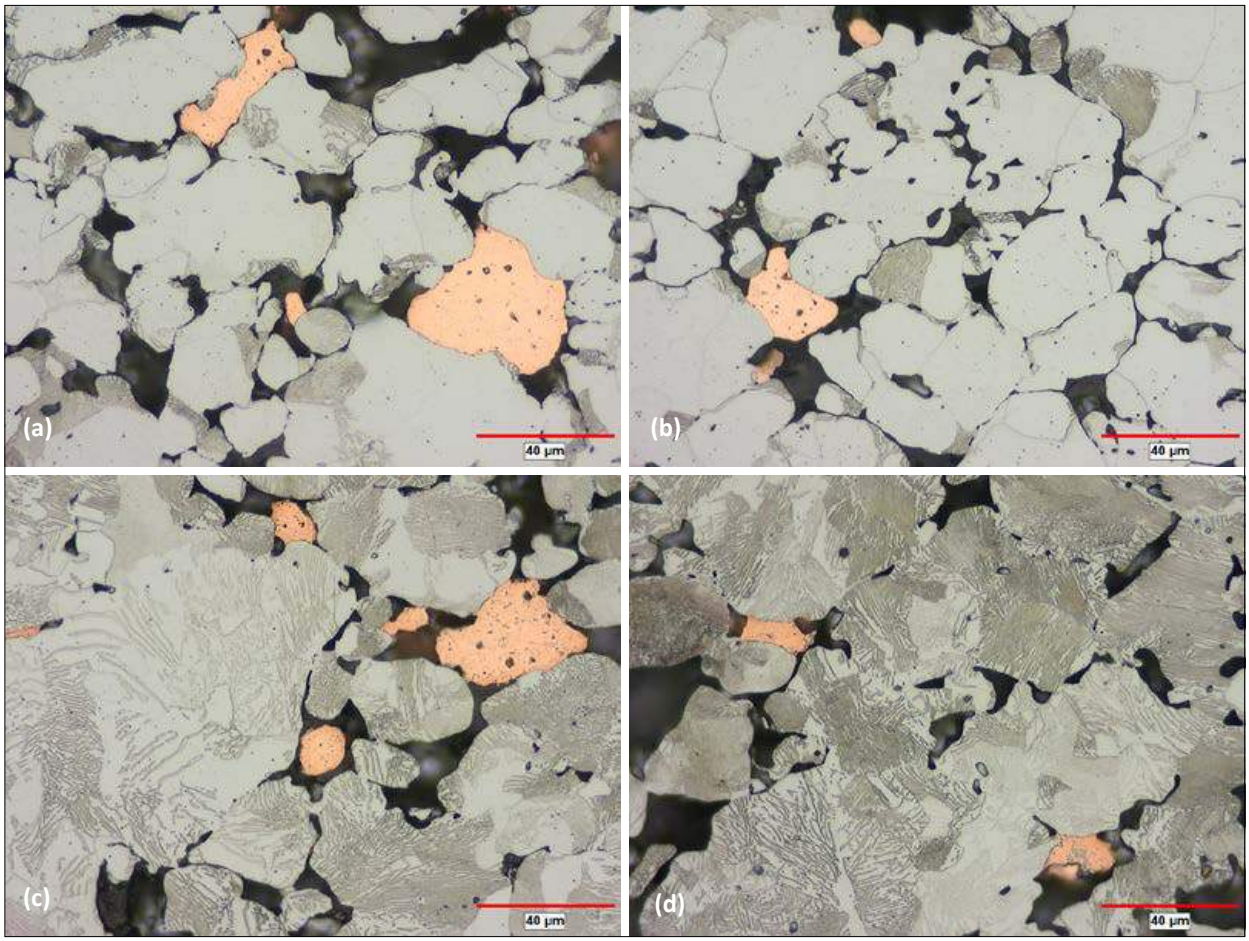

Fig. 15 Carbon diffusion at various temperatures. (a) Sintered at 845°C. (b) Sintered at 870°C (c) Sintered at 980°C and (d) Sintered at 1065°C

TRS bars compacted to 7.0 g/cm³ green density and sintered at 1120°C in a 75% hydrogen / 25% nitrogen atmosphere for 30 minutes at temperature.

"At the start of the project, dimensional variations were resulting in unacceptable levels of rejected parts. Analysis showed that the major cause for part rejection was an under size condition on the critical 84 mm diameter dimension," stated Hanejko.

Modifications to the premix

To produce immediate results, production of the premix was modified to produce greater sintered dimensional change. "This was initially accomplished by substituting ~10% of the standard size copper (-150 micron) with fine copper (-15 micron). This proved successful, but required lot-to-lot adjustments of the amount of the fine copper addition, so as to produce the desired result."

A further modification to the premix evaluated the use of only fine copper to affect the dimensional change desired. This iteration was pursued vigorously because it offered the potential to chemically bond the fine copper, thus preventing potential segregation effects and it offered the possibility of a slight reduction in the total amount of copper added to achieve the same dimensional change, added Hanejko.

Adjusting the copper content

Prior to any changes to the premix, the absolute dimensional change (DC) and difference from standard (DFS) of DC were monitored and recorded. The absolute DC varied by approximately 0.09% and the difference from standard (DFS) varied 0.06%. Both of these values were well within the original specification jointly developed. Analysis of the reject causes showed that the major cause was undersize on the critical 84 mm diameter. Thus, the first change implemented was a transition utilising copper additions of 90% regular copper (-150 microns) and 10% fine copper (-15 microns).

The second major adjustment was the switch to 100% of the -15 micron copper powder. Because of the higher growth associated with the smaller copper particle size, the actual addition rate of the copper was lowered by ~8%, but still within the MPIF specification for FC-0208. The transition to 100% of the -15 micron powder showed an additional 0.1% reduction in non-conformity rates. It was also rationalised that the use of the fine copper enabled more complete chemical bonding of the copper alloy addition to the iron powder. As such, this promoted greater uniformity of the copper distribution with a corresponding improvement in flow rates of the powder.

Metallographic analysis to understand the process

A metallographic analysis of the conditions presented in Fig. 15 show that the onset of graphite diffusion is about 843°C and 100% of the graphite is in solution at approximately 954°C. Thus the dominant variable associated with the copper growth is the melting and diffusion of the copper. Smaller particle size copper did not alter the graphite going into solution. Even with the fine copper addition, the copper particles are readily apparent at temperature up to 1065°C.

Tom Murphy, Scientist, Research and Development, at Hoeganaes, commented, "Just below the melting point of the copper, the fine copper particles show significant solid state diffusion. This would explain the higher growth associated with the smaller copper particle sizes."

Fine copper additions have the disadvantage of giving higher growth for an equivalent weight percentage addition. "This experimental work suggested that a 1.85% fine copper addition gave the same growth as a 2.1% addition of the regular copper. This 1.85% addition is within the specification limits for an FC-0208 and a minor reduction in TRS strength was observed. However, the TRS strength met the nominal limits established in MPIF Standard 35 for FC-0208," added Murphy.

Increasing productivity and reducing rejects

As a result of the collaborative work, it was concluded that it is extremely important to specify the correct standard and specification limits for PM parts, as choosing an inappropriate standard can lead to potentially high rates of non-conforming parts. Careful design of the tooling is also necessary to compensate for the differences in dimensional change resulting from varying part densities, particularly valid in copper steels. It was found that utilising smaller particle size copper additions reduces or eliminates large pores resulting from copper melting, which has the potential advantage of improved mechanical properties. Using a -15 micron copper particle size instead of a -150 micron particle size necessitates that lesser amounts of copper be used. The fine copper addition has a significant large number of copper-iron particle contacts and promotes greater copper diffusion into the iron. With careful control of the premixing and utilising the proper standards, it is possible to maintain a +/- 40 micron tolerance on an 84 mm diameter.

By working closely with the Innovation Centre it was possible to achieve a significant reduction in non-conforming parts, along with a corresponding reduction in inspection costs and improvement in part productivity.

Fig. 16 ExOne binder jet system allows Hoeganaes to apply its primary metal powder understanding to the development of advanced metal powders for the growing Additive Manufacturing sector

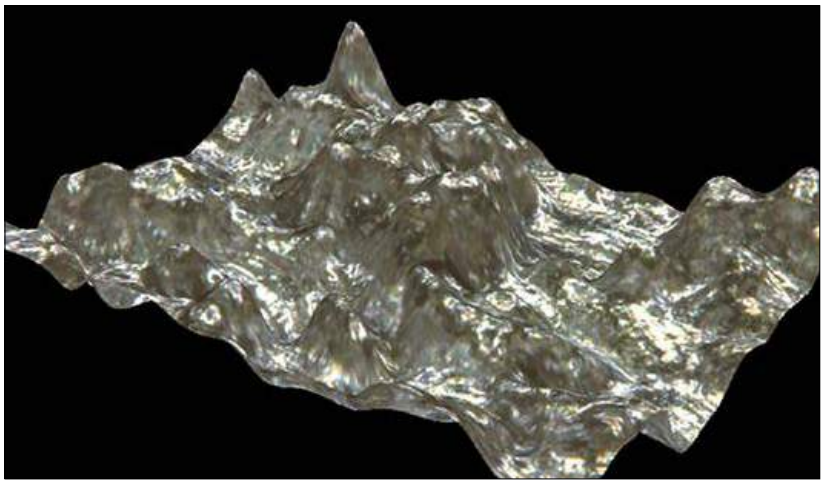

Fig. 17 Stereomicroscopy showing the side of a build in an area without direct contact with the electron beam

A resource for the Additive Manufacturing sector

As well as the newly installed pilot gas atomiser, the Innovation Centre has some of the latest Additive Manufacturing production equipment on-site including an ExOne binder jet printer (Fig. 16). This allows Hoeganaes to apply its primary metal powder understanding to the development of advanced metal powders for the growing Additive Manufacturing sector.

Numerous projects have already been undertaken at the Innovation Centre including work to analyse titanium powders for use in Additive Manufacturing. Much of the existing analytical equipment is ideally suited to understanding issues with metal AM components and processes. "An integral part of producing titanium

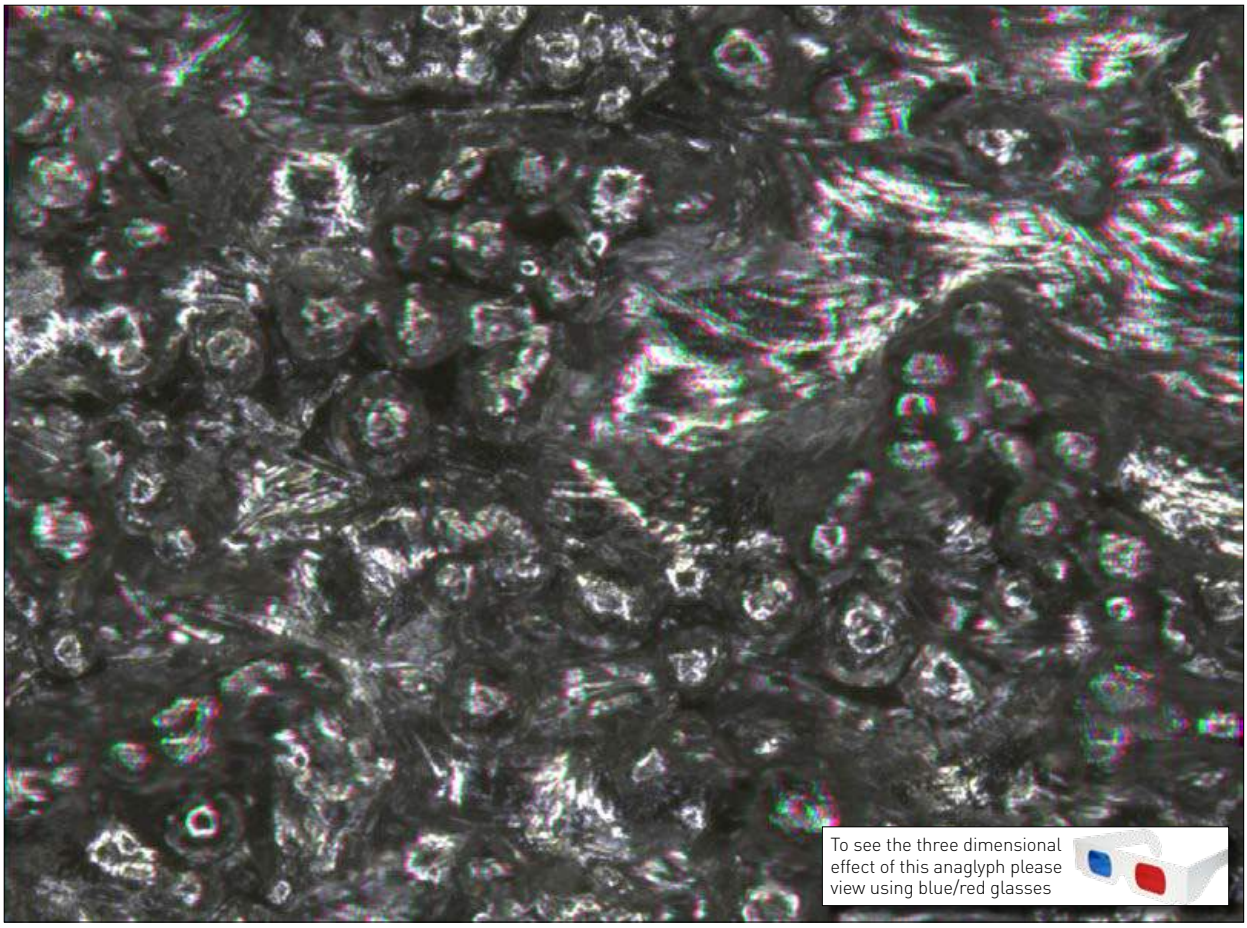

Fig. 18 When viewed using simple red/blue glasses the three dimensional nature of this anaglyph can be clearly seen

powders for use in AM is providing test data demonstrating the quality, uniformity and consistency of the products. Typically, chemical, mechanical, physical, and metallographic tests are performed to ensure the powders meet or exceed the expectations and requirements of specific applications," stated Murphy. "Each test discipline provides unique information on the particle properties and expected behaviour of the powder as the AM parts are produced."

The use of metallographic testing demonstrates the physical characteristics of particle shape and size distribution, along with allowing the surface textures to be examined as shown in Fig. 17. In addition, the microstructural constituents of internal porosity, non-metallic inclusion content, microstructure and alloy distribution can be identified.

During our visit, Murphy also presented a series of anaglyphs, essentially three dimensional micrographs, of titanium components. When viewed using simple red/blue glasses these produced stunning images, highlighting the real depth of surface textures (Fig. 18).

As previously stated, Hoeganaes is also actively developing water atomised ferrous powders for the AM process in what could result in an extremely cost effective supply option and open up the metal AM sector to further applications.

Conclusion

What became clear from *PM Review's* visit is that the real value of the Innovation Centre lies in the scientists and engineers, past and present, who have developed new powders, solved problems and passed on a wealth of knowledge to the Powder Metallurgy industry for more than fifty years.

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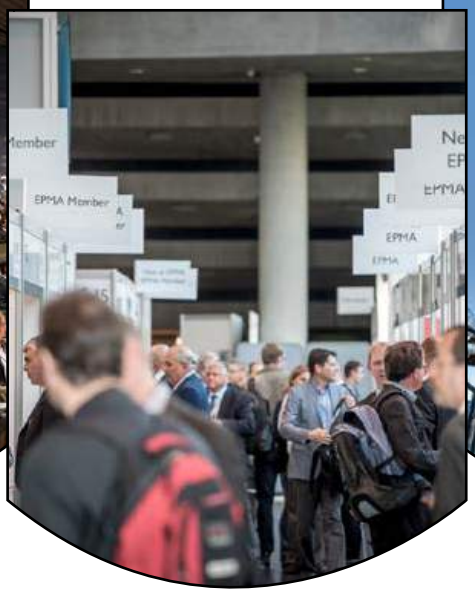

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The master alloy route: Introducing attractive alloying elements in Powder Metallurgy steels

The use of Cr, Mn and Si as alloying elements could offer improved properties in sintered steels whilst at the same time reducing powder costs. Successful sintering of these powders is, however, a challenge that requires deep knowledge of the chemistry behind the sintering process. Dr Raquel de Oro Calderon describes work undertaken by her and colleagues at TU Wien that identifies the master alloy route as a promising solution to address the challenges of applying these elements.

Improving the properties of highly loaded structural parts, combined with reduced and stable alloying costs, may create the key to new and challenging applications that could boost the use of PM components. The addition of effective alloying elements such as Cr, Mn and Si offer high potential for improving the properties of sintered steels, at a low and stable pricing level. For this reason, these elements have been the main focus in the so called 'lean steels' (steels with improved properties at limited levels of alloying content) which have been a prolific area of research during recent years. However, the use of these promising alloying elements in sintered steels requires a deep knowledge of an aspect of sintering that traditionally plays a secondary role, namely the chemistry of the sintering process. In this article, the most significant challenges to successfully sintering steels containing Cr, Mn and Si are analysed. In particular, the master alloy route is explored, as a promising area of research that offers the possibility of tailoring the composition of the alloying particles in order to adjust the final properties to the requirements of different applications.

	Prealloying Route	Master Alloy Route
Oxygen Affinity	(M) Homogeneous oxygen affinity of oxidation sensitive elements	(M) Oxygen affinity depends on the master alloy composition. Differences in oxygen affinity between base powder and master alloy (heterogeneous)
Compressibility	(M) Lower than in mixes, but in part compensated by shrinkage in sintering	(F) Small additions allow preserving the compressibility of the base powder
Flexibility	(U) Fixed compositions	(F) Composition can be tailored by modifying the amount of master alloy added, or by using different base powders
Homogeneity in distribution of alloying elements	(F) Fully homogeneous microstructures	(M) Homogenization depends on diffusion rate of alloying elements in the base powder. It can be improved by designing master alloys that form a liquid phase
Cost	(U) High price in comparison with the common iron grades	(M) When master alloys are added in small amounts, the overall effect in price is limited

Fig. 1 Characteristics of the two most relevant alternatives to introduce elements with high oxygen affinity: Prealloyed or Master Alloy route. Code: (F)= Favourable, (M)=Medium, (U)= Unfavourable

The search for alternative alloying elements

In recent years, the volatility in prices of the most common PM alloying elements (Cu, Ni, Mo), together with recent regulations limiting the use of Ni and environmental problems related with Cu containing parts, are demanding the search for new alloying alternatives that allow a lower-cost production combined with the achievement of a high level of properties.

Cheaper and more efficient alloying elements such as Cr, Mn and Si, are widely used in the production of wrought steel parts. Cr is the most common alloying element in heat treatable structural steels, offering attractive properties at moderate alloying cost. Manganese is one of the cheapest alloying additions and gives the highest multiplying effect in terms of hardenability. Silicon increases the strength of ferrite by solid-solution hardening, refines the structure of pearlite and increases hardenability. Additions of Si cause a large shrinkage of PM parts, but the combination of Si with Mn increases the effect on hardenability, compensates for the dimensional changes and accelerates sintering, leading to high mechanical properties [1, 2].

Implementing the use of combinations of alloying elements, such as Cr, Mn and Si, in sintered steels could open the door to a new variety of compositions, properties and prices. However, processing these systems seems to be demanding, both with regard to the atmosphere purity needed to avoid oxygen pickup and to the sintering conditions needed to remove the oxygen introduced through the starting powders.

The traditional alloying elements used in sintered steels - mainly Cu, Ni and Mo - have an oxygen affinity very similar to that of Fe and, as a consequence, any conditions suitable for sintering Fe powders should be sufficiently good to efficiently remove the oxides present in these alloying powders. However, the situation changes when considering the addition of elements such as Cr, Mn and Si, which have higher oxygen affinity than Fe and therefore form more stable oxides. This does not mean that sintering is not possible, but it means that the chemical aspects of sintering – traditionally ignored- will now play a major role [3].

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The easiest way to assess the problems related to the introduction of alloying elements with a high oxygen affinity is to combine them with other elements with a lower affinity for oxygen, for instance Fe [4, 5]. In such a way, the chemical activity of the oxidation-sensitive elements can be significantly reduced. There are basically two main routes to achieve this (Fig. 1), either by the use of completely prealloyed iron powders, or by mixing a plain iron base powder with a master alloy powder (a powder which contains all of the alloying elements in a combined form, typically also including Fe). Compared to prealloying, the master alloy route presents clear advantages such as the possibility to maintain the compressibility of the base powder, more flexibility in the selection of the final composition of the steel and the potential for overall cost reduction (as prealloyed powders are among the most expensive grades on the market). In addition, it is possible to specifically tailor the composition of the master alloy to promote the formation of a liquid phase that enhances the sintering mechanisms.

However, in order to implement the use of master alloys as a real alternative, a deep understanding of aspects such as the effect of the master alloy composition on microstructural homogenisation, dimensional stability and suitable sintering conditions is a necessity. This article presents some of the keys to understanding these phenomena, which represent a challenge for the use of master alloys, but can also provide some very interesting potential benefits.

Sintering of steels containing additions of Cr, Mn and Si

A mandatory prerequisite for a successful sintering process is to reduce the oxides naturally covering the surface of all powder particles. This then allows the interdiffusion of atoms between particles and thus the growth of sintering necks. A very useful and efficient tool for studying the chemical reactions taking place during sintering is the use of advanced thermal analysis techniques. Particularly, the combination of thermogravimetry analysis with mass spectroscopy is very effective, as it allows the registration of the mass gains/losses in the sample simultaneously with the observation of the gaseous species evolved during the process. This provides information about the chemical species involved in different oxidation/reduction reactions.

As a simple example, the reduction of a water atomised plain iron powder mixed with graphite is shown in Fig. 2-a. In an inert atmosphere (such as Ar), the only reducing agent available is carbon, admixed to the plain iron powder as graphite. Reduction of the oxides with the admixed graphite takes place through the

carbothermal reactions indicated in equations (1) and (2). Either C or CO (produced at temperatures above 700°C due to the Boudouard equilibrium equation (3)) will assist the reduction processes. As is observed in Fig. 2a, the first mass loss registered in these conditions is at ~800 °C and, at this temperature, a simultaneous m28 (CO) peak is also observed. This phenomenon is associated with the reduction of the iron oxide layer that covers most of the surface of the iron powder. After this first mass loss, a second reduction process is observed with an m28 (CO) peak of lower intensity and a further mass loss. This second reduction process (observed at ~1100°C) has been attributed to the reduction of more stable oxides, or internal oxides that need high temperatures to diffuse to the powder surface [6, 7].

$$Me_xO_y + yC = xMe + yCO \quad (1)$$

$$Me_xO_y + yCO = x\,Me + yCO_2 \quad (2)$$

$$C + CO_2 = 2CO \quad (3)$$

It is therefore clear from these experiments that the common sintering temperature (1120°C) would be sufficient to reduce most of the oxides present on water atomised Fe powders, by reaction with the admixed graphite. Therefore, successful sintering can be easily carried out at conventional sintering conditions. However, what are the differences when oxygen sensitive alloying elements are introduced? How does the presence of these elements modify the oxidation/reduction reactions typical of the iron base powder?

Figs. 2 b,c and d show the oxidation/reduction phenomena observed when sintering steels containing small additions (4 wt. %) of alloying elements with high oxygen affinity (Cr, Mn and Si). A very interesting effect is clearly observed in mixes with Cr and Mn (Fig. 2b,c): The first reduction peak at ~800 °C is considerably reduced in intensity (or even completely absent) and a flat line is observed in the thermogravimetry curve. This effect takes place because the oxygen-

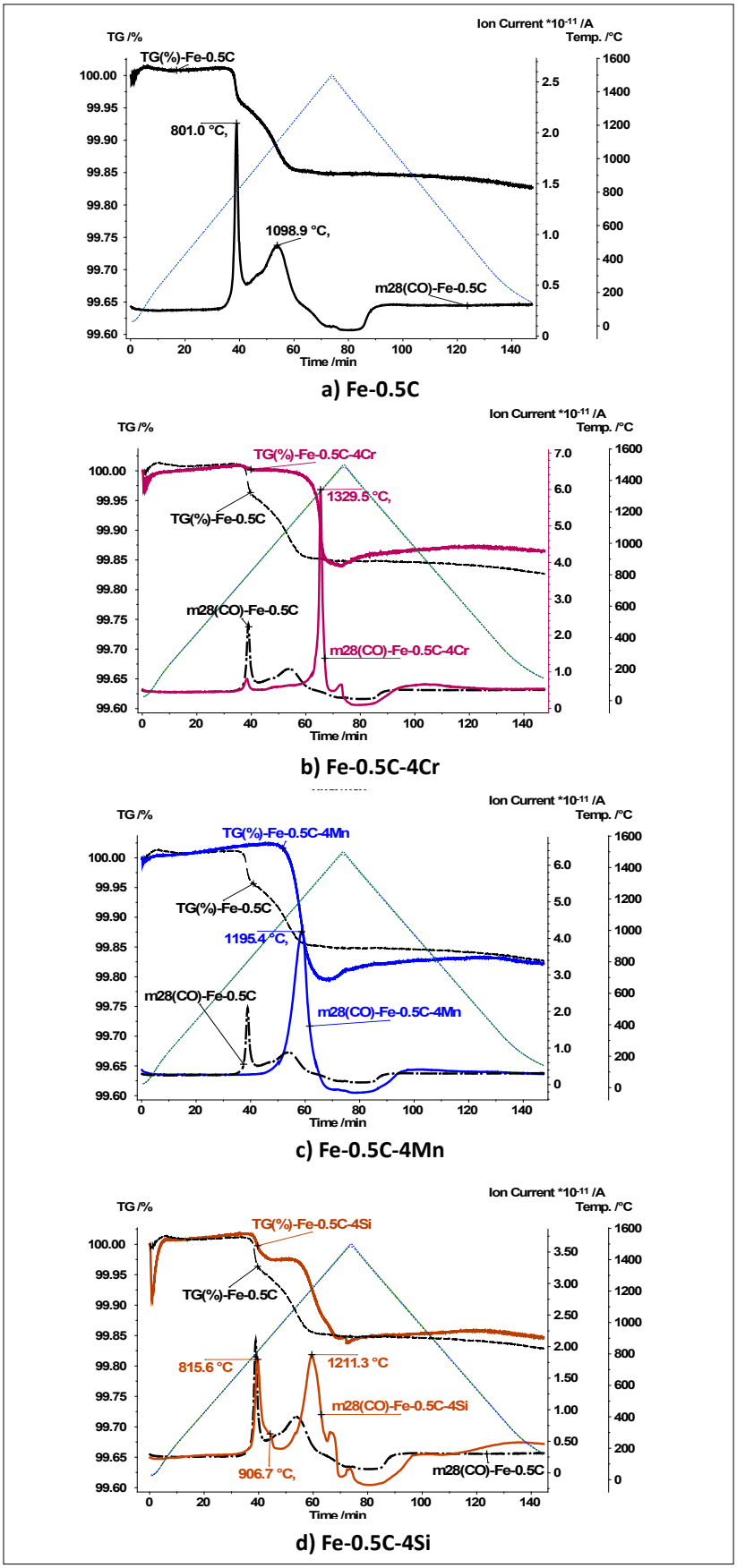

Fig. 2 Oxidation/Reduction phenomena when sintering steels containing elemental additions of Cr, Mn, Si: (a) Fe+0.5C, (b) Fe+0.5C+4Cr, (c) Fe+0.5C+4Mn, (d) Fe+0.5C+4Si

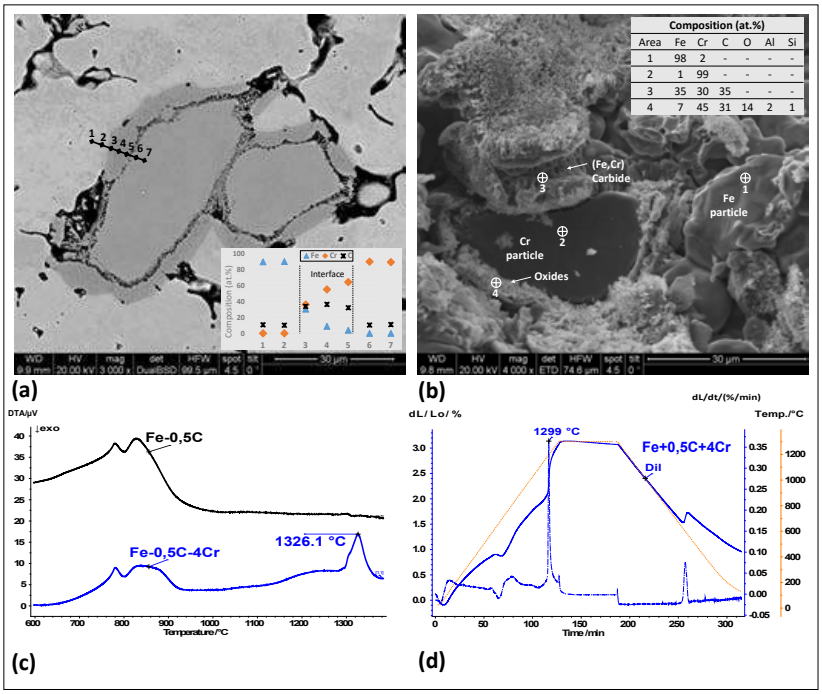

Fig. 3 Features of the Fe-0.5C-4Cr system: Cross section (a) and fracture surface (b) of Fe-0.5C-4Cr steels sintered at 900°C for 30 min in Ar. (c) Differential thermal analysis (DTA) curve and dilatometry curve (d) for sintering runs in Ar atmosphere

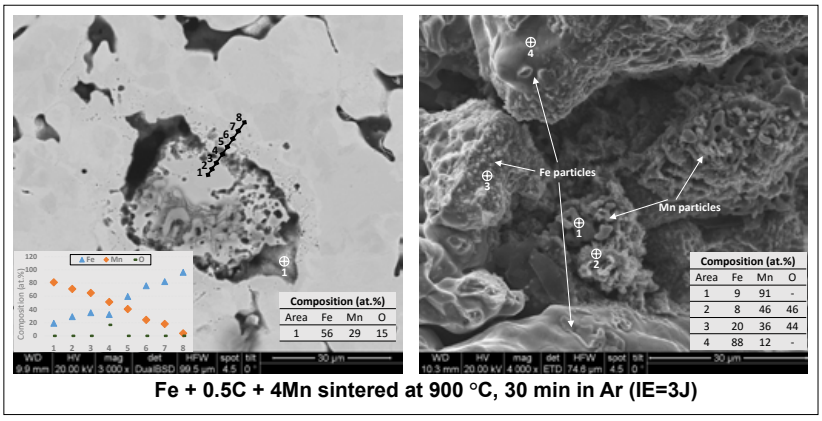

Fig. 4 Cross section (left) and fracture surface (right) of Fe-0.5C-4Mn steels sintered at 900°C in Ar for 1h

sensitive alloying elements are acting as "internal gettering agents", which means that, after the reduction of the iron oxides, the gaseous products (CO or CO_2) immediately react, oxidising the alloying particles. Thus, at this temperature, there is simply an oxygen transfer from the iron base powder to the alloying particles and, for this reason, the mass of the sample is constant. As a consequence, the reduction reactions are shifted to considerably higher temperatures, due to the formation of oxides with high stability. This oxygen transfer is a phenomenon to always consider when sintering compacts from powder mixes with widely differing oxygen affinity [3].

One of the most important practical implications of the internal gettering effect observed in steels containing oxidation-sensitive elements is the fact that, even in atmospheres of very high quality, this type of oxidation cannot be avoided, as the main source of oxygen is the base powder itself. A redesign of the sintering cycles (delubrication temperatures, heating rates, etc.) is therefore an imperative in this case. In fact, for steels containing Cr and Mn, the temperature range of maximum susceptibility to this internal gettering effect is approximately between 400 and 1100°C, which overlaps with the common delubrication temperatures (~600°C).

The experiments with Si show a slightly different behaviour. As Si forms a protective oxide, no oxidation of the Si particles is hinted below 900°C (Fig. 2d). In this case, the reduction of the iron oxide layer is observed at the expected temperature of ~800°C. However, at ~900°C the mass loss stops, indicating that the Si particles start acting as internal gettering agents. As a consequence of this effect, more intense reduction peaks are observed at high temperatures due to the presence of an increased amount of oxides with higher stability. It is interesting to note that, in spite of being the element with the highest affinity for oxygen, the risk of oxidising Si particles in the lower temperature range (400-900°C) -by the internal gettering effect- is considerably lower than with Mn and Cr.

The consequences of this internal gettering effect can be observed when sintering these steels at temperatures within the 'risky' range. As can be observed in Fe-C-Cr steels sintered at 900°C for 30 min in Ar (Fig. 3a-b), the oxides are concentrated on the surface of the Cr particles and a carbon rich layer is formed on the interface between Cr and Fe particles. The presence of this carbon rich layer is in agreement with the findings of Danninger et al. who reported the formation of a carbide layer at the Fe-Cr interface in Fe-Cr-C compacts [8, 9]. As a consequence, the oxides formed by the internal gettering effect are enclosed inside the carbide shells and their reduction is only possible after these carbides melt through the formation of a transient liquid phase at ~1330°C (see thermal analysis in Fig. 3c). This is the reason why the reduction processes in

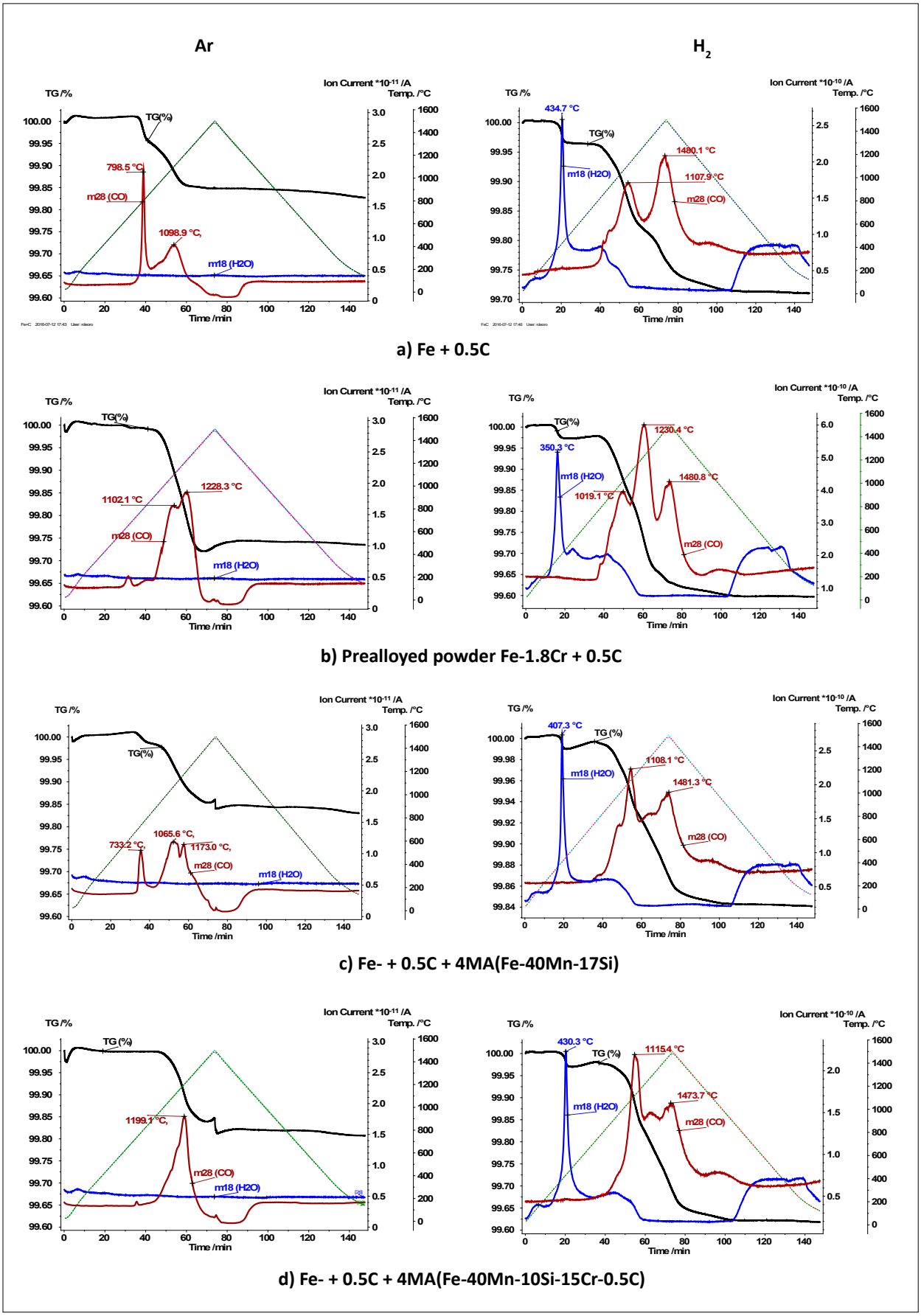

Fig. 5 Oxidation/Reduction phenomena when sintering different types of steels: a) Fe+0.5C, b) Cr-prealloyed powder Fe-1.5Cr + 0.5C, c) Master Alloy Fe+0.5C+4MA(Fe-40Mn-17Si), d) Master Alloy Fe+0.5C+4MA(Fe-40Mn-10Si-15Cr-0.5C)

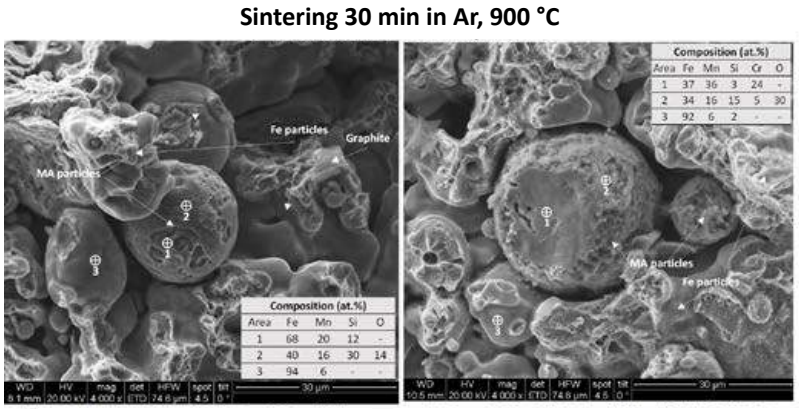

Fig. 6 Fracture surfaces of steels containing master alloy additions, sintered at 900°C for 30 min in Ar: a) Fe+0.5C+4MA(Fe-40Mn-17Si), b) Fe+0.5C+4MA(Fe-40Mn-10Si-15Cr-0,5C)

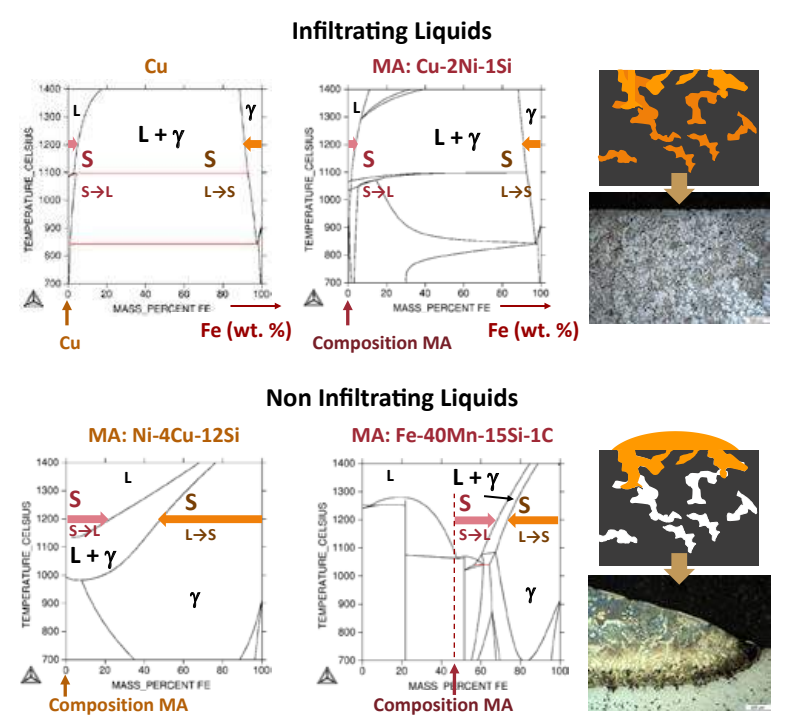

Fig. 7 Design of liquid phases. Typical phase diagrams for non dissolutive/ infiltrating, and dissolutive/non infiltrating liquids

Fe-C-Cr mixes (Fig. 2b) are shifted to temperatures of ~1330°C, much higher than the temperatures needed to reduce Cr oxides. Besides causing a pronounced swelling effect (see Fig. 3d), formation of these carbides has another practical implication, the need for using high sintering temperatures in order to achieve sufficient microstructural homogenisation.

When sintering Fe-Mn-C mixes under the same conditions (900°C for 30 min in Ar), no compounds are formed at the interface and the diffusion of Mn in Fe at this temperature is obvious, as shown by the concentration profile observed between the particles (Fig. 4). The unique gas phase transport mechanism of Mn is responsible for the homogenisation of this element, apparent even at low temperatures [10, 11]. On the other hand, oxidation of manganese vapour and its subsequent condensation on the surrounding iron particles creates an oxide network that suppresses interparticle neck development in areas extending up to a couple of hundred micrometres around the manganese source [12, 13]. This has a very detrimental effect on mechanical properties. For instance, for a Fe-0.5C sample sintered at the same conditions, the impact energy was ~15 J and the addition of only 4 wt. % Mn decreased the impact energy to 3 J (about 5 times lower).

Chemical reactions during sintering when using prealloyed and master alloy powders

The use of prealloyed or master alloy powders, as an alternative to the introduction of elemental Si, Mn or Cr, has been traditionally used as a means of reducing the risk of oxidation. The chemical processes occurring when sintering plain iron powder, Cr-prealloyed iron, as well as combinations of plain iron with different master alloys are summarised in the results from thermal analyses gathered in Fig. 5. In the case of water atomised plain Fe (Fig. 5a) it is interesting to observe that the iron oxide layer covering the powder surface can be reduced with H_2 at fairly low temperatures (~400°C) producing H_2O. The reduction of more stable oxides, however, necessarily takes place by reaction with C, which is the most effective reducing agent at high temperatures [6, 7, 14].

In the case of Cr-prealloyed powders, the first reduction process in H_2 is also observed at ~400 °C (Fig. 5b, right), which confirms that the surface of Cr-prealloyed powders is mainly covered by an easily reducible iron oxide [6, 7, 14, 15]. If the sintering process is carried out in inert atmosphere (Fig. 5b, left), the first reduction peak, indicating removal of these surface oxides, should emerge at 700-750°C, as encountered in Fe-C (see Fig. 5a, left). However, there is virtually no reduction peak (m28 =

CO) at this temperature, but the first reduction stage occurs at about 1000°C. This indicates that, within the temperature interval 400- 700°C, the iron oxides present at the powder surfaces must be transformed into more stable oxides, primarily Cr oxides. This transfer process is in fact an internal getter effect within each powder particle and occurs at temperatures below 700-750°C [3].

The internal gettering effect is also present when using master alloy particles, but its intensity is strongly dependent on the alloy composition [16]. In this case, the oxygen transference occurs from the base iron powder to the master alloy particles (as in the case of mixes with elemental powders). Compared to the addition of elemental Cr, Mn, Si powders, the use of Fe-40Mn-17Si master alloys considerably reduces the internal gettering effect, as the reduction peak expected at ~700 °C is clearly present but at a reduced intensity (Fig. 5c, left). However, the addition of Cr to the master alloy composition causes a dramatic increase of the internal gettering effect and the peak at ~700°C is now virtually absent.

It is important to remark that, for both master alloy and prealloyed powders, the use of H_2 atmospheres is very efficient in the alleviation of the internal gettering effect, because the Fe oxides are reduced by H_2 at temperatures at which the oxygen transference is still not kinetically favoured. However, as stated above, interference with delubrication processes has to be considered.

The introduction of Mn in the form of a master alloy powder presents further advantages, as this can be used to control Mn evaporation. Formation of Mn gas is reduced through diluting it in a master alloy and, as a consequence, the condensation of Mn oxides on the surrounding Fe particles is considerably lower (see Fig. 6). This has a clear effect on the properties, increasing the impact energy of Fe-Mn-C compacts sintered at 900°C to values similar to those obtained in Fe-C compacts under similar conditions.

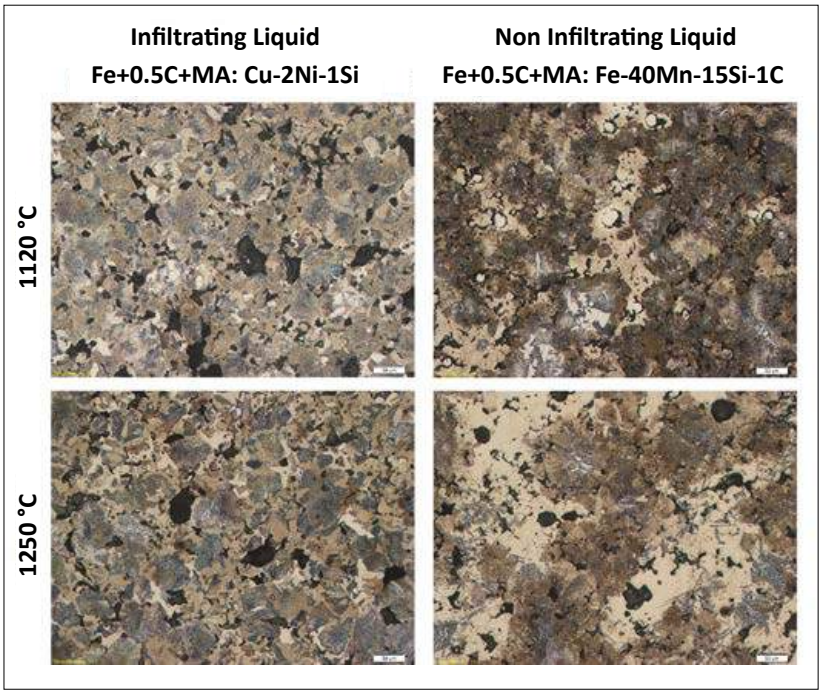

Fig. 8 Typical microstructures obtained with infiltrating and non infiltrating liquids

Dimensional stability and microstructural homogenisation in steels containing master alloys

Probably, one of the most interesting benefits of using master alloys is the fact that its composition can be specifically designed to promote the formation of a tailored liquid phase that enhances the distribution of alloying elements and accelerates the sintering processes [6, 17-20]. In order to control the final properties of the steel, the design of compositions must consider not only the melting point/ranges of the master alloys, but also the expected interactions with the Fe base powder. In particular, the solubility ratio between the liquid and solid phases, that can be deduced from phase diagrams such as those shown in Fig. 7, plays a very important role [21-24].

The solubility conditions between the liquid phase and the solid substrate strongly determines the infiltration behaviour of the liquid. As can be observed in Fig. 7, infiltrating liquids present significantly lower solubility of the liquid-forming elements in the solid ($S_{L\rightarrow S}$ in the graph) and lower solubility of the base metal Fe in the liquid phase (highlighted as $S_{S\rightarrow L}$ in the graph).

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The final microstructure of the steel is clearly affected by the infiltration properties of the liquid formed (Fig. 8). Infiltrating liquids have the ability to penetrate the pore network and spread through it immediately after melting. An excellent distribution of the liquid within the green compact promotes the development of homogeneous final microstruc-

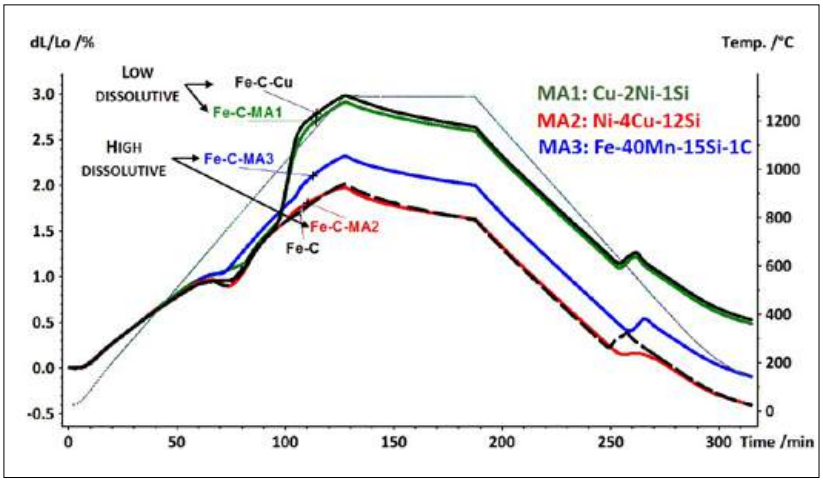

Fig. 9 Effect of dissolutive/non-infiltrating, and non-dissolutive/infiltrating liquids on the dimensional stability of steels containing master alloys

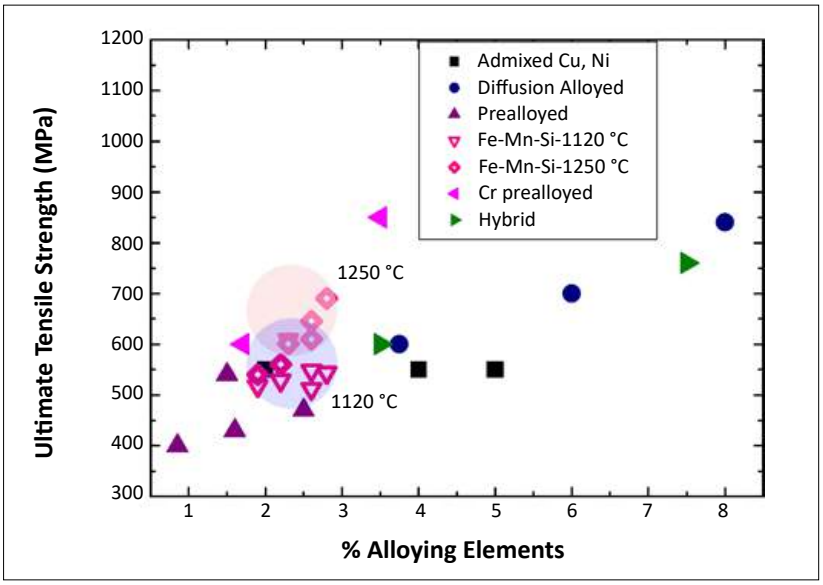

Fig. 10 Ultimate Tensile Strength (UTS) vs. % Alloying elements for commercial steels and steels containing Fe-Mn-Si master alloys sintered at 1120°C and 1250°C

tures. With this type of liquid, the particle size of the master alloy powder determines mainly the size of the secondary porosity in the final microstructure, but the homogenisation of the microstructure is ensured by the good infiltration capacity of the liquid.

On the other hand, in non-infiltrating liquids, both the dissolution of the surrounding Fe base particles and the dissolution of the alloying elements from the liquid in the Fe base particles are enhanced by the high $S_{L\rightarrow S}$ and $S_{S\rightarrow L}$- values. As a consequence, the composition of the liquid phase changes, eventually leading to solidification and the blocking of the access to the interconnected porosity (similar to reactive fillers used for brazing of PM steels). Thus, the alloying elements remain concentrated in the vicinity of the original master alloy particles. These non-infiltrating liquids have a tendency to provide heterogeneous microstructures unless the particle size of the master alloy is already sufficiently small to grant fairly even distribution in the green compact. In this case, the final microstructures and therefore the mechanical properties can be expected to be more sensitive to the particle size of the master alloys and their proper distribution within the mix. In that respect, masteralloys that form dissolutive liquid phases even through congruent melting can be compared to alloy elements that form transient liquid phase through (eutectic) reaction between alloy and base elements [25].

In addition to the microstructure, the dimensional changes observed during sintering are also strongly dependent on the infiltrating properties of the liquid phase (Fig. 9). Infiltrating liquids present significant swelling exactly at the temperature at which the liquid phase is formed, the so called copper swelling effect [26-28]. For non-infiltrating liquids, in contrast, the dimensional changes during heating are considerably lower.

A proper study of the solid-liquid interaction during the design of master alloy compositions, therefore, offers the possibility of adapting the composition of the master alloy to meet the requirements needed for specific applications.

Mechanical properties of steels modified with master alloy additions

A preliminary evaluation of mechanical properties has been carried out using non-infiltrating Fe-Mn-Si master alloys with slightly different compositions (in some cases with small additions of C and Cr). The objective of this first study was to evaluate the potential level of properties that can be obtained by sintering in conditions similar to industrial ones. Steels modified with small additions of Fe-Mn-Si based master alloys were delubricated at 600°C in N_2 atmosphere and sintered at 1120°C and 1250°C for 30 min in N_2-5%H_2. The master alloy powders were produced by gas atomisation in N_2 and the"as atomised" particle size distribution was used (d_{50}~20 µm and d_{90}~80 µm). Mechanical properties are compared with the properties

of conventional commercial steels sintered in equivalent conditions (data obtained from [29, 30]). Most of these commercial steels contain Ni, Cu and Mo as admixed alloying elements, prealloyed, diffusion alloyed or in a hybrid condition (prealloyed powder with diffusion alloyed particles). Cr-prealloyed grades are considered individually from prealloyed grades, as the latter ones include only Mo or Ni-Mo prealloyed powders.

Fig. 10 presents the Ultimate Tensile Strength (UTS) values against the amount of alloying elements introduced in the steel. In general, the UTS values seem to be improved at higher additions of alloying elements. However, the use of Fe-Mn-Si master alloys and Cr prealloyed grades can provide very competitive values of UTS, with a total addition of inexpensive alloying elements that is below 3 wt. %. In Fig. 11, the mechanical properties of different types of steels are represented as UTS vs. Elongation and Apparent Hardness vs. Impact energy graphs. The UTS values obtained for steels containing Fe-Mn-Si master alloys are combined with elongations of around 1-2%, comparable with the values obtained with many commercial grades. When sintering steels containing master alloy at 1250°C, the increase in elongation can be substantial and a similar effect is observed with the impact energy, which underlines the well-known effect of better microstructural homogeneity and oxide reduction.

In general, the properties of steels containing master alloy particles, processed in standard conditions, are comparable with the properties obtained with many commercial grades and therefore could be used in practice as a low cost alternative. However, it has to be considered that the sintering conditions in this case have not been adapted for the specific requirements of these materials and this would provide a very significant beneficial effect on the properties and the robustness of the process

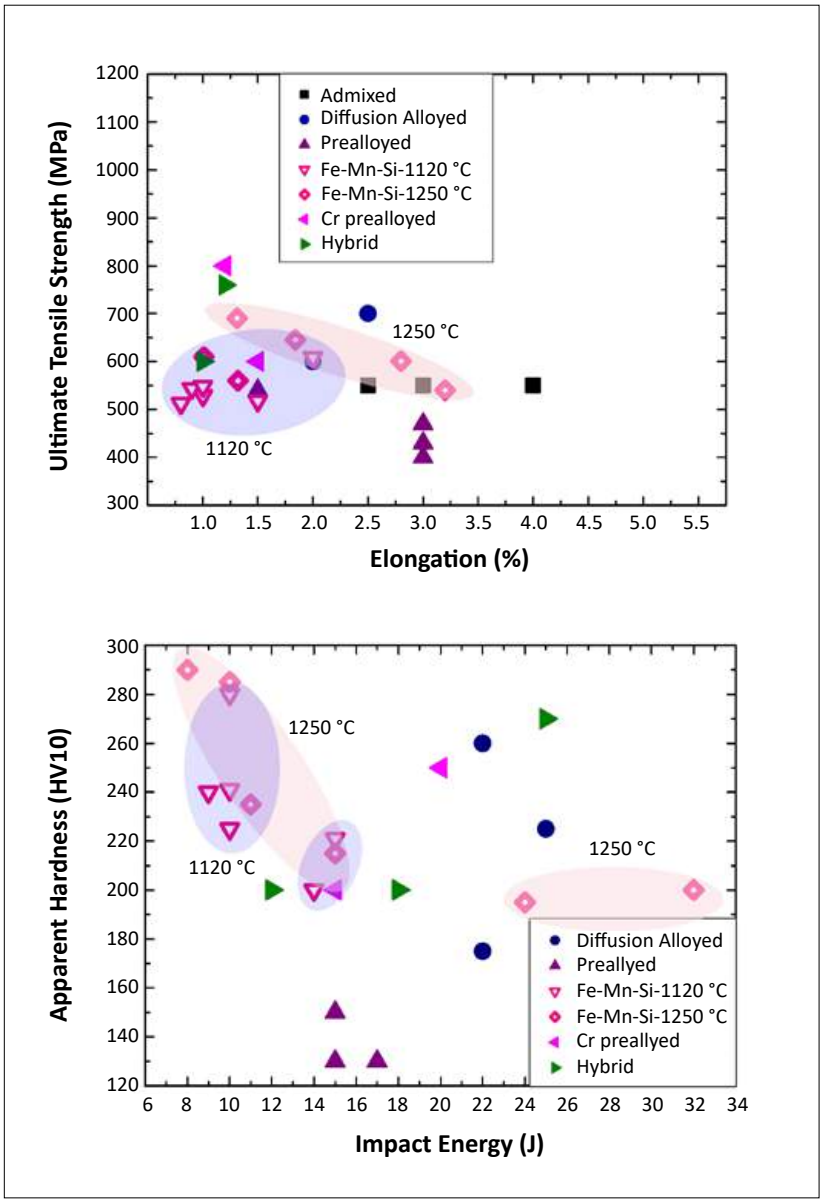

Fig. 11 Ultimate Tensile Strength (UTS) vs. Elongation (%)- left, and Apparent Hardness vs. Impact energy for commercial steels and steels containing Fe-Mn-Si master alloys sintered at 1120°C and 1250°C

Challenges to the commercial adoption of master alloys

The introduction of promising alloying elements such as Cr, Mn and Si has been a matter of research since the early 1970s. Significant advances have been made in the field of Cr-prealloyed grades, which nowadays are commercially available and are used by many parts producers. The use of master alloys however is not so extensive, mainly due to the following restrictions.

The high cost associated with the production of the master alloy

Favourable particle sizes and oxygen contents require the use of gas atomisation techniques and the amount of powder with interesting particle sizes yielded by this technique is low in many cases. However, nowadays, new alternative production methods are being developed. The ultra-high pressure water atomisation developed by a major manufacturer of atomising equipment can produce master alloys containing high amounts of Cr, Mn and Si, with low oxygen contents (below 1 %) and

small particle size distributions (as indicative values d_{50}~10 µm, d_{90}~30 µm), at very low production costs.

The small particle sizes needed to ensure a good distribution of alloying elements
For many master alloy compositions, small particle sizes are needed to obtain a reasonable distribution of alloying elements. This should mainly be a challenge if using non-infiltrating master alloys, but, in the case of infiltrating liquids, in contrast, particle sizes below 40 µm might be enough to control the size of the secondary porosity and avoid a detrimental effect on properties. Also, the new production methods, able to provide very low particle sizes, should be a way to overcome this problem. Of course, when using small particle sizes, special care must be taken to avoid agglomeration problems in particular.

The risk of oxidation and therefore the robustness of the production processes
This is one on the main challenges and requires a deep understanding of the chemical reactions occurring during sintering. A proper design of the sintering conditions adapted to the master alloy composition should provide robust products and processes. However, this would require adapting specific stages of the process that coincide with the temperature ranges of maximum risks (400°C-1000°C), one of the most important being the delubrication cycles.

A promising alternative to the existing commercial powders

There are, however, some very interesting advantages that make the master alloys field a promising alternative to the existing commercial powders.

Improvement of properties at a reduced alloying cost
Master alloy powders can provide the properties needed even when added in very small amounts, so that the overall costs are generally reduced. In addition, they provide the opportunity to work with alternative alloying systems, containing attractive alloying elements such as Cr, Mn and Si that are cheaper and more stably priced.

Flexibility in the selection of the final compositions
Compared to prealloyed powders, combinations of different amounts of master alloys with different types of base powders provide a wide range of properties that can be suited to different applications.

Possibility to adjust the properties for specific applications
A proper design of the master alloy composition can be used to adjust characteristics of the final product, such as microstructure and dimensional stability. This brings the opportunity to tailor the master alloy compositions from the design stage, in order to obtain the required properties for a specific final application.

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Powder Metallurgy fundamentals: An introduction to the principles of sintering metal powders

Understanding the principles of sintering is essential for all who work with metal powder based technologies. In this overview of the sintering process Professor Randall M. German looks at the interplay between temperature, particle size and heating time and explains how these factors impact on the final products. Many combinations of these adjustable parameters provide similar levels of sintering, reflecting how the process required to sinter a powder can be delivered in many forms. Options range from short times with small particles at high temperatures to long times with large particles at modest temperatures.

Sintering is the bonding of particles that occurs when they are heated. It is a natural process that happens in all materials, including metals and polymers. Associated with sintering are significant changes in strength, ductility, hardness, conductivity and other properties. The idea has been practised for about 25,000 years as a means to make pottery stronger. Sintered iron has been reclaimed from Egyptian tombs dating back 5,000 years and the Incas were sintering platinum long before Columbus arrived!

Clearly, the use of heat to bond particles is not new. In the 1800s, sintering was applied to bonding iron oxide particles into briquettes for use in steel melting. The sintered hard clumps improved handling and avoided nuisance dust in blast furnaces. Once protective atmospheres became available, sintering was extended to tungsten (lamp filaments), tungsten carbide (metal cutting tools), copper (electrical contacts) and bronze (bearings). Today, sintering is widely employed in automotive, electronic and consumer products.

The explanation for how sintering works starts by looking at atoms and their motion. Sintering concepts awaited the maturation of atomic models for diffusion that finally were

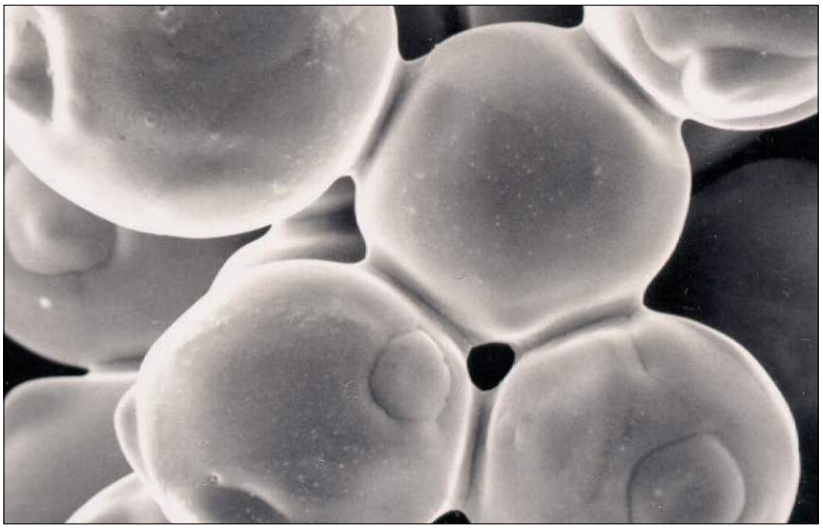

Fig. 1 Scanning electron micrographs of particle bonding during sintering. These 32 μm nickel spheres were loose prior to heating to 1030°C for 1 h in vacuum

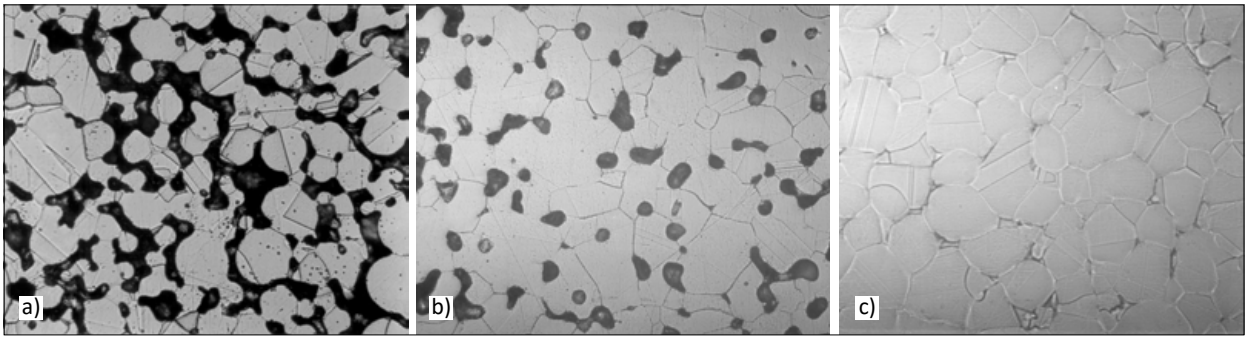

Fig. 2 Cross section optical micrograph through 316L stainless steel at various degrees of sintering, where the pores are black: a) early sintering with a high level of porosity and small interparticle bonds, b) densified structure with reduced porosity and enlarged grains, c) fully dense material

accepted in the 1940s. When heat is applied to a powder, the individual atoms (or ions) move in a random manner. The amplitude of atomic vibration increases with temperature up to the melting point, where the structure turns liquid. Prior to melting, but at an elevated temperature, the atomic motion results in a reduction in surface energy as manifested by a reduction in surface area. As illustrated in Fig. 1, loose particles bond and grow necks during heating. These 32 µm nickel spheres were poured into a container and heated to 1030°C to induce the interparticle bonding evident in this view.

Just as water flows downhill, particle bonding and subsequent densification occurs by random atomic motion. These events are biased by the energy reduction that accompanies surface area reduction due to growth between particles. Once a bond forms, random atomic motion continues to enlarge the contact and subsequently densify the powder. The process can be very slow, such as in glacier formation where snow sinters to form ice over hundreds of years, or very fast, as employed in flash processing of silver inks in microelectronic circuits.

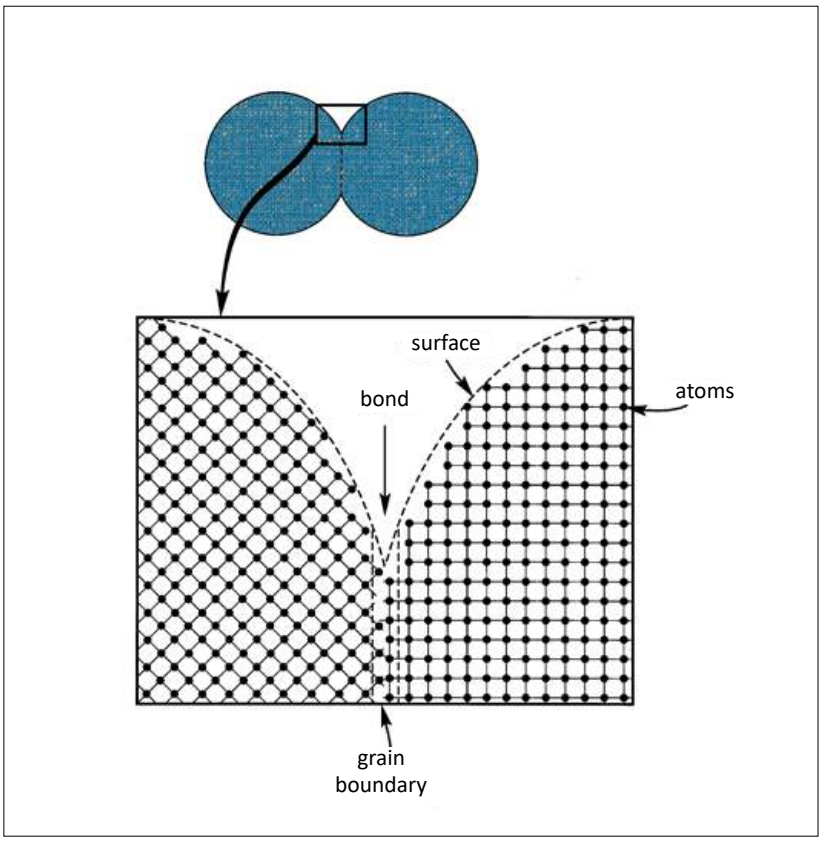

Fig. 3 A sketch of the two particle sintering to show how the misaligned crystal structures forms at the contact. As surface diffusion grows the interparticle bond, a grain boundary emerges due to misorientation, leading to grain boundary diffusion becoming active to move atoms from between the grains into the pores with compact shrinkage. Atoms along the grain boundary in this image would move up to fill in the space, leading to progressive densification

Sintering stages

We treat sintering as a sequence of stages, reflecting pore and grain morphology changes. The shifts in pore-grain configuration are paralleled by shifts in the mathematical treatment. In simple terms, the early portion of sintering focuses on the growth of interparticle bonds, followed by densification and pore elimination and, finally, slow densification with significant grain growth. The images shown in Fig. 2 illustrate an example of the evolution for a 316L stainless steel powder using cross section micrographs after heating to progressively higher temperature. The pores are black and the final image corresponds to full density. Pores are regions of missing atoms that are annihilated by atom flow into

the pores. Mass is conserved, but volume is lost as density increases. The image in Fig. 2a is representative of a sintered filter, while the image in Fig. 2b corresponds to an industrial handle and the image in Fig. 2c is typical of a watchcase.

Early sintering produces bonds between contacting particles. As that bond enlarges, surface area declines. For crystalline materials, the atomic misalignment between contacting particles results in a grain boundary in the bond. Fig. 3 sketches the idea of bond growth accompanied by creation of a grain boundary. This grain boundary is the main pathway for densification. So, after early bonding without densification, the emerging grain boundaries enables atomic mass flow to accommodate the shrinkage of the grains toward each other, giving densification. Effectively, the grain centres move together while the atoms between the grains move outward, to fill the neighbouring pores.

A good visualisation of this is possible using computer simulations of sintering, as illustrated in Fig. 4. These are molecular dynamic calculations involving 33,700 atoms in each particle. The atom positions are frozen at various times. Note first the bond formation and then eventual fusing of the particles. These calculations show the start of sintering, while there is no inter-particle grain boundary, occurs by surface diffusion over the particle surface with negligible shrinkage. As the grain boundary emerges, significant densification occurs.

Grain boundaries represent interfacial energy and that energy is progressively removed by grain growth. The average grain size enlarges while the number of grains decreases. Grain growth takes place by atoms jumping across the grain boundary, with a progressive mass loss from the smaller (higher energy) grains while the larger (lower energy) grains gain mass. All of these steps occur by random atomic motion that progressively reduces energy.

The pore network becomes geometrically unstable at about 90 to 95% density. The pore diameter shrinks due to densification, but the pore length increases due to grain growth. Eventually, the elongated pores pinch-off into near spherical pores with the process atmosphere captured inside the pores. Sintering in vacuum keeps the pores empty, so they can be fully eliminated during sintering. A trapped process gas (say argon or nitrogen or even impurity reaction products such as steam, carbon monoxide or carbon dioxide) resists full densification. In optical microscopy, gas filled pores are readily evident in cross-section since they form spheres that reflect the light, as evident in Fig. 5. Besides trapped atmosphere retarding final stage sintering, concurrent grain growth eliminates the fast diffusion grain boundary paths responsible for densification. Thus, final sintering is comparatively slow and it is common to not reach full density.

"Sintering in vacuum keeps the pores empty, so they can be fully eliminated during sintering"

To make sintering go faster, one option is to form a liquid phase. A wetting liquid naturally spreads between the particles, acting akin to rapid diffusion grain boundaries. Atomic diffusion rates in liquids are hundreds of times faster than in solids, so liquid phase sintering is an effective means to reach full density in short times. One option is to heat prealloyed powder (say Ti-6Al-4V, tool steel, superalloy, cobalt-chromium, or stainless steel) to the solidus temperature. Alloy powders preferentially form liquid at particle contacts

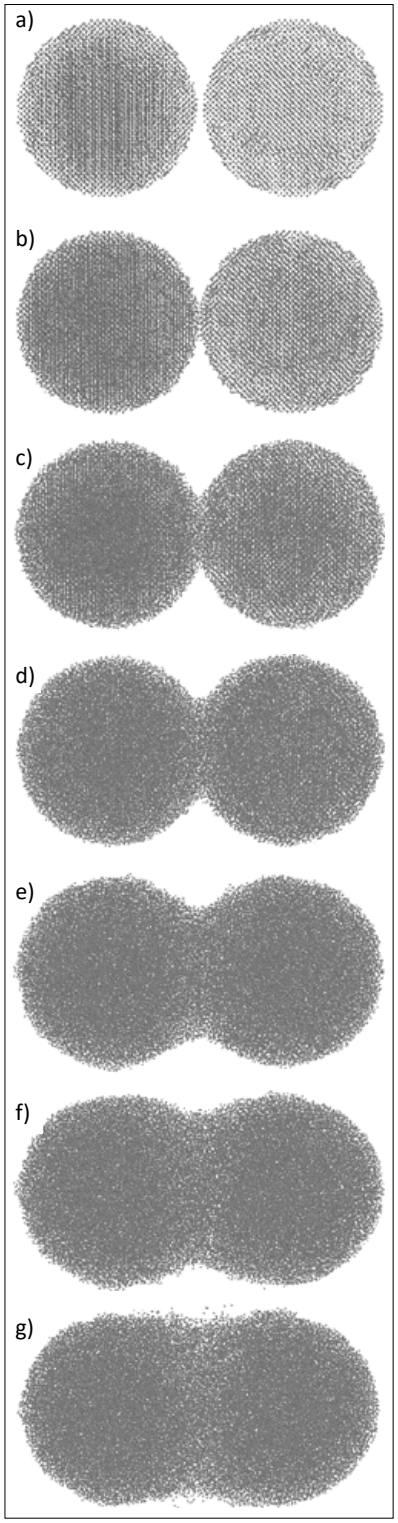

Fig. 4 These are images taken as two small tungsten particles in molecular dynamic simulations. Each sphere consists of 33,700 atoms that are allowed to move under the rules of atomic motion: a) prior to particle contact, b) incipient bonding, c) bond growth by surface diffusion, d) and e) progressive densification, f) and g) coalescence

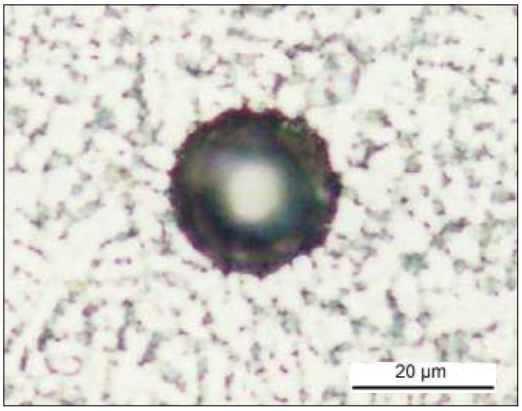

Fig. 5 Optical micrograph of a gas filled spherical pore in cross-section. Light reflects off the bottom of the spherical pore, a clear indication that the closed pore is stabilised by trapped atmosphere

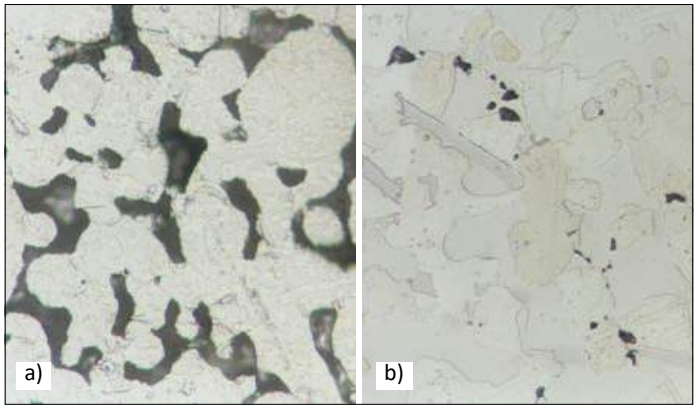

Fig. 6 An illustration of supersolidus liquid phase sintering for a nickel alloy powder. A dramatic jump in density occurs when the material passes the solidus temperature; a) 72 % dense after heating to 1080°C and b) 98 % dense after heating to 1085°C

and on grain boundaries, giving a low strength semisolid mixture. The capillary force from the liquid combines with rapid diffusion and particle sliding to give rapid densification. Formally, the process is known as supersolidus sintering.

The potent densification associated with supersolidus sintering is demonstrated by the cross-section images in Fig. 6 for a nickel alloy (nominally Ni-24Co-15Cr-3B) powder heated to two peak temperatures; a) 1080°C and b) 1085°C. Density jumps from 72 to 98% with this small temperature increase. This is not melting, since densification occurs when about 15% of the structure is liquid. Boron doping is a means to separate the liquidus-solidus temperatures in many alloys to facilitate easier process control in supersolidus sintering. The sintered material is dense with excellent properties, suitable for aerospace and medical components. A microstructure of martensitic stainless steel sintered this way is shown in Fig. 7. The solidified liquid phase, evident between the grains, can be removed by an annealing treatment if desired.

Shrinkage

A common basis for tracking sintering is shrinkage, defined as $\Delta L/L_0$, corresponding to the change ΔL in a dimension from the size prior to sintering L_0. The convention is to drop the negative sign for shrinkage. An example of sintering shrinkage versus hold time during sintering is plotted in Fig. 8 for Fe-20Cu sintering at 1120°C and W-20Ni sintering at 1500°C. On this log-log plot, the sintering shrinkage is described by a one-third time dependence, expressed mathematically as follows:

$$\left(\frac{\Delta L}{L_0}\right)^3 = \frac{g\, D_B\, \delta\, \Omega\, t}{R\, T\, G^4} \qquad (1)$$

where D_B is the diffusivity ($D_B = D_{B0}\exp[-Q_B/RT]$, consisting of a frequency factor D_{B0} and activation energy Q_B), g is a geometric constant near 20, δ is the diffusion

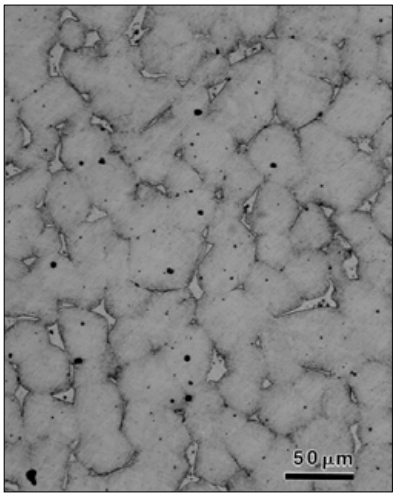

Fig. 7 Microstructure after supersolidus sintering for a boron doped martensitic stainless steel

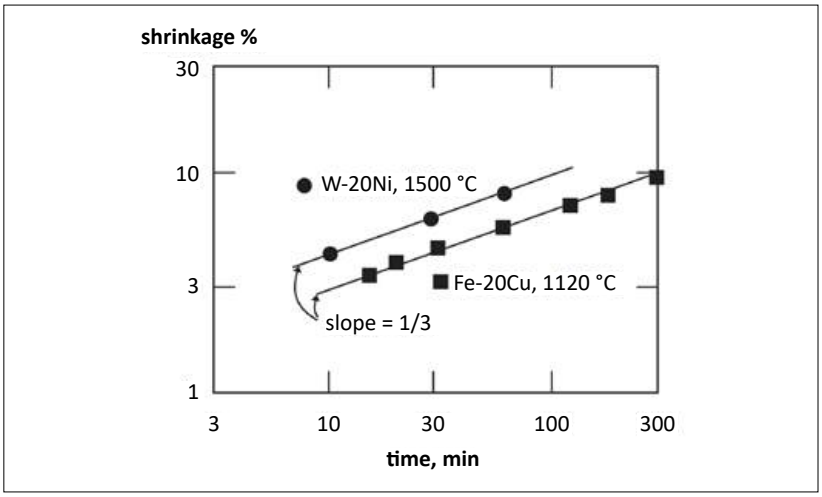

Fig. 8 A log-log plot of sintering shrinkage versus hold time for two alloys, showing agreement with the behaviour expected from Equation (1)

path width estimated as five atomic diameters, Ω is the atomic volume, t is the sintering time, R is the gas constant, T is the absolute temperature and G is the grain size. Grain size enlarges during sintering, as discussed below. Once a shrinkage model is created, then it is possible to predict the changes resulting from new processing conditions. Most properties improve in proportion to sintering shrinkage. Accordingly, it is possible to track hardness, strength, elastic modulus, thermal conductivity, magnetic saturation and related properties, although shrinkage and density are the most common monitors for sintering behaviour.

The one-dimensional form in Equation (1) is the shrinkage, but shrinkage occurs in all three dimensions. An illustration of the net change is given in Fig. 9 for a latch. The upper image is after sintering and the lower version is prior to sintering. The relation between shrinkage $\Delta L/L_0$, sintered fractional density f and the initial fractional density f_0 is:

$$f = \frac{f_O}{\left[1 - \frac{\Delta L}{L_O}\right]^3} \qquad (2)$$

This assumes no mass loss during sintering. The measured density is obtained by multiplying the fractional density by the theoretical density. For example, W-10Cu has a theoretical density of 17.3 g/cm^3, so, at 95% density, the measured density would be 16.4 g/cm^3.

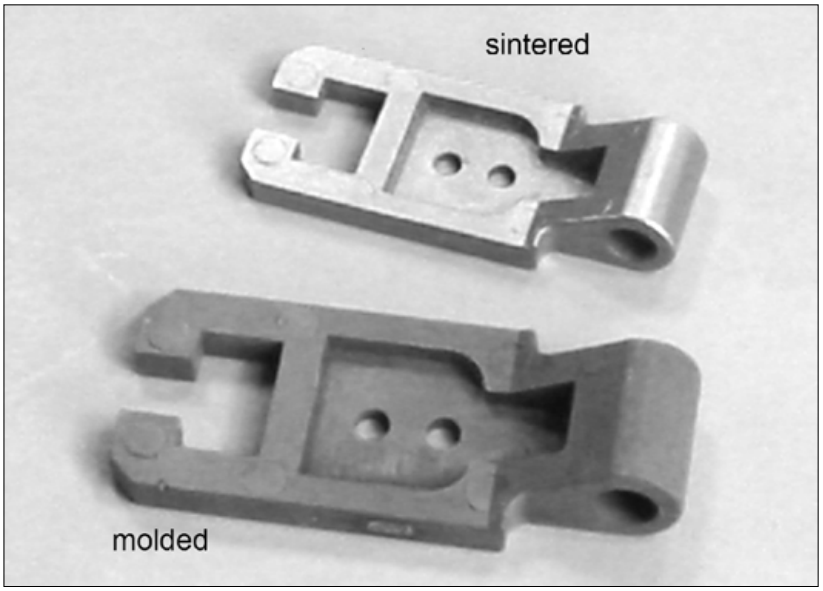

Fig. 9 This picture illustrates shrinkage during sintering for a stainless steel latch. The upper image is after sintering and the lower image is after moulding and prior to sintering

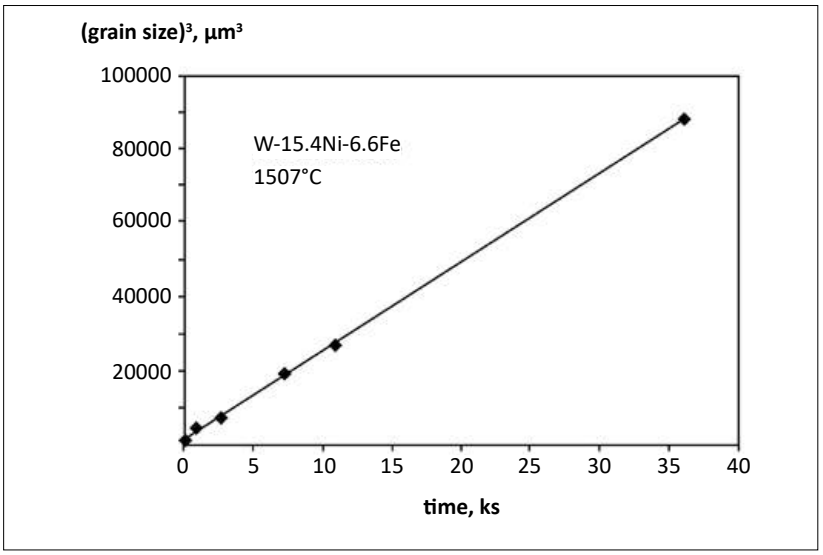

Fig. 10. A plot of the cube of the grain size versus hold time to illustrate agreement with the behaviour anticipated using Equation (3). These data are for a W-Ni-Fe alloy held at 1507°C for times up to 10 h

Grain growth

Grain growth, or coarsening, reflects the increase in the average crystal size that occurs as part of the energy reduction driving sintering. It is accompanied by a decrease in the number of grains over time. Grain growth depends on atomic diffusion, just like sintering, thus densification and microstructure coarsening go hand in hand. Grain growth occurs such that the average grain volume increases linearly with time, expressed as follows,

$$G^3 = G_O^3 + k\,t\,exp\left[-\frac{Q_G}{R\,T}\right] \qquad (3)$$

where G is the grain size, so G^3 is proportional to the grain volume, G_0 is the starting grain size (usually equal to the particle size), k is a growth rate constant that depends on the material, t is the hold time and Q_G is the activation energy for grain growth, R is the gas constant, and T is the absolute temperature. A plot of mean grain volume (grain size cubed) versus sintering time is given in Fig. 10 (ignoring the starting grain size) for a tungsten alloy, to illustrate the behaviour expressed by Equation (3).

Many initial particles coalesce to form each sintered grain during sintering. Higher temperature promotes faster atomic motion, resulting in faster grain growth. This is especially true in liquid phase

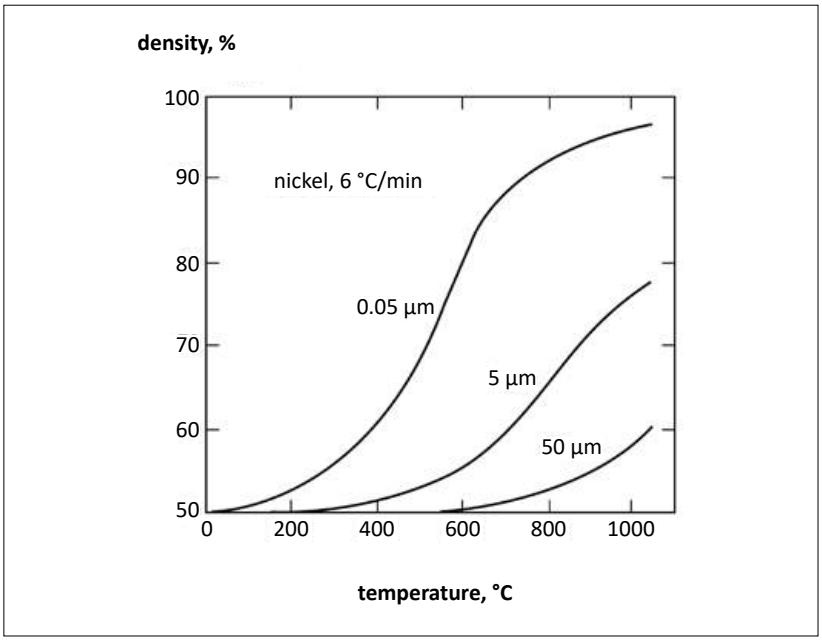

Fig. 11 Density versus temperature data for three nickel powders during heating at a rate of 6°C/min. The smaller powders undergo the onset of densification at lower temperatures

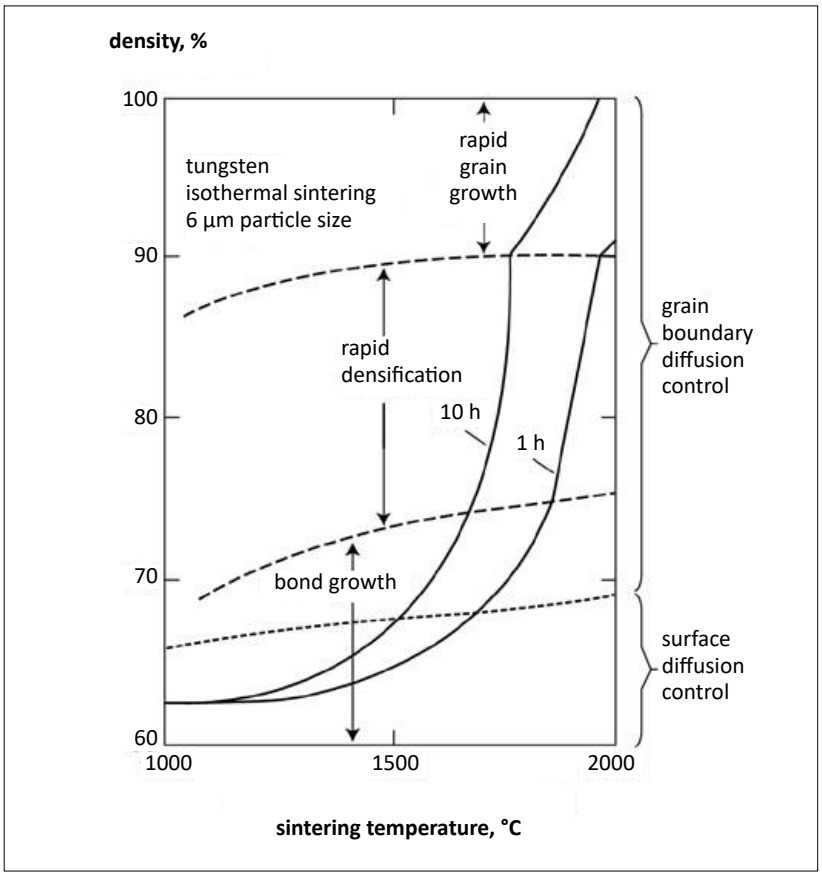

Fig. 12 A sintering map for 6 µm tungsten giving the density versus temperature for two sintering hold times (1 and 10 h). The dashed lines differentiate the regions where bond growth, densification, and grain growth are dominant, and the lower dotted line indicates the transition from surface diffusion to grain boundary diffusion as the dominant process

sintering. Sintering with a liquid phase produces microstructure consisting of grains surrounded by an interpenetrating network of solidified liquid, as evident in Fig. 7. Indeed, in this example, each grain is composed of approximately 125 initial particles.

Densification

Densification is associated with the grain centre contraction arising from the capillary forces that pull the grains together. The force acting to densify the typical powder during sintering is equivalent to about 10 atmospheres pressure. This inherent sintering pressure can be supplemented by an external stress in pressure-assisted sintering. That is what happens, for example, in hot isostatic pressing.

Many combinations of time, temperature and particle size lead to sintering densification. Faster sintering occurs with smaller particles and higher temperatures. An experimental demonstration is given in Fig. 11, where three different nickel particle sizes are used to show sinter density versus temperature while heating at a constant rate of 6°C/min. Similar to this plot, it is possible to formulate maps that link the key adjustable sintering parameters. For example, 10 µm nickel powder requires about 60 min at 1400°C to reach full density. However, a 2 µm nickel powder reaches the same density in 30 s at 1400°C.

Such interplay is treated using sintering maps, generated for density or shrinkage versus time, temperature and applied pressure, with possible variations in starting material, particle size, green density, grain size and gas pressure. Fig. 12 plots density versus temperature for isothermal sintering for 6 µm tungsten at times of 1 hour and 10 hour. The initial part of sintering, corresponding to surface diffusion controlled bond growth, is marked by the lower dotted line and the region of rapid densification by grain boundary diffusion is in the interme-

diate region. Over about 90% density, sintering continues by grain boundary diffusion, but is accompanied by rapid grain growth. Trade-offs are evident, showing how longer time or higher temperature give equivalent density.

Two different behaviours are seen in sintering. One behaviour is associated with sintering densification, as typical with smaller particles (≈ 10 µm or less) and higher temperatures. The other sintering behaviour is associated with larger particles and lower sintering temperatures, where sinter bonding occurs without densification. Sinter bonding without shrinkage is useful for forming filters, bearings and ferrous automotive components, such as timing gears. In the latter, iron powder is mixed with alloying additions (Ni, Cu, C) and compressed at 800 MPa to about 85% density. Sintering is at 1120°C for 20 min, producing substantial strengthening but no shrinkage. Tool design is easier since dimensional change and distortion are avoided. Literally, the pressed compact is the same size as the tooling. However, the remaining 15% porosity lowers strength to about 50% of the full density value.

A hybrid option is to sinter with no shrinkage, then infiltrate the porous compact with a low melting temperature metal, such as copper or bronze. The liquid solidifies on cooling, and provides some assistance with strength, but is most effective in sealing pores against fluid leakage and corrosion. Fig. 13 is a picture of the final microstructure. It is similar to a liquid phase sintered microstructure, since it consists of grains that were solid and solidified liquid filling the gaps between the grains.

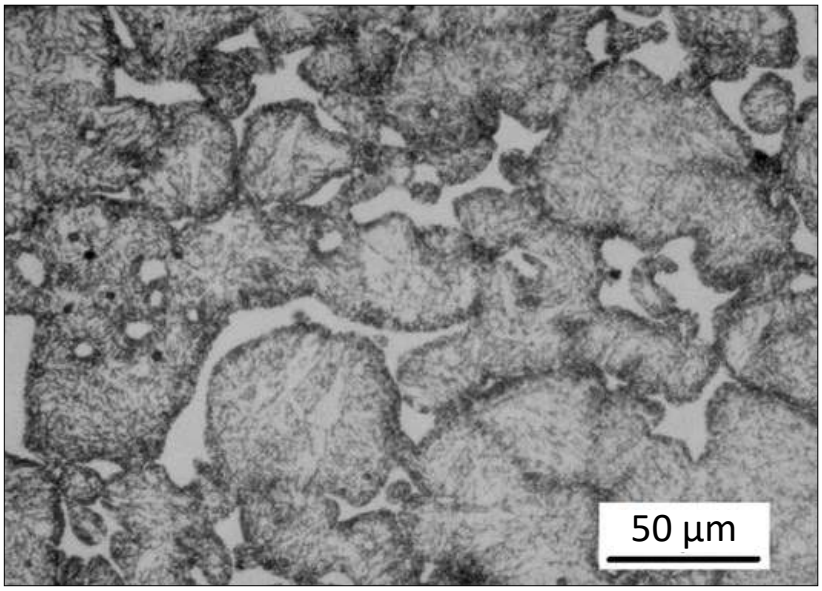

Fig. 13 This optical micrograph shows the microstructure observed after a sintered steel was infiltrated with a copper alloy

Atomic level events

So, now back to explaining sintering in terms of the atomic level events. As heat is applied to any material, the atomic vibrations increase, mostly by increasing vibration amplitude. On occasions, an atom breaks free and moves to a neighbouring site, leaving a vacancy behind. The motion is random, but, at times, the new location is lower in energy so there is a reduced tendency for the atom to jump elsewhere. Sintering occurs because these random atomic jumps progressively discover combinations that reduce energy, via bonding, surface area loss and grain size enlargement.

The conditions needed to induce sintering vary with the material, powder and heat delivery. Greenland snow sinters at -15°C to form glacial ice over about a century, but tungsten powder requires about one hour at 2500°C. The wide temperature difference is explained by the homologous temperature, defined as the fraction of the absolute melting temperature. Materials with high melting temperatures require higher sintering temperatures. For example, the absolute melting temperature for tungsten is 3683 K, so, at 2500°C or 2773 K, the homologous temperature is 0.75. Most materials exhibit measurable sintering at homologous temperatures between 0.5 and 0.8. With higher temperatures or smaller particles, the bond grows more rapidly. The time required to reach a given density depends on these two parameters.

Atomic motion is understood in terms of the statistics of random events, termed statistical mechanics. The treatment involves horrendous numbers. For example, a 2 µm nickel particle contains 400 trillion atoms. Typically, atoms try to jump to a new location about 10^{14} times per second. At the sintering temperature, successful jumps by an atom to new locations only occur once in 10 trillion attempts. Then, when atoms move, the shifted volume is only 10^{-29} m^3. Seemingly, the explanation of sintering is lost in the numbers. However, statistically, it works out that each atom changes position several times per second during sintering. Some of these atom jumps are to lower energy positions, leading to a random but progressive energy reduction. Initially, these give the sinter bonds. In turn, the bonding delivers major changes in strength,

"The conditions needed to induce sintering vary with the material, powder and heat delivery"

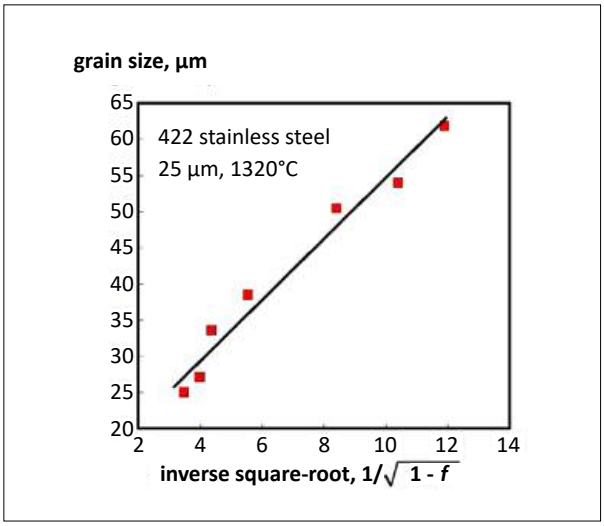

Fig. 14 Grain size data for 422 stainless steel powder sintered at 1320°C for various times. The grain size is plotted versus the inverse square-root of the fractional porosity (1 – f) showing agreement with Equation (5)

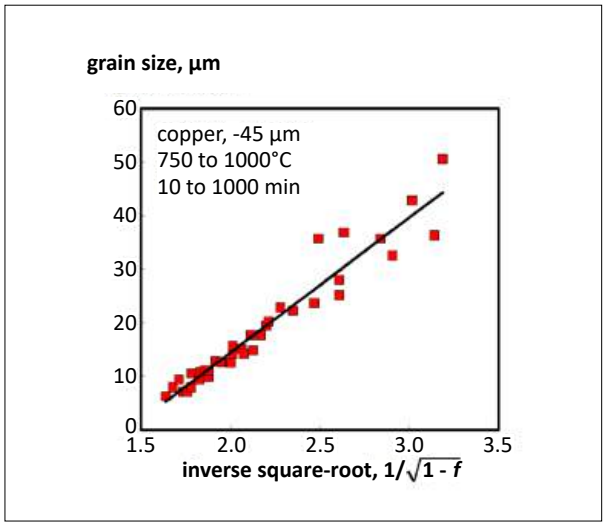

Fig. 15 Grain size versus inverse square-root of the fractional porosity for a range of times and temperatures for a copper powder smaller than 45 µm

hardness, ductility and other properties, over short times at high temperatures.

Fig. 1 showed a scanning electron microscope picture of the sinter bonds formed between spherical nickel particles during sintering. These bonds grew by diffusion over the particle surface. Diffusive atomic motion is sensitive to temperature. For example, the rate of surface diffusion behaves as follows:

$$D_S = D_{SO} \exp\left[-\frac{Q_S}{R\,T}\right] \qquad (4)$$

This is known as an Arrhenius relation, where D_S is the surface diffusivity with units of m²/s, D_{SO} is the frequency factor also with units of m²/s, Q_S is the activation energy for surface diffusion with units of J/mol or kJ/mol, T is the absolute temperature in K and R is the gas constant equal to 8.314 J/(mol K).

Besides surface diffusion, mass flow is possible by other paths, but, for most engineering materials, the sequence is bond formation by surface diffusion without shrinkage, followed by grain boundary diffusion with considerable densification. Each process is temperature dependent in a form similar to Equation (4), but with different frequency factors and activation energies. Typically, the activation energy is proportional to the material's absolute melting temperature. For example, gold melts at 1063°C (1336 K) and has an activation energy for grain boundary diffusion of 110 kJ/mol, while lead melts at a lower temperature of 327°C (600 K) and has an activation energy for grain boundary diffusion of 68 kJ/mol.

Grain size

The mathematical relations describing sintering first emerged in the 1940s and reached maturation by the 1980s. They involve adjustable processing parameters to predict features such as density or shrinkage and properties such as hardness, strength, or conductivity. Sintering shrinkage is the most common measure. At the same time, microstructure coarsening, as measured by an increase in grain size, was noted but poorly understood. Grain growth leads to a progressive increase in the grain size as captured by Equation (3). Because grain growth and sintering densification depend on atomic motion across and in the grain boundary, it turns out they are closely linked during sintering. As long as pores are linked to grain boundaries, the densification and grain growth events are inherently coupled.

Today we recognise the close interdependence. The median grain size G starts at a value of G_0 (similar to the particle size) and increases as the fractional density f increases as follows,

$$G = G_O\,\theta/\sqrt{1-f} \qquad (5)$$

The parameter θ is usually near 0.6, but varies slightly with the powder. Note that the fractional porosity is 1 – f. Grain size enlargement accelerates as densification progresses. Already, we noted that densification slows as full density is approached and Equation (5) emphasises how grain size enlarges. This leads to plots of grain size versus the inverse fractional density term, such as shown in Figs. 14 and 15. The first plot reports data taken from a 25 µm 422 stainless steel powder during sintering at 1320°C and the second plot corresponds to -45 µm copper powder sintered using a variety of time-temperature combinations. Although more scattered in behaviour, still the grain size relates to the sintered density.

Particle size changes

A question is how do you adjust sintering to accommodate changes in particle size, temperature, or hold time? The relation between time and temperature is taken up in the next section and here the focus is on particle size. Assuming similar heating and hold cycles, the estimated change in sintering temperature to accommodate a change in particle size relies on what are known as scaling laws. Here, we treat the problem of what sintering temperature (absolute, or K) T is required to accommodate a change in particle size *D*.

Assume two sets of experiments, the first reaching sintering shrinkage $Y = \Delta L/L_0$ with particles of size D_1 at temperature T_1. Then to reach the same degree of sintering Y with a new powder of size D_2 requires a temperature T_2. Manipulation of the scaling laws gives the desired estimate for the second temperature (in K) as follows:

$$T_2 = \frac{1}{\frac{1}{T_1} + \frac{m}{T_M\,(16+V)}\,ln\left(\frac{D_1}{D_2}\right)} \quad (6)$$

This form uses a reference experiment with particle size D_1 and sintering temperature T_1 to estimate the temperature for equivalent sintering using a new particle size of D_2. The second temperature is restricted by the melting temperature T_M. The parameter *V* depends on the crystal structure (*V* = 1 for body-centred cubic, 2 for hexagonal close packed, 3 for face-centred cubic and 4 for diamond). The parameter m is ideally 4 to reflect grain boundary diffusion, but best agreement occurs with *m* = 3.5.

As an example, using data for 316L stainless steel, sintering a 13 µm powder at 1400°C (1773 K) gives full density. For a 10 µm powder, the equivalent densification temperature would be 1323°C (in good agreement with 1320°C found in experiments) and, for 8 µm, the prediction is 1263°C while experiments report full density at 1281°C. Most likely, the scaling calculations are less reliable as the particle size change becomes large.

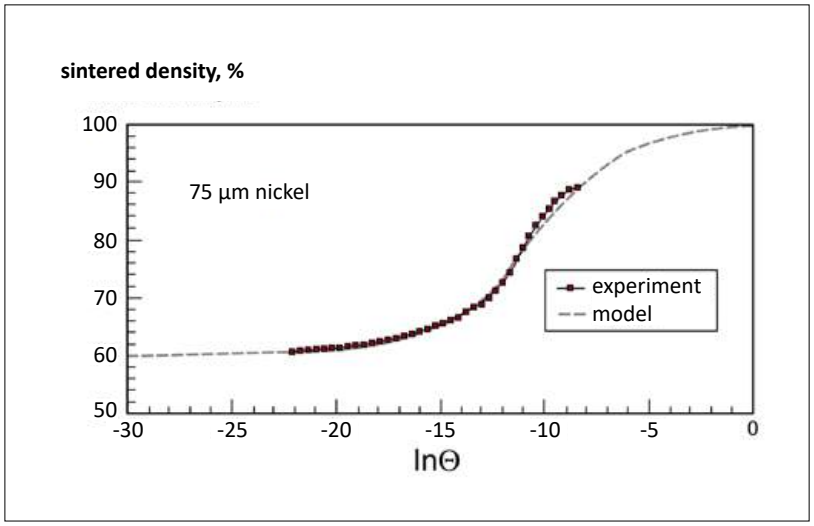

Fig. 16 Sintered density versus the integral work of sintering θ for 7 µm nickel powder subjected to non-isothermal heating, comparing the model from Equation (7) with the experimental data

Integral work concepts

A final concept that is important is a new simple means to handle the complexity of sintering with spreadsheet calculations. Sintering theory focuses on idealised conditions - monosized spheres, uniform loose packing and isothermal conditions. Most sintering practice is far from ideal, involving nonspherical powders with wide size distributions heated in non-isothermal cycles involving a sequence of ramps and holds to eliminate impurities, polymers, residual strains and temperature gradients.

A way to handle such issues is by an integral work of sintering treat-

ment. The various terms gathered above - time, temperature, particle size, grain size and starting density - are linked using an integral of the thermal work taken over the sintering cycle leading to a single parameter θ,

$$\theta = \int_0^t \frac{1}{T} \, exp\left[-\frac{Q}{R\,T}\right] dt \qquad (7)$$

The integration is over the heating cycle. In this equation, T is the absolute temperature, t is the cumulative time and R is the gas constant. The activation energy Q is the only material parameter; it is near the activation energy for grain boundary diffusion. The model is implemented in spreadsheets. An example is given in Fig. 16 for 7 µm nickel powder starting at 60% density. Sintered density data were collected over a range of temperatures during heating at 5°C/min to 1100°C in hydrogen. The integral work of sintering model, with only one adjustable material property, fits the experimental data fairly reasonably.

Variants add particle size, grain size, phase transformations and liquid phases and have been extended to predict shrinkage, strength and distortion during various heating cycles. Several references are noted below to help dig further into this topic and the other topics introduced here.

Summary

The science of sintering was thousands of years behind practice. The early mystery is gone as we now understand how atomic motion is induced by high temperatures to cause particle bonding. The publication count on sintering exceeds 600,000 books, journal articles and patents. Sintering cycles range from milliseconds up to days. There are both solid and solid-liquid variants. Although the theoretical treatment of sintering is mathematically complex to handle the many variables and diffusion paths and changing microstructure, at the same time contemporary cycle design is possible with spreadsheet calculations. Hopefully, this brief introduction helps without overly simplifying the topic. A few of the references drawn upon for this article are given below.

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Further reading

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POWDERMET2016: Powder producers focus on the development of cost effective lean alloys

One of the Special Interest Programmes at POWDERMET2016, held in Boston, Massachusetts, USA, June 5-8, 2016, focussed on the development of lean alloy compositions for Powder Metallurgy structural part applications. Dr David Whittaker reports on a number of these presentations and highlights the benefits these material grades offer the part producer.

The elements that have been traditionally used as alloying additions to Powder Metallurgy structural part grades have been chosen on the basis that they enhance hardenability, but that their oxides can be readily reduced during a standard sintering cycle with a maximum temperature of 1120°C. However, the volatility in prices of these commonly applied elements (Cu, Ni, Mo), especially in the period around 2008/2009, together with recent regulations limiting the use of Ni and environmental problems related to Cu-containing parts, have stimulated research on new alloying alternatives that allow more cost-effective production combined with the achievement of a high level of properties.

The Special Interest Programme included perspectives on lean alloy developments from the leading ferrous powder suppliers, Höganäs AB, Hoeganaes Corporation and Rio Tinto Metal Powders.

Cost-effective Cr-alloyed materials for automotive applications

The earliest approach to introducing more cost-effective PM alloys was the development of pre-alloyed Cr-containing grades, first introduced in the late 1990s. The session opened with a contribution from Ulf Engstrom and Karen Han (Höganäs China Co. Ltd.) on the development of these Cr-alloyed grades by the Höganäs AB group and their subsequent exploitation in production [1].

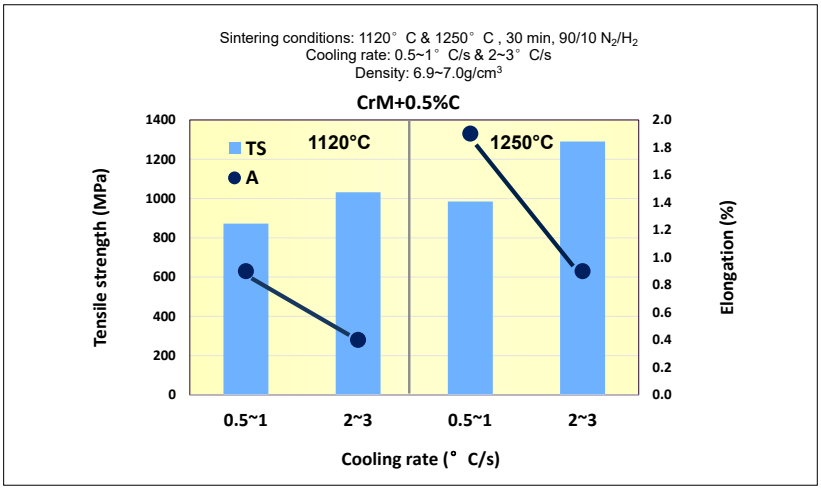

Fig. 1 Influence of sintering temperature and cooling rate on the tensile strength and elongation of FL-5305 [1]

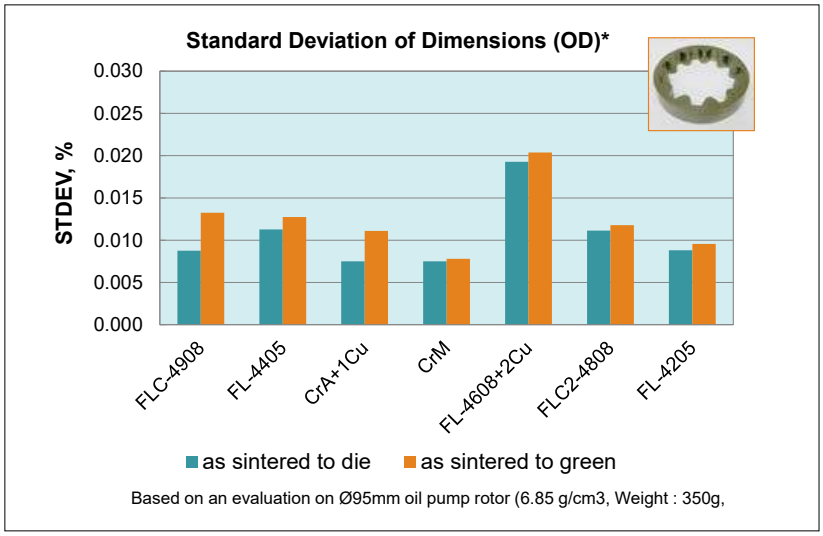

Fig. 2 Comparison of dimensional control capabilities of a range of PM grades [1]

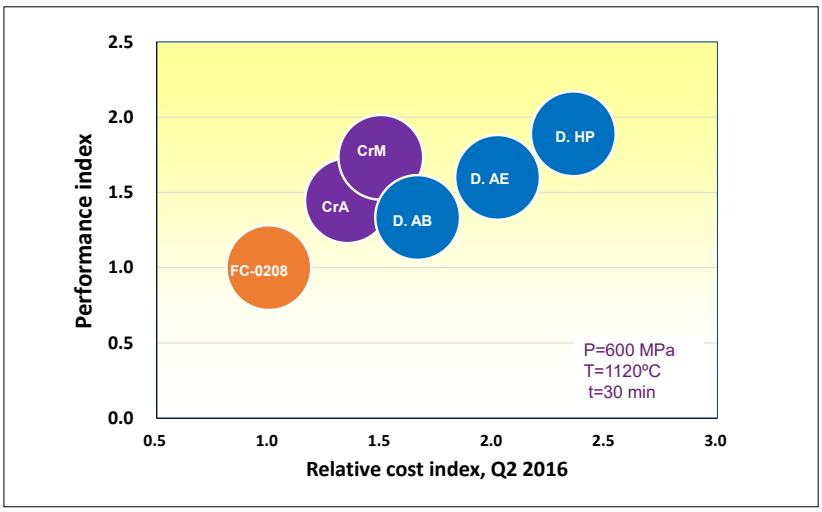

Fig. 3 Comparison of cost/performance ratios of a range of PM grades [1]

The grades featured in this presentation were the pre-alloyed 3%Cr-0.5%Mo grade (originally introduced as Astaloy CrM and now standardised by MPIF as FL-5300), a variant on a leaner 1.5% Cr-0.2% Mo grade, referred to as Hipaloy, and a 1.8% Cr grade (originally introduced as Astaloy CrA and now designated as FL-5100).

Hipaloy is based on the 1.5% Cr - 0.2% Mo composition but uses a special mix concept, in which the lubricant level is reduced to 0.3% to allow a higher green density of 7.45 - 7.55 g/cm^3 to be achieved. The standard composition also contains a carbon level in the range 0.25 to 0.5%. These materials were developed to offer equivalent mechanical properties to the nickel-containing diffusion-alloyed grades.

The presentation began with a review of recommended processing conditions for these materials and, among other issues, highlighted the benefits of high temperature sintering (1250°C) and the faster post-sintering cooling rates (~2-3°C/ sec) in sinter hardening in increasing achievable strength levels. Fig. 1 is an example of these benefits in relation to FL-5300 with 0.5% C, referred to in the figure as CrM + 0.5%C.

The importance of dimensional tolerance control in press/sinter PM was recognised and this issue

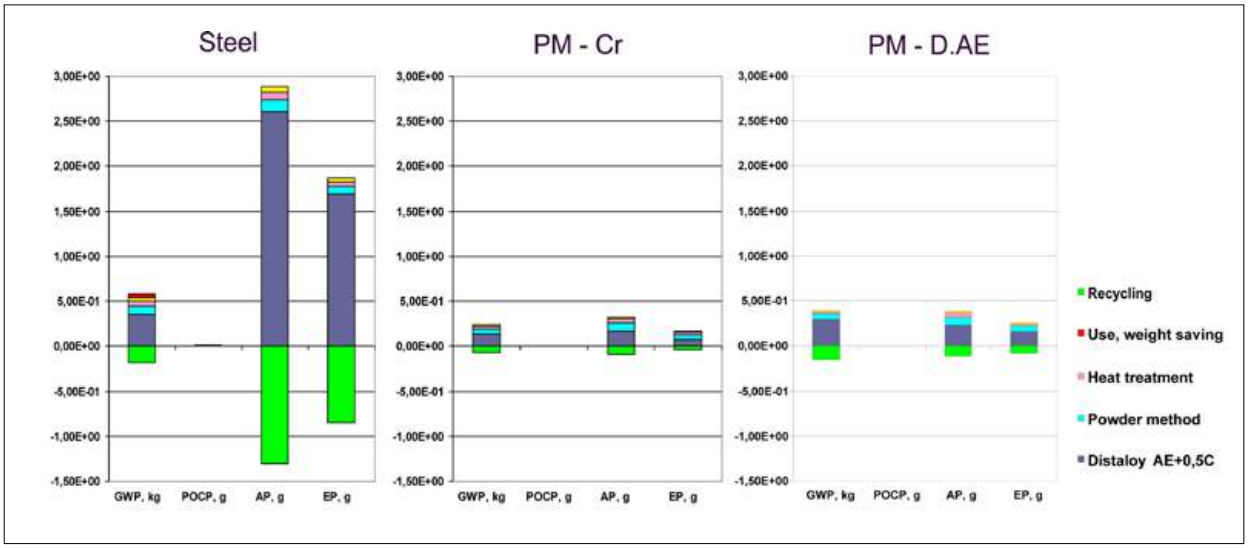

Fig. 4 Life cycle assessments [1]

was discussed in relation to these Cr-alloyed grades. Fig. 2 indicates that FL-5300 (referred to in the figure as CrM) and the 1.8% Cr grade with a 1%Cu admixed addition (referred to as CrA + 1Cu), for instance, are equivalent to or superior to a range of established PM grades in this regard. The cost-effectiveness of the Cr-alloyed grades in comparison with the diffusion-alloyed grades was demonstrated in a plot of performance index against a relative cost index, these indices being normalised against an Fe-2%Cu-C material (Fig. 3).

The green credentials of the Cr-alloyed grades were then underlined with the results of life cycle assessments in a case study of production routes for an injection yoke by wrought steel processing and by PM, using two different PM materials (FL-5300 + 0.3%C and FD-0405 or D.AE + 0.5%C). The results, presented in Fig. 4, showed that PM technology has a significant environmental advantage over the wrought steel route and that the pre-alloyed Cr material was superior, in this context, to the 4% Ni diffusion-alloyed grade. Further detail on the life cycle assessment process has been previously published in *Powder Metallurgy Review* (Vol. 2, No. 3, pp. 57-58).

The presentation concluded with the identification of established and potential target automotive component applications for the range of Cr-alloyed grades (Fig. 5). The proposed process route for VVT belt pulleys would involve the use of the 1.8% Cr grade in the nitrocarburised condition. 1.8% Cr + 1% admixed Cu, 1.8% Cr + 2% admixed Ni and FL-5305, with 0.4 to 0.7%C, pressed to a density of 7.0-7.2 g/ cm^3 and sinter hardened from an 1120°C sintering temperature, were identified as viable material options for synchroniser hubs. A potential route for PM connecting rods was identified as involving the warm compaction and sinter hardening of FL-5305. The proposed material solution for PM cam lobes was 80% 1.8% Cr grade/20% FL-5300 + 0.8%C + 0.5%MnS, compacted to ~7.2g/cm^3 and sinter hardened from 1120°C.

Finally, the Hipaloy material, compacted to 7.45-7.55 g/cm^3 and sintered at 1250°C, was identified as being suitable for high performance gears and, indeed, it was stated that a ring gear based on the use of this material in the carburised condition is already in commercial production at KSM, Korea.

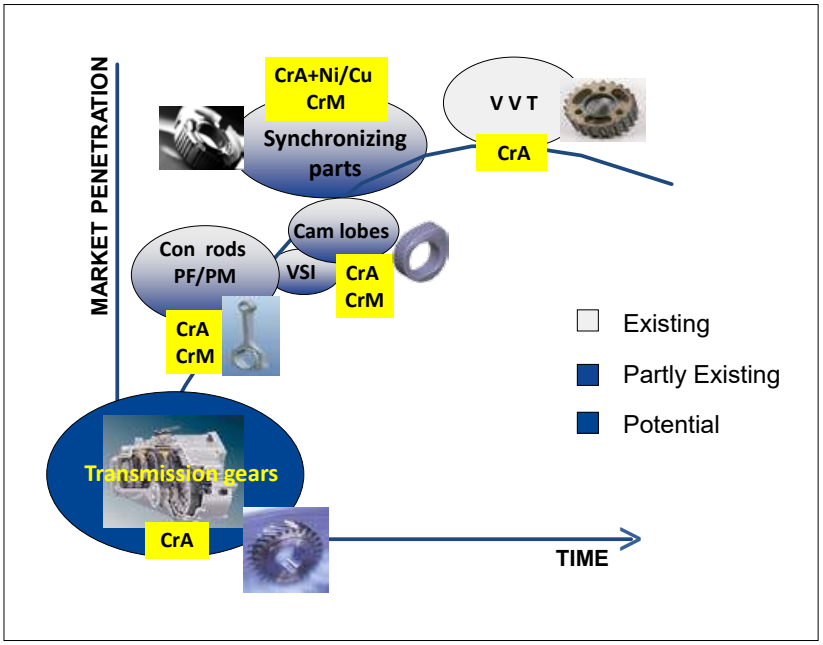

Fig. 5 Suitable automotive applications for the FL-5100 (CrA) and FL-5300 (CrM) materials [1]

Lean alloys in heat treated and sinter hardened applications

The Hoeganaes Corporation's strategy in developing lean alloy grades was outlined in a contribution from Bruce Lindsley (Hoeganaes Corporation, USA) [2]. Although the use of lean alloys in the as-sintered condition was

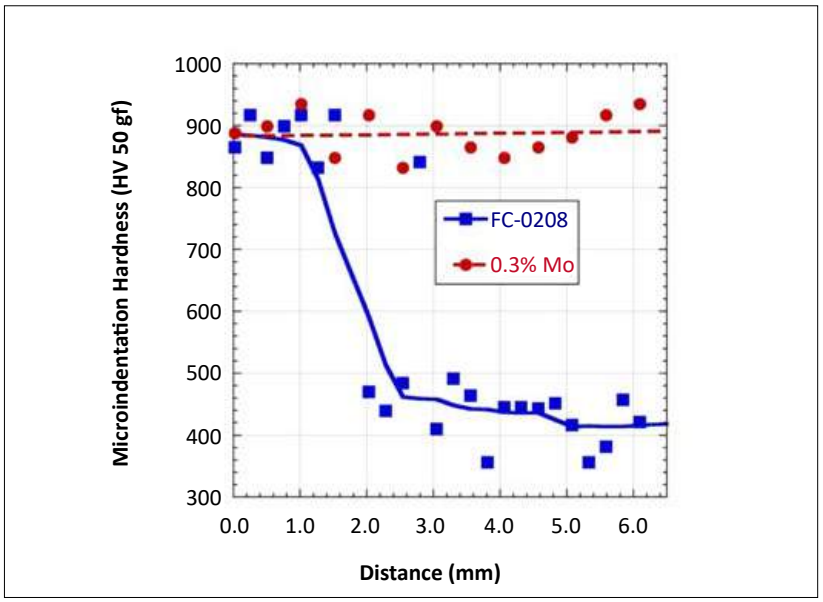

Fig. 6 Influence of a 0.3% Mo addition on hardening response in oil quenching of a 25 mm compact (graphite content of 0.9%) [2]

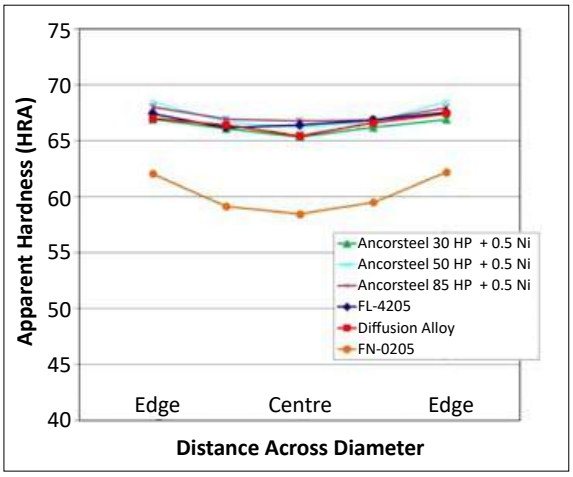

Fig. 7 Effect of Mo content on hardening response in oil quenching of a 13 mm slug (from K McQuaig and P Sokolowski, "Hardenability Response of Lean Fe-Mo-Ni-C PM Alloys", PowderMet 2012, MPIF) [2]

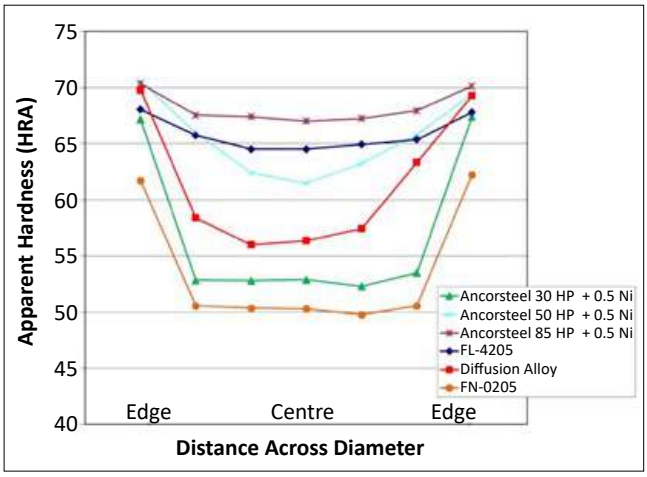

Fig. 8 Effect of Mo content on hardening response in oil quenching of a 38 mm slug (from K McQuaig and P Sokolowski, "Hardenability Response of Lean Fe-Mo-Ni-C PM Alloys", PowderMet 2012, MPIF) [2]

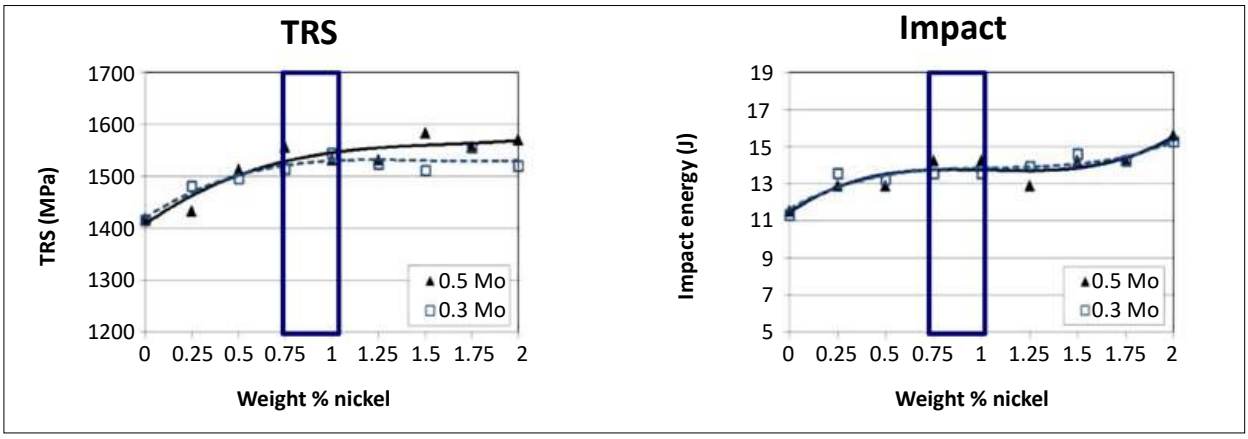

Fig. 9 Influence of Ni content on heat treated properties (from P Sokolowski, B Lindsley, and K McQuaig, "Designing Lean Heat-Treating Alloys for the PM Industry", IJPM Spring 2013 vol. 49, issue 2, pg. 51-60) [2]

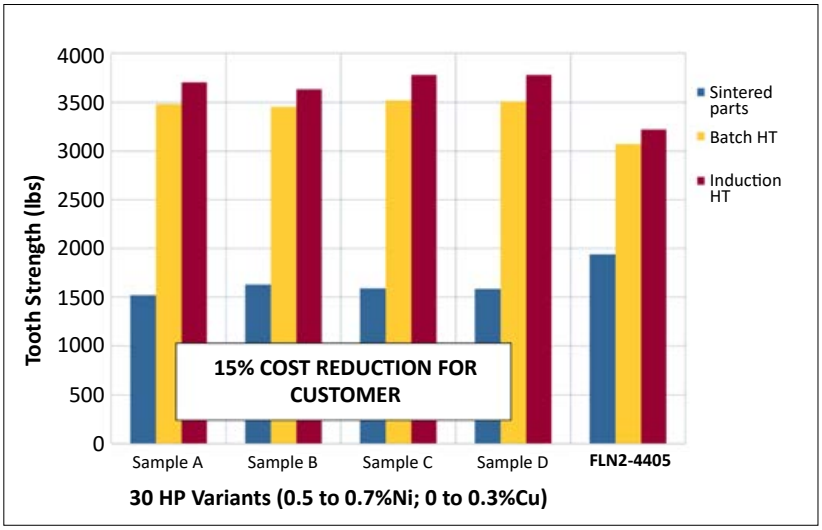

Fig. 10 Lean alloy case study (crank sprockets) (from S Shah, G Falleur, J O'Brien and FHanejko, "Cost-Effective / High-Performance Lean Alloys", PowderMet 2015, MPIF) [2]

touched upon, this presentation concentrated largely on materials used in the heat treated or sinter hardened conditions.

In the heat treated (oil quenched and tempered) condition, the alloy development concept adopted was to use the minimum alloying content to form martensite on quenching and to include a small amount of nickel for toughness (rather than to seek to eliminate the use of nickel entirely).

In this context, the main focus has been on the development of hybrid alloys, with a base of a pre-alloyed Mo steel with binder-treated elemental additions. Pre-alloyed molybdenum has been shown to have no significant detrimental effect on compressibility of the base powder at

addition levels up to 0.85% and this material type can therefore be used for high density applications..

Mo additions at levels as low as 0.3% have been shown to have a large effect on hardenability in oil quenching (Fig. 6). The author, however, pointed out that there was a "mass effect" in relation to the cooling rate in oil quenching that may influence the minimum Mo level required for a given application. Figs. 7 and 8 show that, for a slug diameter of 13 mm, 0.3% Mo was sufficient to create full through-hardening and further Mo additions had no incremental effect, whereas at 38 mm diameter the influence of increasing Mo levels was significant.

The assessment of the required level of nickel addition has shown that the normal 2% may not be needed and that 0.75-1% can offer a sufficient level of properties (Fig. 9). A case study of these alloying concepts, based on a customer trial with MPG Gear Technologies, was discussed. This trial showed that, for a crank sprocket, equivalent properties, to those for a 0.85% Mo pre-alloyed material with a 2% Ni addition, could be achieved with a 0.3% Mo – 0.75% Ni material with a consequent 15% cost saving (Fig. 10).

Lean sinter hardening grade versions within the Mo-Ni-Mn pre-alloy family have been introduced. Studies on a number of Mo-Ni-Mn grades (Table 1) have shown that Mo and Mn additions are more effective than Ni in raising hardenability (Fig.11). In these studies, it was concluded that, whereas high alloy sinter hardening materials do not require precise cooling rate control, the leaner versions save on material costs, but need better process control.

Finally, it was demonstrated that the adoption of process modifications, such as high temperature sintering, can provide property improvements that can enable the use of leaner alloys. For instance, Fig. 12 shows that the sintering of a lean 1%Ni-0.3%Mo material at 1260°C can offer better properties than a 4%Ni-0.8%Mo material sintered at 1120°C, with an alloy reduction of 3%Ni and 0.5%Mo.

ID	Ni	Mo	Mn	Fe	Total
FL-4200	0.5	0.6	0.25	Bal.	1.35
Ancorsteel 721 SH	0.5	0.9	0.4	Bal.	1.8
FL-4600	1.8	0.5	0.15	Bal.	2.45
FL-4800	1.4	1.2	0.4	Bal.	3

Table 1 Sinter hardening alloys [2]

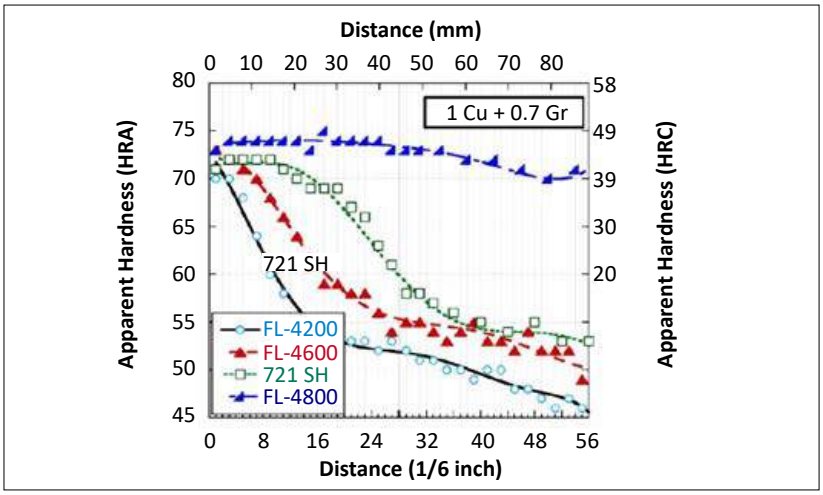

Fig. 11 Hardenablity of sinter hardening grades (from P Sokolowski and B Lindsley, "Influence of Chemical Composition and Austenitizing Temperature on Hardenability of PM Steels", PowderMet 2009, MPIF) [2]

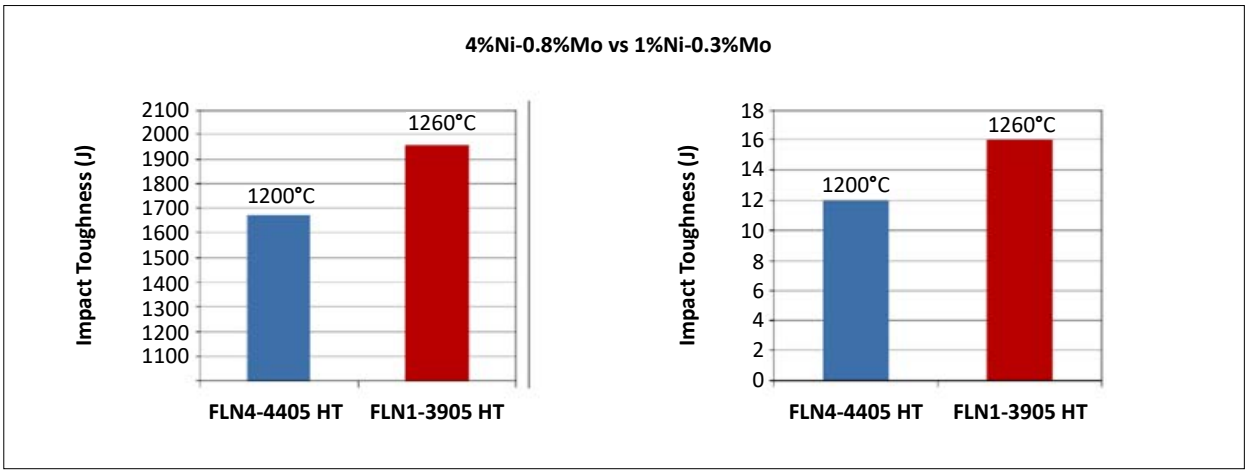

Fig. 12 Properties of heat treated hybrid alloys [2]

#	Mn (wt%)	Cr (wt%)	C (wt%)	Sint. Temp. (°C)	Density (g/cm³)	C.R. (°C/s)
1	0.50	0.25	0.35	1120	6.75	3.0
2	0.50	0.25	0.55	1170	6.90	2.2
3	0.50	0.25	0.75	1200	7.05	1.7
...	...	...	...	...	...	...
10	0.90	0.25	0.35	1200	6.90	1.7
11	0.90	0.25	0.55	1120	7.05	3.0
12	0.90	0.25	0.75	1170	6.75	2.2
...	...	...	...	...	...	...
25	1.30	0.65	0.35	1120	6.75	1.7
26	1.30	0.65	0.55	1170	6.90	3.0
27	1.30	0.65	0.75	1200	7.05	2.2

Table 2 First Taguchi array [3]

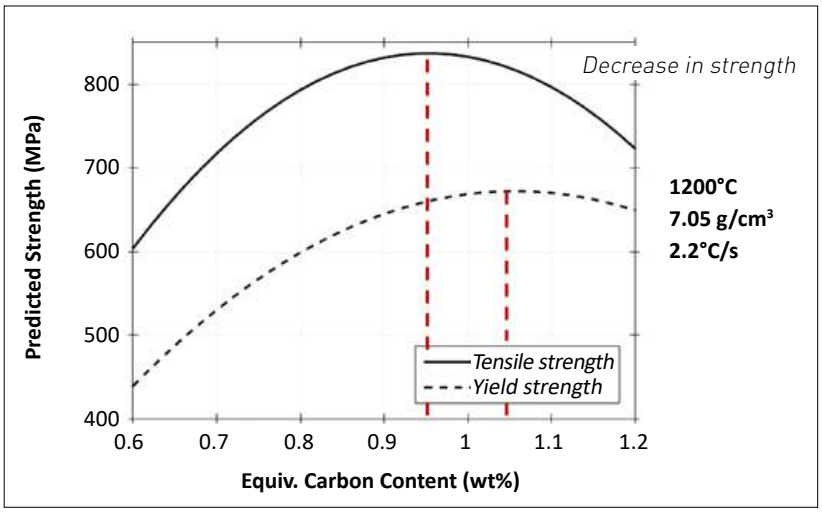

Fig. 13 Relationships between Tensile strength and Yield Strength and E.C.C. [3]

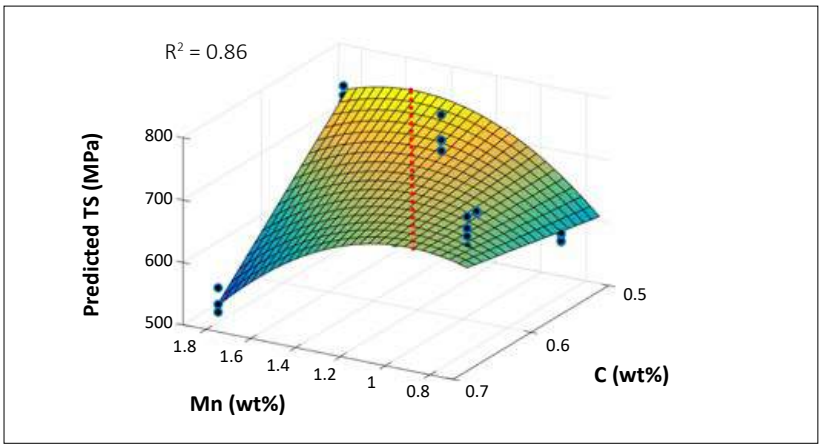

Fig. 14 Effect of C and Mn contents on Tensile Strength (second Taguchi experiment) [3]

A new perspective on the potential of lean alloy PM steels

Simon Gelinas (Universite Laval, Canada) reported on a new perspective on the potential of lean alloy PM steels, that involved a collaboration with Carl Blais (also Universite Laval) and Ian Bailon-Poujol and Francois Chagnon (Rio Tinto Metal Powders, Canada). The alloy system studied was free of any nickel addition, but included low levels of manganese, chromium and silicon, introduced through ferro-alloy additions.

The study involved two design of experiment assessments using Taguchi arrays and had two objectives: the primary objective of defining means of maximising tensile strength and a secondary objective of investigating and modelling microstructure/strength relationships.

For the first experiment, samples were processed by sinter hardening from sintering temperatures of 1120°C to 1200°C at cooling rates of 1.7 to 3°C/sec. The first Taguchi array is shown in Table 2. The chemical compositional variables were grouped into a single Equivalent Carbon Content (E.C.C) term,

$$\text{E.C.C.} = \%C + \frac{\%Mo}{4} + \frac{\%Cr}{5} + \frac{\%Mn}{6} + \frac{\%Si}{24}$$

and relationships with achieved levels of tensile strength and yield strength were derived as follows:

$$\text{T.S.} = 46087 + 3562 \cdot (\text{E.C.C.}) + 0.83 \cdot (\text{Sint.Temp.}) - 14309 \cdot (\text{Density}) - 1868 \cdot (\text{E.C.C})^2 + 1065 \cdot (\textit{Density})^2$$

$$\text{Y.S.} = 63130 + 2360 \cdot (\text{E.C.C.}) + 0.71 \cdot (\text{Sint.Temp.}) - 18910 \cdot (\textit{Density}) - 1117 \cdot (\text{E.C.C})^2 + 1383 \cdot (\textit{Density})^2$$

The relationships, between strength and E.C.C,. are plotted in Fig. 13 and show that tensile strength and yield strength pass through maxima at 0.95 and 1.05 wt% E.C.C respectively.

The second Taguchi array is shown in Table 3. All samples were compacted to a fixed green density of 7.05 g/cm³ and were sintered at 1200°C. Tensile strength, the propor-

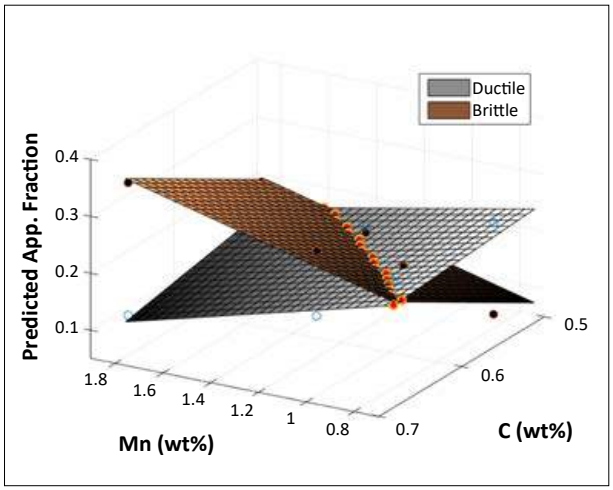

Fig. 15 Effects of C and Mn contents on proportions of ductile and brittle fracture (second Taguchi experiment) [3]

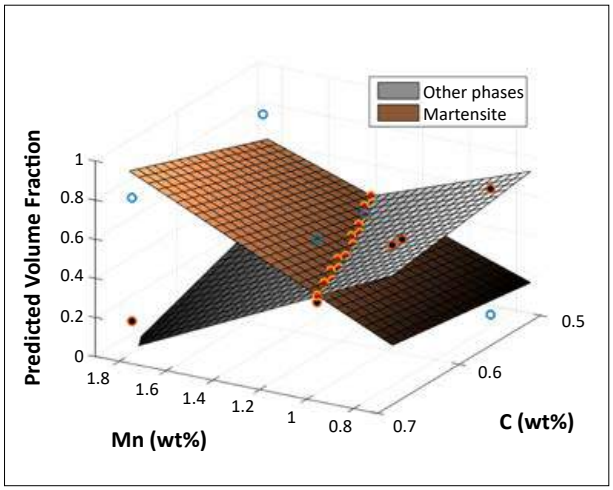

Fig. 16 Relationship between volume fractions of martensite and other phases and C and Mn contents (second Taguchi experiment) [3]

tion of brittle fracture in the fracture face and the proportions of martensite and other phases in the microstructure were plotted against C and Mn contents in Figs. 14 to 16 respectively.

It was concluded, from these experiments, that:

- Lean alloys based on admixed ferro-manganese are highly susceptible to "over-alloying".
- Optimum tensile properties are observed at low C and high Mn contents. Cr is still a beneficial addition, although it is not essential.
- Beyond 0.44 volume fraction of martensite, there is a transition from ductile to brittle fracture and a consequent decrease in tensile strength.

#	Mn (wt%)	C (wt%)	Si (wt%)	Mo (wt%)
1	1.30	0.65	0.20	0.40
2	1.30	0.55		
3	0.85	0.65		
4	0.85	0.55		
Centre point	1.08	0.60	0.20	0.40
5	1.90	0.70		
6	1.90	0.55		

Table 3 Second Taguchi array [3]

Grade	C (%)	Si (%)	Mn (%)	Cr (%)	Mo (%)	Ni (%)
16MnCr5	0.14-0.19	Max 0.40	1.0-1.3	0.8-1.1		
20MnCr5	0.17-0.22	Max 0.40	1.1-1.4	1.0-1.3		
17NiCrMo6	0.14-0.20	Max 0.40	0.6-0.9	0.8-1.1	0.15-0.25	1.2-1.5
SAE 8620	0.18-0.23	0.15-0.35	0.7-0.9	0.4-0.6	0.15-0.25	0.4-0.7

Table 4 Typical wrought steels for transmission gears [4]

Suitability for highly loaded applications

In order to attain the maximum benefit from lean PM alloys used in the heat treated condition, it is generally necessary to optimise the applied heat treatment schedule. Mats Larsson (Höganäs AB, Sweden) addressed this issue, in the context of the case carburising of transmission gears [4]. Before reviewing potential PM materials for transmission gears, the author identified the types of alloys that are used in wrought steels for this application (Table 4).

The general challenges in heat treatment of a transmission gear were identified as:-

- Attaining the correct case depth
- Attaining a similar case depth in the flank and tooth root
- Obtaining sufficient core hardness (usually around 400 MVH)
- Obtaining a fully martensitic case, both on the tooth flank and in the tooth root
- Achieving residual compressive stresses in the surface

Also, if parts are to be welded, the sintered carbon content is limited, typically to a maximum of 0.23%.

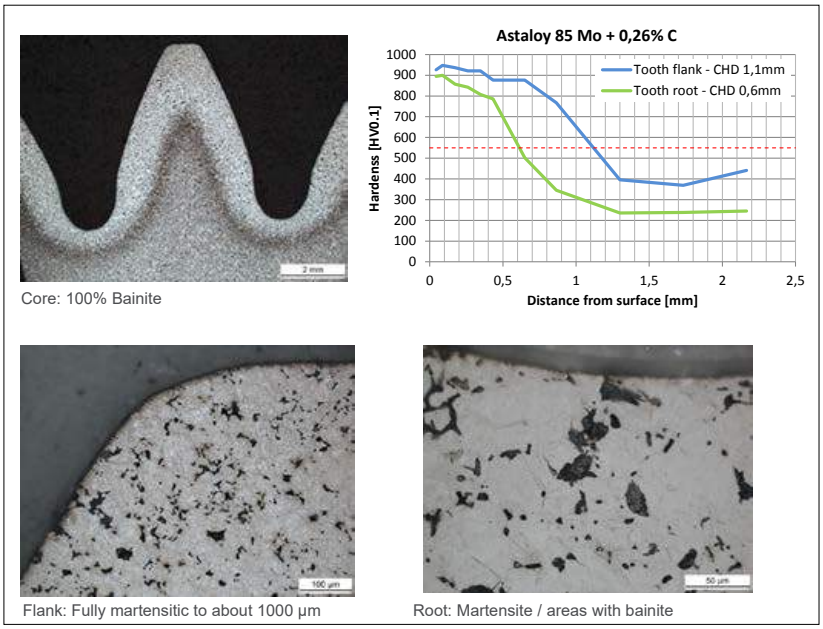

Fig. 17 Low pressure carburised and gas quenched Astaloy 8 5Mo (FL-4400) [4]

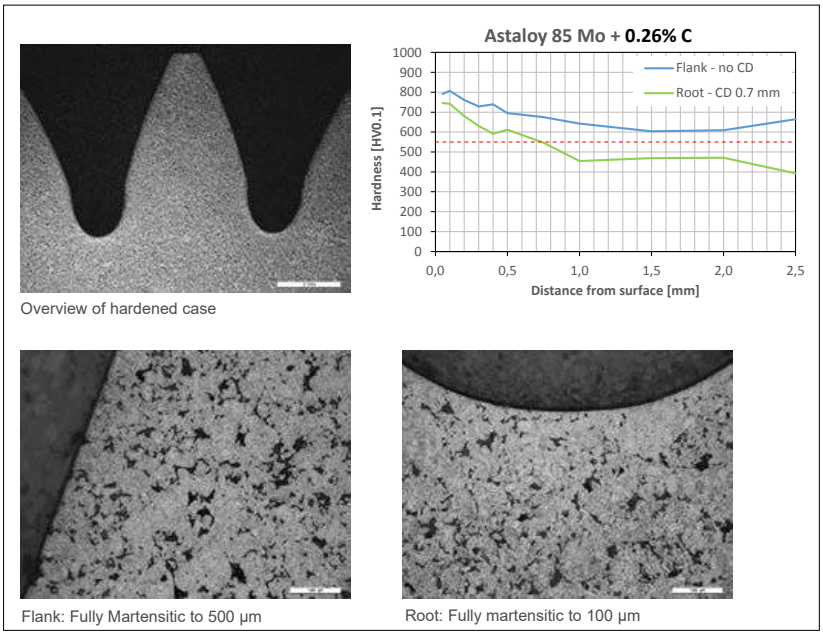

Fig. 18 Gas carburised and oil quenched Astaloy 85Mo (FL-4400) [4]

Fig. 19 M32 4th drive gear [4]

There are additional challenges in the heat treatment of PM gears. Firstly, porous surfaces are more reactive and pick up carbon faster. As a result of this, carburising depth is density dependent. In the specific context of "lean" PM steels alloyed with Cr, Mn and Si, oxidation will occur in a gas carburising furnace.

In relation to these challenges, the advantages offered by using the Low Pressure Carburising (LPC) and Gas Quenching process, as compared with the conventional gas carburising and oil quenching approach, were discussed. LPC is a boost-diffuse process, in which the surface layers are saturated with carbon in short boost cycles followed by diffusion of carbon into the material under low pressure with a nitrogen back-fill. In relation to the challenges, identified above for the carburising of PM gears, the process allows the production of a well-defined case not possible with conventional gas carburising (compare Figs. 17 and 18). Also, because LPC is an oxygen free process, it enables case hardening of PM steels with alloying elements prone to oxidation such as Cr, Mn and Si. In particular, chromium alloyed PM steels can be effectively used in combination with LPC.

A case study was presented, relating to the heat treatment of M32 4th drive gears (Fig. 19). This gear is viewed as an excellent test case for the heat treatment of transmission gears, as its size and geometry is relevant to the target applications.

The PM materials included in the reported study are shown in Table 5. Three of these grades were assessed in the gas carburised and oil quenched condition (with Astaloy 85Mo (FL-4400) being assessed after two different carburising times, 40 and 60 minutes) and the obtained case characteristics are summarised in Table 6. None of these grades in this condition satisfied the full range of case requirements listed earlier. Even Astaloy Mo (FL- 4900), which complied with the sintered carbon content and core hardness criteria, did not achieve similar case depths in the tooth flank and the tooth root.

Seven of the grades were subjected to the LPC process and the case characteristics attained are summarised in Table 7. With the LPC treatment, three grades showed a good match with the range of case requirements i.e. Astaloy CrA (FL-5100) + 2%Ni, Distaloy DC (FLDN2-4900) and Distaloy DH (FL-4900).

From the results of these studies, it was possible to conclude that:

- Wrought case hardening steels have alloying contents in the range 2 –3% and carbon content 0.16 –0.20%.
- Viable case hardened PM steels for highly loaded parts will require similar alloying contents to the wrought steels, with which they are competing.
- Distaloy AQ (FD-0100) and Astaloy 85 Mo (FL-4400) are too lean for a 0.5 kg case hardened transmission gear.
- Low pressure carburising (LPC) and gas quenching requires somewhat higher alloying contents compared to conventional case hardening, but enables the use of Cr alloyed PM steels

Micro-alloyed bainitic steel for lower cost PM alloys

A novel concept in lean alloy compositional development was the subject of a contribution from Christopher Schade (Hoeganaes Corporation, USA), co-authored by Thomas Murphy (also Hoeganaes Corporation) and Alan Lawley, Roger Doherty, Mitra Taheri, George Bernhard, Colleen Hyde and Madeline Bouchard (Drexel University, USA) [5]. This was the latest in a series of assessments of the application in PM materials of alloying/processing concepts, 'borrowed' from wrought steel physical metallurgy (for example, micro-alloying, dual phase microstructures, precipitation hardening, refinement of microstructure).

Previously reported work had identified the benefits of developing a lower bainite microstructure directly

Base powder	MPIF	Mo (%)	Ni (%)	Cr (%)	Mn (%)	Cu (%)
D. AQ	FD-0100	0.50 (d)	0.50 (d)			
Astaloy 85 Mo	FL-4400	0.85				
Astaloy Mo	FL-4900	1.50				
Astaloy CrA	FL-5100			1,80		
Ast. CrA + 2% Ni	FL-5100 (+Ni)		2.00 (e)	1,80		
Astaloy A	FL-4600	0.55	1.90		0.20	
D. DC	FLDN2-4900	1.47	2.00 (d)			
D. DH	FLC-4900	1.47				2.00 (d)

Table 5 PM alloys included in the study [4]

	Dist. AQ (FD-0100)	Ast. 85 Mo (FL-4400)	Ast. 85 Mo (FL-4400)	Ast. Mo (FL-4900)
Sintered C-content (%)	0.28	0.26	0.26	0.21
CHD flank [mm]	0.95	T.H.	T.H.	0.7
CHD root [mm]	0.38	0.7	0.6	0.35
Δ CHD [mm]	0.57	***	***	0.35
Core hardness [$HV_{0.1}$]	300	450	450	400

Table 6 Summary of case characteristics for gas carburised and oil quenched PM materials [4]

	Ast. 85 Mo (FL-4400)	Ast. Mo	Ast. CrA (FL-5100)	Ast. CrA + 2% Ni	Ast. A (FL-4600)	D. DC (FLDN2-4900)	D. DH (FLC-4900)
Sintered C-content (%)	0.26	0.28	0.21	0.22	0.19	0.19	0.19
CHD flank [mm]	1.10	1.15	0.80	0.95	0.82	0.70	0.84
CHD root [mm]	0.60	0.72	0.60	0.70	0.50	0.57	0.57
Δ CHD [mm]	0.5	0.43	0.20	0.25	0.32	0.13	0.27
First bainite In root [mm]	0	1.6	0.6	1.0	0.35	0.6	0.95
Core hardness [$HV_{0.1}$]	~240	~400	~300	~420	~260	~380	~400

Table 7 Summary of case characteristics for low pressure carburised and gas quenched PM materials [4]

on cooling from sintering temperature. A lower bainite microstructure was seen as conferring a superior combination of strength and toughness, compared with martensitic steels, and it was found that modest levels of appropriate alloying additions could influence the continuous cooling transformations on cooling from sintering to enhance the formation of this microstructural phase. The CCT diagram in Fig. 20 shows that the additions of 1.2% Cr, 0.6% Mo and 0.22% V could push the ferrite and pearlite transformation noses sufficiently to the right to enable the formation of bainite at cooling rates below 1°C/sec. Accelerated cooling beyond this limit favoured the formation of lower bainite in preference to upper bainite.

Element	C	S	O	N	Si	Cr	Mn	Mo	V
Weight Percent	0.50	0.01	0.25	0.02	0.75	0.58	0.40	0.89	0.10
Note: Graphite additions were made to have a 0.50% sintered carbon.									

Table 8 Base alloy composition [5]

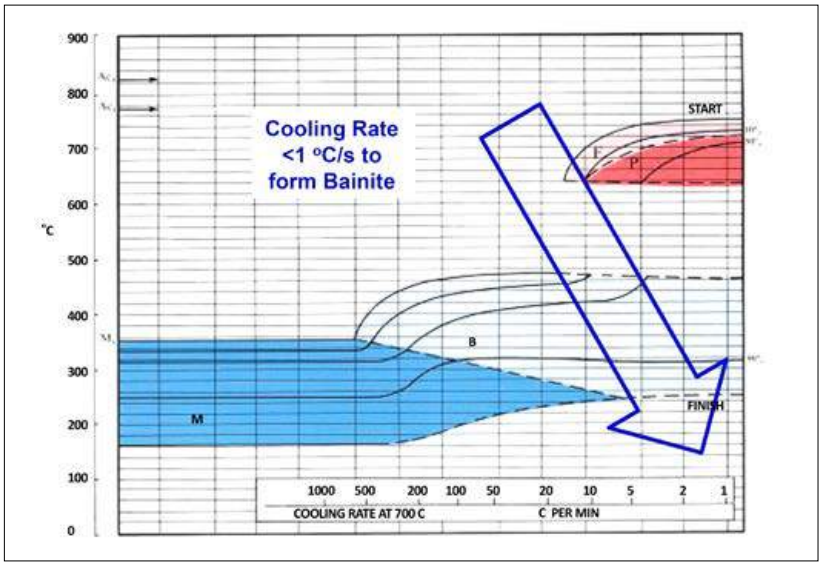

Fig. 20 CCT diagram for low alloy steel with 1.2% Cr, 0.6% Mo and 0.22% V [5]

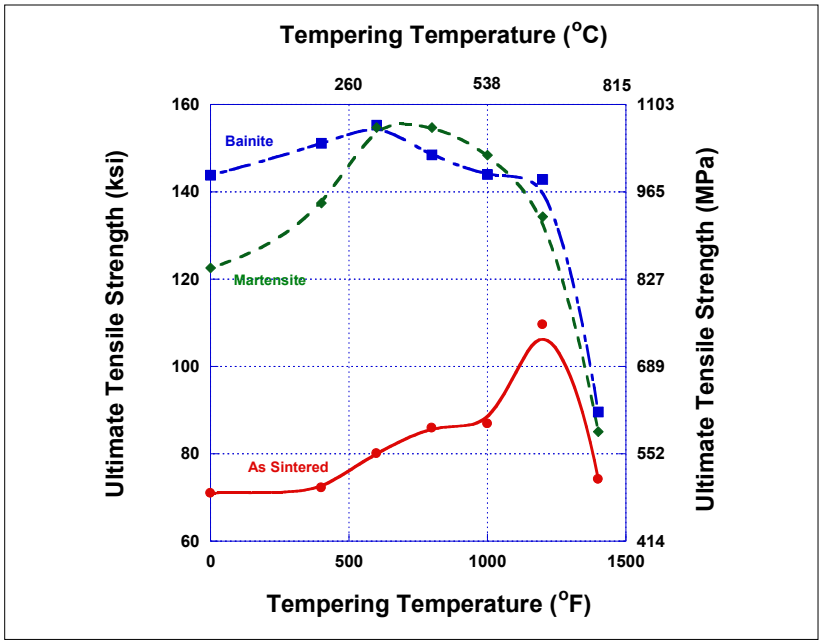

Fig. 21 Ultimate tensile strength levels for Ni/Cu micro-alloyed material [5]

The aim of this currently reported work was to explore the possibility of combining micro-alloying with the generation of lower bainite. The stated primary objectives of micro-alloyng were to refine austenite grain size in sintering or heat treatment and to add precipitation hardening through the formation of carbides, nitrides or carbonitrides.

For the reported work, the base material had the composition shown in Table 8. In the initial experimental study, the micro-alloying additions boron (B), at 0.047%, niobium (Nb) at 0.16%, titanium (Ti) at 0.04% and tungsten (W) at 0.32% were investigated. All elements were pre-alloyed.

Sample bars had sintered densities around 6.9g/cm^3 and were sintered at 1260°C in a 90% nitrogen/10% hydrogen atmosphere. Cooling rates (between 649°C and 316°C) in the range 2 to 3°C/sec were applied.

Boron, niobium and tungsten were all seen to increase the level of lower bainite formed, but niobium and boron, in particular, were rated as being difficult to process. For instance, a boron-containing material needs to be processed in a low nitrogen containing atmosphere.

A second study was carried out to address the question as to whether micro-alloying with small amounts of the commonly used additions of copper and nickel might be effective. It transpired that a higher level of lower bainite was achievable with additions of Cu and Ni at the 0.2% level, than with any of the additions studied in the first round (Table 9).

For the Ni/Cu micro-alloyed material, Figs. 21 to 23 show the achievable UTS, Apparent Hardness and Impact Energy in the as-sintered and the sinter hardened and tempered conditions and also demonstrate the benefits of achieving a bainitic as opposed to a martensitic micro-

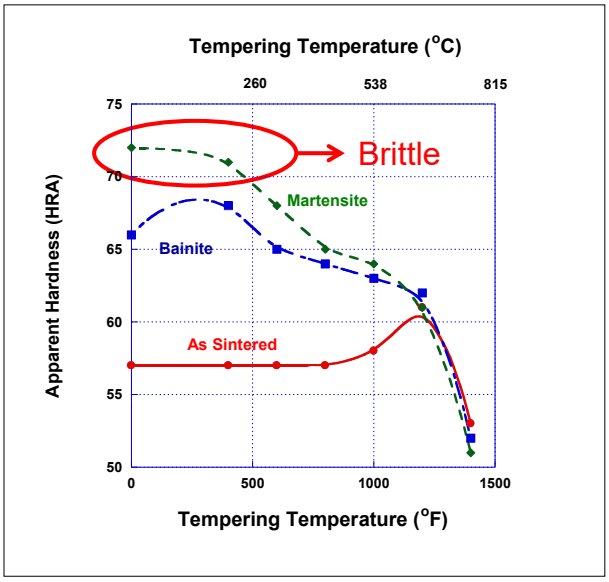

Fig. 22 Apparent hardness levels for Ni/Cu micro-alloyed material [5]

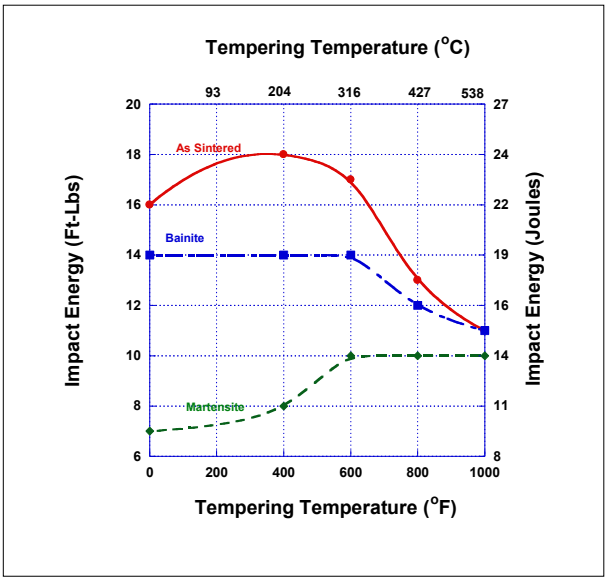

Fig. 23 Impact energy levels for Ni/Cu micro-alloyed material [5]

structure. PM steels with a high percentage of lower bainite can almost match the tensile strength of a martensitic alloy of the same composition, while providing greater impact energy due to the refined microstructure.

The overall conclusions were drawn that the use of steels containing lower bainite should lead to leaner alloy systems, thus lowering the overall cost, and that the potential exists for alloys to be designed that can be sintered at conventional temperatures (1120°C) and still exhibit significant amounts of lower bainite.

Alloy	Cooling	vol% Lower Bainite
Standard	Cooling 3	8.0
Nb	Cooling 3	26.1
B	Cooling 1	28.5
W	Cooling 3	19.5
B&W	No Cooling	13.4
Cu & Ni	Cooling 2	48.6

Table 9 Maximum lower bainite percentages achieved [5]

Adding cost effective alloying elements

As mentioned previously, the alloying additions of major interest in lean alloy developments (Cr, Mn, Si) are characterised by the relatively high stability of their oxides, compared with those of Fe, Cu, Ni or Mo. One approach, which has emerged as a potentially effective means of introducing such elements whilst obviating some of the concerns over reduction of these oxides during the early stages of sintering, has been the use of masteralloy additions.

This approach was the focus of a contribution to the SIP by Raquel de Oro Calderon (Technical University of Vienna, Austria). The research work, reported in this contribution, is the subject of a separate article in this issue of *Powder Metallurgy Review*.

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Improving quality control through effective particle characterisation of metal powders

Advances in Powder Metallurgy production technologies are generating an increased demand for tailored and tightly controlled powders with distinctive properties. The control of particle size distribution, as well as particle shape, is an important step in the quality control process. In this article Jörg Westermann, Retsch Technology GmbH, compares the three most commonly used methods for powder characterisation and highlights the pros and cons of each process.

Production capacities for specialised metal powders are increasing worldwide and the demand for powders with distinctive properties in terms of chemical composition, particle size distribution and particle morphology is growing. The size and shape of metal powders influence process parameters and properties of the final products for all Powder Metallurgy applications.

The control of particle size distribution, as well as particle shape, is an important step in the quality control process of metal powder producers, parts manufacturers and research facilities. A fast and comprehensive powder analysis not only minimises metal powder production costs by enabling optimised process parameters, it also provides understanding of powder flowability, packing density and surface roughness of the final parts.

The three most commonly used methods of powder characterisation are sieve analysis, laser light scattering and dynamic image analysis (Fig. 1). In this article the advantages and drawbacks of the different methods are demonstrated with typical metal powder samples such as steel powders, Ti64, Al, Ni, Cr and W alloys.

Fig. 1 Sieve shakers, laser diffraction analysers and dynamic image analysers are commonly used to characterise the particle size of metal powders

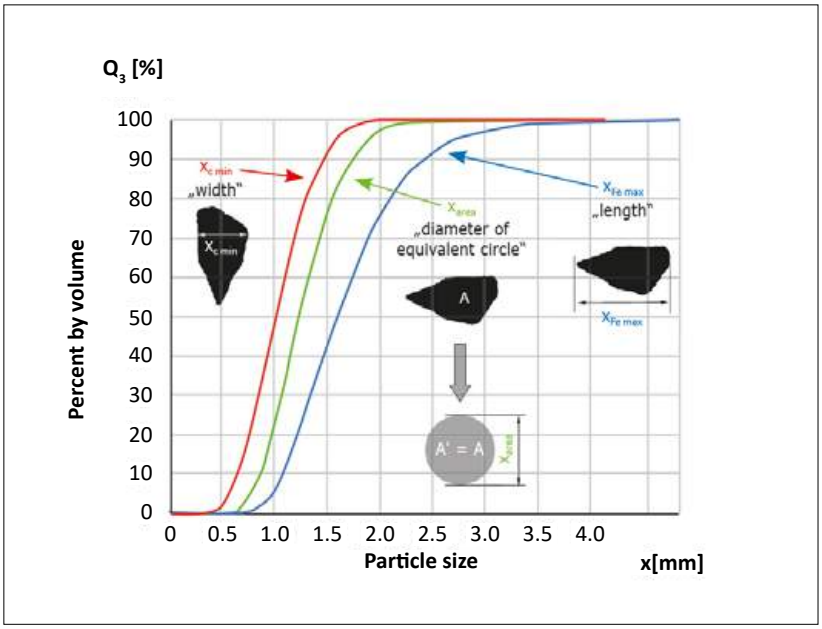

Fig. 2 Selection of basic size parameters used in image analysis

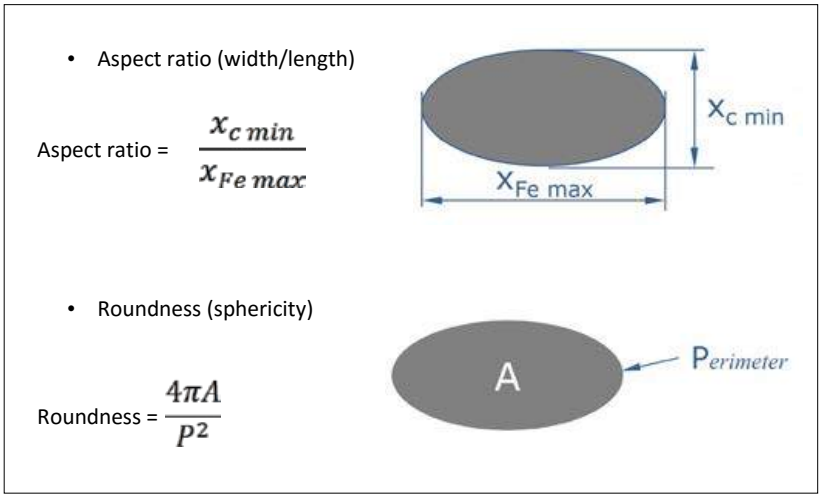

Fig. 3 Selection of basic shape parameters used in image analysis

The most common methods of powder characterisation

Sieve analysis

Traditionally, mechanical sieve analysis is the most common method for particle sizing. For metal powders, ISO 4497 and ASTM B214 describe the most relevant procedures. The absolute lower size limit for sieve analysis is defined by the smallest practically usable mesh size of 20 µm (air jet sieving), which is well above the average particle size of many samples for Additive Manufacturing or Metal Injection Moulding, for example.

As a consequence, air jet sieving is not suited for the precise and reliable analysis of the whole size distribution of fine powders. Therefore, it is often used only for detecting the amount of oversized particles with one sieve size only, for example with 45 µm or 63 µm mesh size. Alternative methods are required for fine metal powders with particle sizes below 100 µm.

Laser light scattering

Very common is the use of a laser diffraction analyser which employs static light scattering, as described in ISO 13320 for example. These instruments are easy to operate and rapidly provide measuring results. However, the method is based on indirect measurement as the particle size is calculated from the scattering angle and light intensity of a laser light beam interacting with the sample. Sophisticated software algorithms are employed to calculate the particle size distribution based on assumptions and approximations.

One basic assumption is, for example, that all particles are spherical. Consequently, any deviation of the actual particle shape from the assumed spherical shape causes discrepancies in the calculated particle size distribution. Thus the comparison of samples with different morphologies may lead to surprising results, especially among different particle sizing methods and even different software versions of the same instrument type. Another drawback is that laser diffraction analysers cannot provide any information about the shape of the particles.

Dynamic image analysis

Optical microscopy offers a more direct approach to particle size analysis. The basic idea is simple, "What you see is what you get". Based on pictures of individual particles, automatic software algorithms analyse the size and morphology. Particle length and particle width can be measured independently (Fig. 2) as well as parameters related to the particle shape like the aspect ratio, roundness, angularity or surface roughness (Fig. 3).

Two imaging methods are available, static and dynamic image analysis (SIA and DIA, ISO 13322-1 and 2). The static optical microscopy has commonly been used to obtain a qualitative impression of the shape of the particles. However, the insufficient dispersion of the particles on the microscope slide and the small amount of material which can be analysed prevent a quantitative analysis.

In dynamic image analysis (DIA), particles in a size range from typically 1 micron to several millimetres

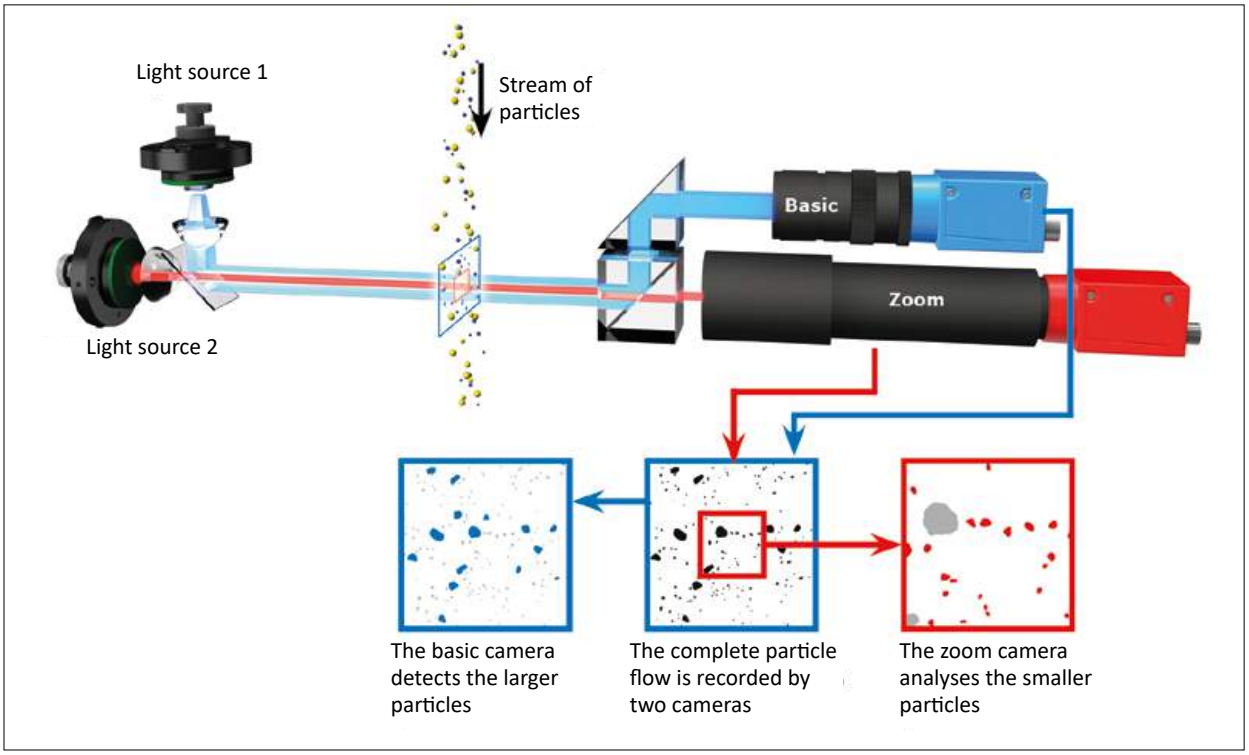

Fig. 4 The patented measuring principle of Camsizer X2

move with respect to a camera, either in an air jet beam or in a liquid cell. Thus it is possible to analyse several millions of particles, i.e. a representative amount of sample material, within one minute. In a simplified way, the DIA may be described as an optical microscope combined with the sample dispersion of a laser diffraction instrument.

Dynamic image analysis allows the measurement of particle size distribution and quantitative particle shape (percentage of round versus irregular shaped particles, satellites, agglomerates etc.). Smallest amounts of oversized, undersized, or irregular shaped particles can be detected, even with a percentage as low as 0.01%. Thus DIA enables the user to obtain a comprehensive overview and understanding of size and morphology related sample properties. Fig. 4 shows the principal set-up of the optics for dynamic image analysis. The sample moves as a particle flow through the measuring zone. A light source illuminates the particles from one direction while a camera takes a picture from the opposite side. Software evaluates the shadow projections of the particles to determine the size distribution of the sample in a very short time. A few hundred particles per picture are evaluated in real time. Advanced DIA systems, such as Retsch Technology's Camsizer X2, use two cameras with different magnifications to cover a wide measuring range: one camera with high magnification is optimised for the analysis of small particles, a second camera with a lower magnification but wide field of view allows the simultaneous analysis of the larger particles with high detection efficiency. The Camsizer X2 system records more than 300 pictures per second. Thus dynamic image analysis allows for the measurement of statistically relevant amounts of a few million particles in a short time.

Wide range of alloys, particle sizes and particle shapes

The suitability of dynamic image analysis for comprehensively characterising metal powders has been demonstrated with a number of application examples. The results of ten metal powders, which are typically used for powder metallurgical applications, are compared in Fig. 5. These samples show a wide variety of mean particle size, distribution width and particle shape.

Irrespective of the differences in chemistry, density, size and shape, all samples can be analysed with one instrument setup. All results

"dynamic image analysis allows for the measurement of statistically relevant amounts of a few million particles in a short time"

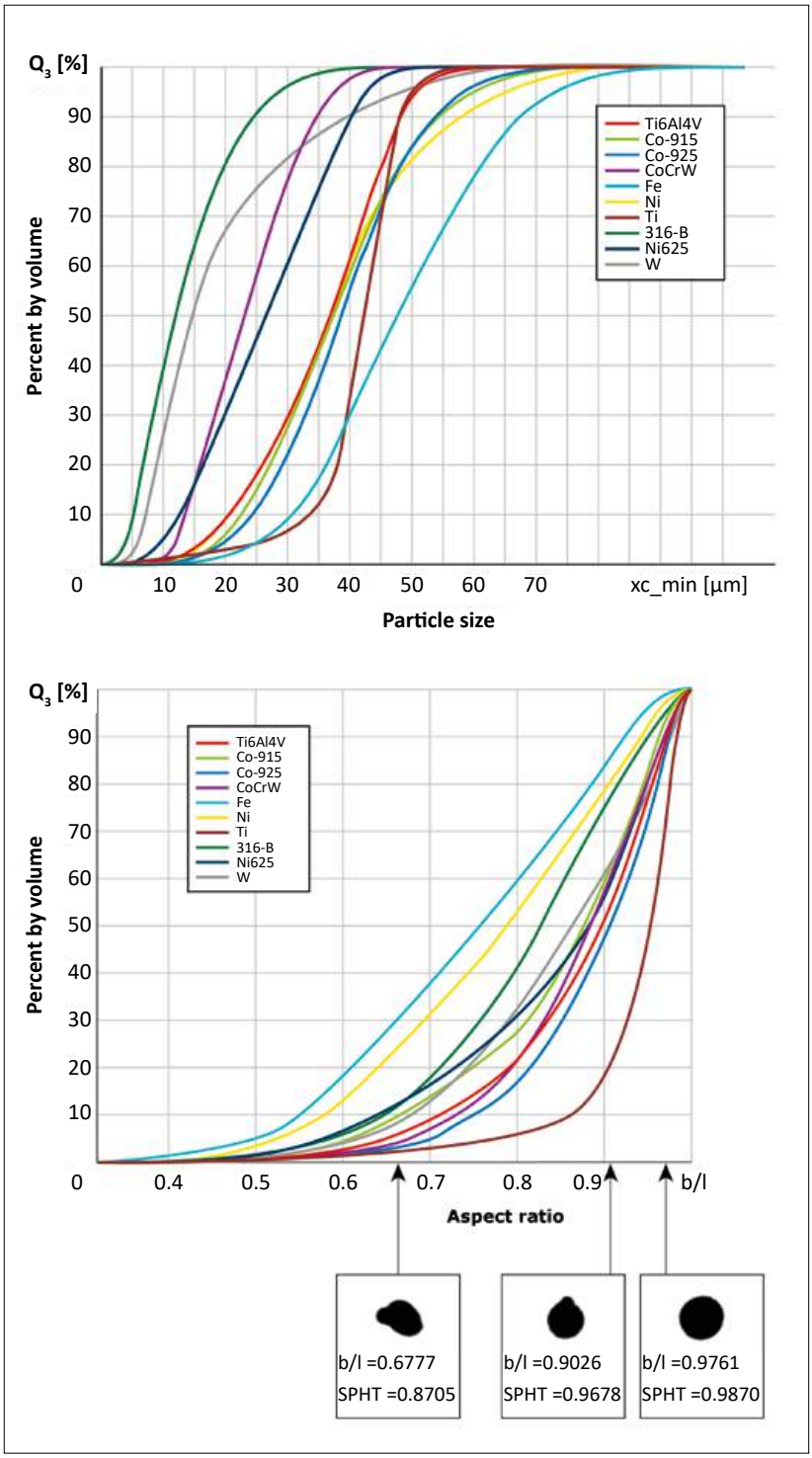

Fig. 5 Analysis of particle size and particle shape of ten different metal powders with dynamic image analysis (Camsizer X2). Besides the quantitative results, the recorded images allow an intuitive understanding of morphology and size differences

show a superior resolution and reproducibility compared to laser diffraction and sieve analysis. Even for samples with an average particle size of approximately 10 µm, a detailed size and shape analysis is possible thanks to recent advances in image resolution. The quantitative results are visualised and easily understood with the help of the recorded particle images. In this example, the iron powder (Fe) is the coarsest, whereas the stainless steel powder (316) is the finest. The shape diagram shows that the titanium powder is most compact, whereas the iron powder particles are the most elongated. The insert shows typical images of steel particles with different shape (satellites, elliptical droplets), and the calculated roundness (SPHT) and elongation (b/l).

Comparison of laser light scattering, sieve analysis and dynamic image analysis

Different analytical methods provide different size distribution curves for the same sample material. In Fig. 6 a comparison of sieve analysis, laser diffraction and dynamic image analysis is shown for a typical steel powder with well-rounded particles.

The systematic differences between the methods have been observed also for many other samples and they become more obvious the more irregular the particles are shaped. The results of the particle width measurement by DIA (red curve, Camsizer X2) agree perfectly with the results of sieve analysis (light blue asterix). DIA provides exactly the same size distribution as sieve analysis. On this basis many laboratories have decided to replace the time-consuming sieve analysis with faster and more accurate dynamic image analysis while maintaining established values for product specifications etc.

The laser diffraction analyser does not differentiate the length and width of particles. The results it provides (black asterix) agree well with the width definition of the DIA (red curve) at the lower part of the curve, but for large particles the agreement is better with the particle length (blue curve). For irregular shaped particles, the result of the laser measurement includes both the length and width mixed into one 'size' result which in general shows a wider size distribution.

Therefore, the laser diffraction measurement results do not match the sieve data, which are identical to the width measurement by DIA. Another problem of laser diffraction

is the limited detection capacity for small amounts of outliers. The analysers are not able to detect small amounts (up to 2%) of over-sized or undersized material reliably as these do not provide a sufficient scattering signal.

Dynamic image analysis, in contrast, is based on detection of individual, single particles, irrespective of the overall concentration. The detection of smallest amounts of oversized particles well below 0.01% is possible. Further information about these few particles can be obtained from studying the captured images to ascertain if these particles are single particles (for example elongated needles) or aggregates and agglomerates.

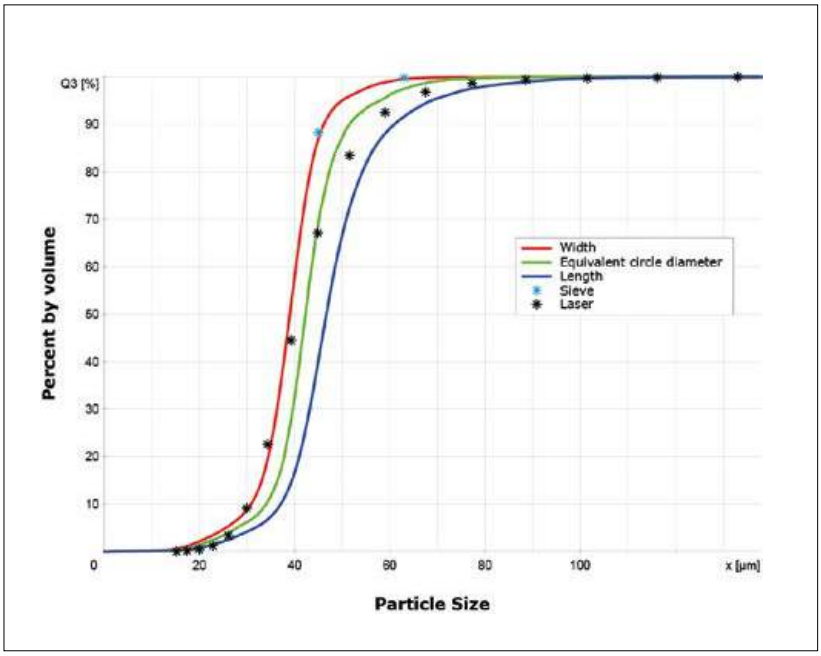

Fig. 6 Identical steel powder, different size analysis methods: The results provided by sieve analysis, laser diffraction and DIA show systematic differences

Conclusion

Several methods are available for the particle characterisation of metal powders. The traditional methods of sieve analysis and laser diffraction are increasingly being replaced or complemented by dynamic image analysis, a method which permits a more accurate and detailed sample characterisation including quantitative shape analysis. This leads to a better understanding of powder properties such as flowability, powder bed density and energy input required to melt the grains. Consequently, a tighter quantitative quality control based on process parameters such as average particle size, amount of over- and undersized material and particle morphology (average roundness, percentage of satellites, needles and other irregular shaped particles) is possible.

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MPIF Powder Metallurgy Design Excellence Awards 2016

Winning parts in the Metal Powder Industry Federation (MPIF) 2016 Powder Metallurgy Design Excellence Awards competition were announced at POWDERMET2016, Boston, USA, June 5-8. The annual awards provide a showcase for the industry and demonstrate the ability of Powder Metallurgy technology to meet high tolerances in a wide range of demanding applications.

Winning parts in the MPIF's 2016 Powder Metallurgy Design Excellence Awards competition demonstrate how conventional press and sinter PM technology is continuing to find new applications in many sectors, whilst also replacing traditional manufacturing processes thanks to the design, performance and economic advantages. The continuing growth in the Metal Injection Moulding (MIM) industry is also evident, reflected in the large number of prizes presented to this sector in this year's awards.

Grand Prize Awards

Automotive-Transmission: GKN Sinter Metals

The Grand Prize in the Automotive-Transmission category was awarded to GKN Sinter Metals, Auburn Hills, Michigan, USA, for a forged PM electronic locking differential gear set made for Ford Motor Company (Fig. 1). Comprising five components, namely a side gear, two pinion gears, a locking side gear and a locking plate, the gear set is used in the rear axle differential of the Ford F-150 light truck, the first time forged PM differential gears have been used in such an application.

The higher performance delivered by the forged PM differential gears compared to that of competing metal-forming processes will help usher in downsized gear systems, satisfying a critical need in future automotive design.

Fig. 1 GKN Sinter Metals manufacture these components for use in the rear axle differential of Ford's F-150 light truck (Courtesy MPIF)

Fig. 2 Keystone manufacture these seven components used in the steering column of the Chevrolet Colorado and GMC Canyon trucks (Courtesy MPIF)

Fig. 3 Metal Injection Moulded front sight base used on the AR-15 rifle by Advanced Forming Technology (Courtesy MPIF)

Fig. 4 Parmatech Corporation make these stainless steel MIM components for an endoscopic surgical device (Courtesy MPIF)

Automotive –Chassis: Keystone Powdered Metal Co

The Grand Prize in the Automotive-Chassis Category was presented to Keystone Powdered Metal Co., St. Marys, Pennsylvania, USA, for a total of seven components used in the steering column of the Chevrolet Colorado and GMC Canyon trucks .

The rake cam, left-hand inner cam, retainer guide, right-hand rake teeth energy-absorbing eccentric strap cam, column mounting insert teeth and left-hand rake teeth (Fig. 2) are made for Nexteer Automotive. The heat-treated diffusion-alloyed steel components are key elements of the steering column's tilt and telescope adjustment feature, serving a vital role in maintaining the column's position during a crash event. The rake cam has features that allow for a mechanical lock of the plastic lever, which is overmolded in an operation performed by Agapé Plastics, Inc.

Aerospace/Military: Advanced Forming Technology

The Grand Prize in the Aerospace/Military Category was won by Advanced Forming Technology, an ARC Group Worldwide Company, Longmont, Colorado, USA, for a Metal Injection Moulded front sight base used on the AR-15 rifle (Fig. 3).

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

Medical/Dental: Parmatech Corporation

The Grand Prize in the Medical/Dental Category was won by Parmatech Corporation, Petaluma, California, USA, for four stainless steel MIM components used in an articulating endoscopic surgical device designed specifically for thoracic surgery (Fig. 4).

The parts, an articulation lock bar, articulation connector, articulation drive block and knife guide, feature complex geometry that would be extremely difficult to machine. The

Fig. 5 Cloyes Gear & Products produce three steel sprockets used in a GM V6 engine (Courtesy MPIF)

Fig. 6 This drive pulley for an electronic power steering system is made by Capstan (Courtesy MPIF)

MIM process saves an estimated 70% over a traditional machining method. The ability of the MIM process to produce parts of different alloys with tight tolerances enabled the design of a smaller endoscopic device, a critical benefit in thoracic surgery.

Awards of Distinction

Automotive-Engine: Cloyes Gear & Products Inc

The Award of Distinction in the Automotive-Engine Category was presented to Cloyes Gear & Products, Inc., Division of HHI/MPG, Subiaco, Arkansas, USA, for three steel sprockets made for Iwis Engine Systems LP. The components, a rubberized crankshaft sprocket and two rubberized oil pump sprockets, are used in a General Motors Generation II High-Feature V-6 Engine, currently installed in the Cadillac CT6 and ATS, GMC Acadia and Chevrolet Camaro (Fig. 5).

The patented rubber design used on the crankshaft sprocket provides improved noise, vibration, and harshness characteristics that exceed the engine manufacturer's demands. Fabrication via PM provides an estimated 30% saving over parts machined from steel bar or forgings.

Automotive-Chassis: Capstan

An Award of Distinction in the Automotive-Chassis Category was given to Capstan, Wrentham, Massachusetts, USA, for a drive pulley for an electronic power steering system (Fig. 6). The iron-copper part is used in assemblies found in the Ford Focus and Escape vehicle platforms.

This unique six-level component requires tight tool-wear control. Powder Metallurgy was chosen as the fabrication method because it offered far better precision than the die-cast alternative at a competitive price.

Fig. 7 GKN Sinter Metals produce this driven pulley for use in an electric power steering system (Courtesy MPIF)

Fig. 8 MIM 17-4 PH stainless steel diesel leak-off union made for Lombardini by Indo-US MIM Tec (Courtesy MPIF)

Fig. 9 Advanced Forming Technology manufacture this aerospace engine ferrule for Rolls Royce (Courtesy MPIF)

Fig. 10 Parts for a pump-action shotgun's adjustable trigger system made by Parmatech (Courtesy MPIF)

Automotive-Chassis: GKN Sinter Metals

A further Award of Distinction in the Automotive-Chassis Category was won by GKN Sinter Metals, Auburn Hills, Michigan, USA, for a copper-steel driven pulley for an electric power steering system made for Nexteer Automotive (Fig. 7).

The pulley is a complex net-shape-compacted part with a unique helical geometry and tight tolerances. Close collaboration with the customer in the design of the part, which includes net-formed lightening holes, yielded savings of more than 10%.

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

The Award of Distinction in the Lawn & Garden/Off-Highway Category was given to Indo-US MIM Tec Pvt. Ltd, Bangalore, India, for a MIM 17-4 PH stainless steel diesel leak-off union made for Lombardini (Fig. 8).

The part goes into the fuel injection of a line of Kohler diesel engines that are assembled in JCB midi and mini excavators, compact wheeled loaders, and Teletruk forklifts. A conversion from a previously used plastic part, whose performance suffered in the tough working environment, the MIM part delivered savings of around 10% through improved quality.

Aerospace/Military: Advanced Forming Technology

The Award of Distinction in the Aerospace/Military Category was presented to Advanced Forming Technology, an ARC Group Worldwide Company, Longmont, Colorado, USA, for an aerospace engine ferrule made for its customer Rolls Royce (Fig. 9). Made of MIM 17-4 PH stainless steel, the part provides a conductive path between the screen and the engine, while offering support to the single cable and preventing the placement of cable loading on the screen.

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

Hand Tools/Recreation: Parmatech Corporation

The Award of Distinction in the Hand Tools/Recreation Category was given to Parmatech Corporation, Petaluma, California, USA, for a MIM 4605 low-alloy steel trigger used in an adjustable trigger system on a pump-action shotgun (Fig. 10).

The extremely complex part geometry, which features multiple thickness changes and slots, required precise tooling to address sufficient machine stock for effective secondary operations. The MIM trigger delivers savings of around 50% over the machined version it replaced.

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

An Award of Distinction in the Electronic/Electrical Category was presented to Indo-US MIM Tec Pvt. Ltd, Bangalore, India, for three parts, a mirror cover, a base, and a middle, made for Optosense (Fig. 11).

Moulded from MIM-316L stainless steel, the parts are assembled into an infrared gas sensor for methane and carbon dioxide detection that has extremely low power consumption. A new application designed specifically for the MIM process, these are medium-complexity parts that have an aesthetic requirement on a few reflective surfaces.

Electronic/Electrical: GKN Sinter Metals

A further Award of Distinction in the Electronic/Electrical Category went to GKN Sinter Metals, Auburn Hills, Michigan, USA, for an aluminium heat sink made for Visteon (Fig. 12). The heat sink is used in a high-volume automotive stereo application.

The part is produced to net shape with no secondary machining operations needed. The high material ductility of the special aluminium PM alloy, combined with the precise positioning of the tooled-in assembly

Fig. 11 Indo-US MIM Tec make these MIM-316L stainless steel components for a gas sensor (Courtesy MPIF)

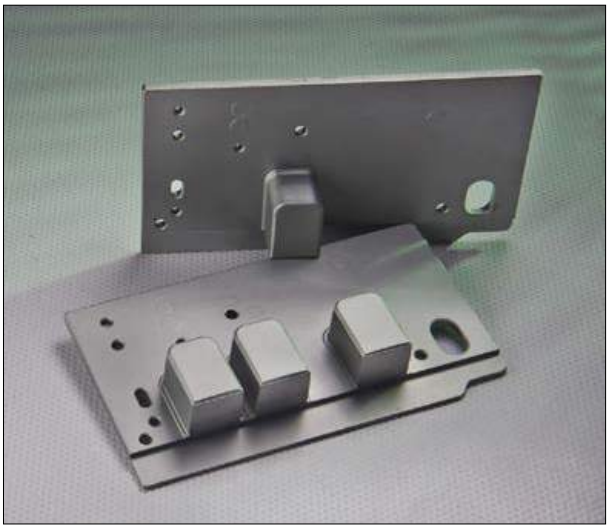

Fig. 12 Aluminium heat sink made for an automotive stereo application by GKN Sinter Metals (Courtesy MPIF)

Fig. 13 Flomet, LLC, make these MIM tungsten electrodes for use in a surgical ablation device (Courtesy MPIF)

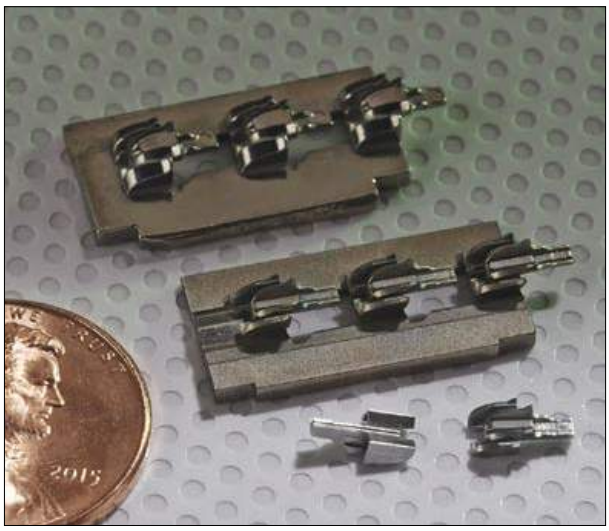

Fig. 14 Advanced Forming Technology produce these MIM components for an endoscopic staple gun (Courtesy MPIF)

holes, enables assembly of the heat sink without the need for attachment screws.

Medical/Dental: Flomet, LLC

An Award of Distinction in the Medical/Dental Category was presented to Flomet, LLC, an ARC Group Worldwide Company, DeLand, Florida, USA for a MIM tungsten electrode used in a surgical ablation device (Fig. 13). The device uses high temperature for the removal of tissue and the use of tungsten enables the electrode to reach its operating temperature more efficiently, maintaining it for a longer time than with other alloys.

Medical/Dental: Advanced Forming Technology

A further Award of Distinction in the Medical/Dental Category was given to Advanced Forming Technology, an ARC Group Worldwide Company, Longmont, California, USA, for a MIM wedge blank used in an endoscopic staple gun (Fig. 14).

Made from a MIM-440 stainless steel, the part has a complex and very small geometry that pushed the MIM process to the very limits of tolerance capabilities. The part's 5 mm diameter, less than half the previous low of 12 mm, enables new procedures to be created and enhances procedures in smaller patients, particularly in the area of paediatrics.

POWDERMET2017

The 2017 MPIF awards will be presented at POWDERMET2017 taking place June 13-16, 2017 in Las Vegas, USA. In addition to the conference, there will be an international exhibition focused on the PM, PIM and metal Additive Manufacturing industries.

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