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POWDER METALLURGY REVIEW

INDUSTRY 4.0 AND POWDER METALLURGY

NEW OPPORTUNITIES FOR MASTER ALLOYS

HAGEN SYMPOSIUM 2018

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POWDER METALLURGY REVIEW

Industry 4.0 and Powder Metallurgy

There can be few that are unaware of Industry 4.0, otherwise called the fourth industrial revolution. Digitalisation, artificial intelligence, Internet of Things, cyber-physical systems, smart factories and big data are just some of the terms commonly associated with Industry 4.0. How this will translate into real-world manufacturing, and in particular the Powder Metallurgy industry, is yet to be fully understood.

The topic has been the subject of a number of presentations at recent industry events, and leading PM part manufacturers have already begun to evaluate and engage in Industry 4.0. In this issue of *PM Review*, we report on how these data driven processes can be integrated into the PM industry and how this can be beneficial for all involved.

Adopting Industry 4.0, streamlining production, even changing the way goods are manufactured, will of course be of little use if the market for those goods no longer exists. This is where Powder Metallurgy does have an advantage - the process offers improved properties, reduced costs and is more environmental friendly than many competing technologies.

Research into further improving the production process and enhancing material properties, opening up new opportunities for the technology, is on-going. We also report on work presented at two recent industry events, as well as on the development of new master alloy powders that can significantly increase the performance of PM steels.

Paul Whittaker
Editor, Powder Metallurgy Review

Cover image
High-voltage contacts for welding units made from dispersion strengthened copper (Courtesy CEP - Compound Extrusion Products GmbH)

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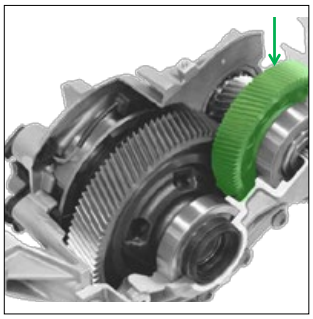

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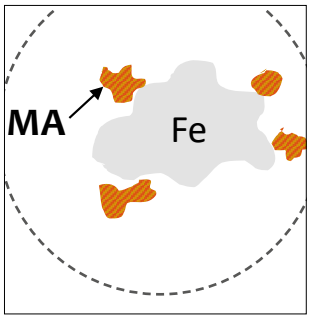

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industry news

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

Significant rise in Fuel Cell Vehicles predicted

Sales of Fuel Cell Vehicles (FCVs) will see substantial growth by 2025, a report by Wards Intelligence forecasts. The report, 'FCVs on the Horizon', was compiled with input from a survey of automotive OEMs and suppliers, and projections from automotive market intelligence provider LMC Automotive, and identifies a number of factors that will drive growth in FCVs in the near future. The primary factors are expected to be reductions in the cost and size of fuel-cell stacks; improvements in fuel-cell output and durability; public and private efforts to expand the fuelling infrastructure and clean sources of hydrogen; improvements in electric motors, energy storage and control systems; and the application of fuel cells to economically power a wider, more varied range of vehicles, including large trucks.

While it is expected that numbers will remain relatively small when compared to vehicles fitted with conventional Internal Combustion Engines (ICEs), Battery Electric Vehicles (BEVs) or other hybrid vehicles, it was stated that automakers and suppliers are preparing for substantial growth in the FCV segment. Fuel cell demand in light vehicles is forecast to increase its momentum with the greatest opportunities initially being in full-sized SUVs and trucks, with buses, heavy-duty trucks, forklifts and commercial vehicles likewise providing significant growth opportunities.

At present, the main barrier to FCV adoption is a lack of convenient fuelling infrastructure. Not enough hydrogen fuelling stations exist and hydrogen fuel remains very expensive to produce. In addition, hydrogen production may not be fully clean, depending often on fossil fuel-generated electric power. FCV cell systems for car engines also remain prohibitively expensive. Keith Wipke, Laboratory Program Manager at the U.S. Department of Energy's National Renewable Energy Laboratory, stated, "It is the first part of the curve, the first 100 to 1,000 units, that is most challenging. If an automaker like Toyota is producing 30,000 (FCVs) in 2020, then 100,000 in 2025 is reasonable."

Saudi Arabia's first hydrogen fuel cell vehicle fuelling station, to be jointly built by Saudi Aramco and Air Products (Courtesy Air Products)

First hydrogen fuelling station in Saudi Arabia

Although a country built on the global oil business may not at first seem the obvious location for a hydrogen fuelling station, a pilot project in Saudi Arabia will aim to showcase the potential this technology has to offer the region. Saudi Aramco, an integrated energy and chemicals company located in Dhahran, Saudi Arabia, and industrial gases company Air Products, Allentown, Pennsylvania, USA, are to jointly build the first hydrogen fuel cell vehicle fuelling station in Saudi Arabia.

A pilot fleet of fuel cell vehicles will be established, for which high-purity compressed hydrogen will be dispensed at the new fuelling station. Data collected during this pilot phase of the project is expected to provide valuable information for the assessment of future applications of the technology in the local environment.

The hydrogen refuelling station will be located within the grounds of Air Products' Technology Center in the Dhahran Techno Valley Science Park. The project will use Toyota's Mirai FCV, a zero-emission vehicle running on compressed hydrogen gas and only emitting water. Toyota has long maintained that hydrogen fuel cell technology can offer a sustainable zero emission solution across a broad spectrum of vehicle types.

"Hydrogen fuel cells offer an effective means for the electrification of transport while maintaining easy, five minute refuelling and long driving ranges," stated Ahmad O Al Khowaiter, Chief Technology Officer of Saudi Aramco. "The use of hydrogen derived from oil or gas to power fuel cell electric vehicles represents an exciting opportunity to expand the use of oil in clean transport."

www.wardsintelligence.com
www.airproducts.com

Kobe Steel to expand production capacity at its Steel Powder Plant

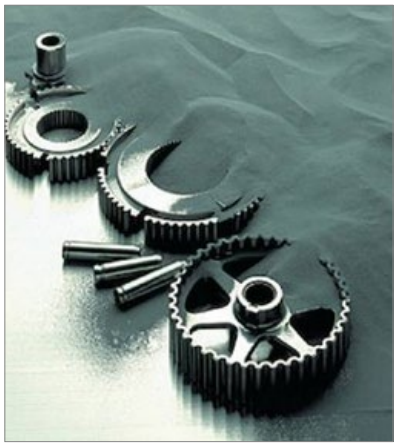
Kobe Steel, Ltd., Kobe, Japan, has revealed plans to invest approximately 1.8 billion Japanese yen to increase the production capacity of its Steel Powder Plant in Takasago, Hyogo Prefecture, Western Japan. The company plans to increase steel powder production to 110,000 metric tons per year, from the current 96,000 metric tons per year, with manufacturing scheduled to begin in the second quarter of 2021.

Kobe Steel's steel powder is mainly used to make PM parts found in automotive engines and transmissions. In the steel powder field, Kobe Steel estimates that it has nearly 50% share of the Japanese market, making it the largest powder producer in Japan. With car production forecast to increase over the medium to long term, the company expects demand for steel powder to grow.

The planned expansion will include the installation of a new reduction furnace to enable higher treatment temperatures than the current furnaces. Kobe Steel will also install a new mixer to increase production capacity of its Segless range of powders. Once established, Segless powders will account for 60,000 tons per year, an increase from the current 40,000 tons per year.

Through this investment, Kobe Steel stated that it will be able to further provide a stable supply of steel powders to customers. At the same time, it will be able to better respond to its customers' diverse needs using equipment that can produce high-performance steel powder products.

www.kobelco.co.jp



Kobe Steel's steel powder products are mainly used in Powder Metallurgy to make automotive components such as engine and transmission parts (Courtesy Kobe Steel, Ltd.)

Kennametal reports eighth consecutive quarter of sales growth

Kennametal Inc., Pittsburgh, Pennsylvania, USA, has reported the results for its fiscal 2019 second quarter ended December 31, 2018. The company reported sales of $587 million, up 3% year-on-year with organic growth of 4%, making this its eighth consecutive quarter of sales growth. Operating income was reported at $79 million, compared to $64 million in the prior year quarter. Adjusted operating income was $81 million, compared to $65 million in the prior year quarter.

Chris Rossi, Kennametal's President and Chief Executive Officer, stated, "In the second quarter of fiscal 2019 we delivered strong earnings per share results, margin improvement year-over-year and the eighth consecutive quarter of sales growth. These results reflect our continued transformation of Kennametal and the ongoing monetisation of our growth and simplification/modernisation initiatives."

Net cash flow provided by operating activities was $62 million compared to $41 million in the prior year period. Free operating cash flow (FOCF) was negative $24 million compared to negative $18 million in the prior year period. The change in FOCF was reportedly driven primarily by greater net capital expenditures due in part to modernisation initiatives, in addition to changes in working capital, partially offset by increased cash flow from operations before changes in certain other assets and liabilities.

Industrial segment

The Industrial segment saw sales of $317 million, an increase of 2% from $312 million year-over-year, reflecting organic sales growth of 3%. Operating income was $58 million, compared to $41 million in the prior year quarter.

Widia segment

The Widia segment saw sales of $49 million, an increase of 3% from $48 million year-over-year. Operating income was $2 million, compared to less than $1 million in the prior year quarter.

Infrastructure segment

The Infrastructure segment saw sales of $221 million, increased 5% from $211 million year-over-year. Operating income was $21 million, or 9.3% margin, compared to $24 million, or 11.3% margin, in the prior year quarter.

www.kennametal.com

Submitting news..

To submit news to *PM Review* please contact Paul Whittaker: paul@inovar-communications.com

Atlas Pressed Metals facility expansion

Atlas Pressed Metals, DuBois, Pennsylvania, USA, has completed a 45,000 ft^2 (approx. 4,000 m^2) expansion to its facility at Beaver Meadow Industrial Park, DuBois. The addition is said to bring the company's total plant size to nearly 100,000 ft^2 (approx. 9,200 m^2).

This is Atlas' third addition to its original Tom Mix Drive plant and features twenty feet of under-beam clearance at its peak. Original office space has been retained and unchanged, but due to recent growth in professional staff and skilled labour at the company, the sales department was relocated to a nearby office building in Spring 2018.

Total employment at Atlas is currently around 115 employees, following a staffing increase of 15% in 2018. Immediate use of the new space is set to provide additional room for shipping, finished goods, work in process and inspection.

Jude Pfingstler, President of Atlas Pressed Metals, stated, "With the building done we have turned our focus internally. Over the next several months we will install some new equipment including the installation of some secondary equipment to support increased demand."

www.atlaspressedmetals.com

Umicore reports record results in 2018

Belgian-based speciality materials group Umicore states that it has achieved record results for the full fiscal year 2018. The company further stated that it has reached its Horizon 2020 targets two years ahead of schedule. For the full year 2018, the company reported revenues of €3.3 billion, a 17% increase on the previous year, and recurring net profit across the group of €326 million, an increase of 22% on the previous year. Capital expenditures for the year amounted to €478 million, compared to €365 million in 2017.

Umicore won significant new business in the latter half of 2018 which, it was said, will accelerate its growth in the coming years. In Automotive Catalysts, Umicore is said to have won the largest share of the gasoline platforms requiring particulate filters in Europe and China, while in Rechargeable Battery Materials, it reportedly continues to secure major xEV platforms with OEMs globally. The company is also continuing its R&D efforts, which is reflected in a 56% increase in the number of patent family filings compared to the previous year.

Marc Grynberg, Umicore CEO, stated, "I am really pleased to see that our strategic choices and recent investments are paying off. We have reached the original Horizon 2020 objectives two years ahead of schedule and are on track to achieve our raised ambitions notwithstanding a less favourable macro-economic environment in 2019."

"Umicore is uniquely positioned to respond to societal trends and regulatory demands for cleaner mobility and recycling," he continued. "We have the technologies and are expanding our capacity to ensure that we continue to grow and meet the rising demand for our products and services. I am also proud that Umicore is a pioneer in providing customers in the rechargeable battery value chain with materials of a certified clean and ethical origin."

In order to meet continued fast-growing customer demand for its cathode materials used in rechargeable batteries for automotive applications, Umicore stated that it is rapidly expanding its production capacity. An investment programme of €460 million in China and Korea was reportedly completed in 2018.

In February 2018, Umicore announced an additional investment programme of €660 million in greenfield production sites in China and Europe. The new production lines in China will start to come on stream in the second half 2019, while construction of the European plant is expected to begin in spring 2019. Investments in the new Process Competence Center in Olen, Belgium, are expected to be commissioned in late 2019.

www.umicore.com

Plansee Powertech opens newly constructed manufacturing facility

Plansee Powertech AG, a leading producer of arcing contact systems for the power transmission and distribution sector, has officially opened a new facility in Seon, Switzerland. With the new building, the company stated that it has created the conditions for flexible, competitive and highly-automated production that also offers higher manufacturing capacity.

An opening ceremony included company employees and guests such as the Chief of Government Dr Urs Hofmann and other representatives of Switzerland's Aargau Department of Economic and Interior Affairs. At the opening, Frank Müller, Managing Director of Plansee Powertech AG, commented, "The way that energy will be supplied in the future will change — there will be fewer major power plants and more decentralised energy producers. As a manufacturer of safety components for the power transmission and distribution sector, we must be ready for the change in energy policy."

Plansee Powertech, a division of Plansee Group, manufactures switching contacts made of tungsten-copper, copper-chrome and tungsten carbide-silver materials, using Powder Metallurgy production methods to enable an extremely fine-grained and homogeneous microstructure that results in longer service life for these components. A tour of the facility given at the opening provided guests with insights into the production of these high-precision components.

Plansee's Powder Metallurgy CuCr contacts are pressed near-net shape, then machined to produce finished switch contacts (Courtesy Plansee)

"This new hall is the culmination of our efforts to make the high-wage location Seon competitive," Müller continued. In the early 2000s, the company reported that it had come under pressure as a result of competition from China and a strong Franc. "Following a wave of consolidations in Europe, we are now the only Western supplier of switching contacts and have quintupled our production volume over the last twenty years," he added.

In the years ahead, the company expects that its production processes will be automated further. A detailed analysis of its manufacturing data is expected to produce ideas for process improvements, and unique identification of each of the approximately 500,000 components produced annually is intended to ensure the traceability of every product.

www.plansee.com

Kurt Jofs appointed Chairman of Höganäs Board

Swedish metal powder producer Höganäs AB has announced the appointment of Kurt Jofs to the position of Chairman of the Höganäs Board on February 6, 2019. Jofs succeeds Staffan Bohman, who has held the position since 2013 when Lindéngruppen and FAM bought and delisted Höganäs from the Swedish stock exchange.

"I look forward to taking over the role of chairman and continuing Staffan Bohman's fine work," stated Jofs. "Höganäs is an interesting company with a long and proud history, and today it has great potential in several different markets."

The company stated that Jofs has been a member of the Höganäs Board of Directors since 2013, bringing with him a long and broad experience from leading positions within Swedish industrial companies such as Ericsson and ABB.

"During the autumn last year, Staffan Bohman announced that he would leave the position as chairman for Höganäs after the board meeting in February. Since April 2018, he is the Chairman of Electrolux and on top of that he holds other board assignments. Staffan Bohman's extensive experience, competence and commitment has been of great value to both Höganäs and the board's work," added Lars Wedenborn from FAM and Erik Urnes from Lindéngruppen. "Now we welcome Kurt Jofs as the chairman and look forward to our continued collaboration."

www.hoganas.com

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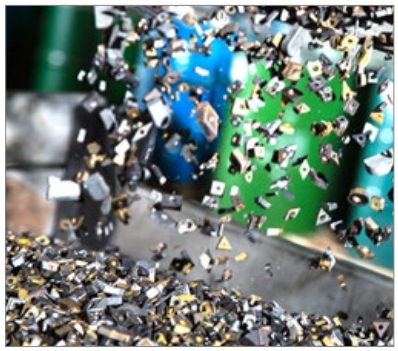
Ceratizit acquires 50% stake in carbide recycler Stadler Metalle

Ceratizit Group, headquartered in Mamer, Luxembourg, has announced the acquisition of a 50% stake in Stadler Metalle GmbH & Co. KG. Based in Türkheim, Germany, Stadler Metalle specialises in trading and processing secondary raw materials, with a strong focus on carbides.

For Ceratizit, the investment in Stadler Metalle is said to be of strategic importance. Thierry Wolter, Member of the Executive Board of Ceratizit, stated, "The investment in Stadler is a unique opportunity for the Ceratizit Group to secure the entire raw materials supply chain. The demand for our main raw materials, tungsten and cobalt, is steadily increasing. Thanks to Stadler's network and expertise in logistics, we will now be able to focus even more strongly on recycling carbide tools in the supply of raw materials."

Stadler offers a wide range of services such as the purchase, analysis, sorting and processing of secondary raw materials. Through the partnership, it is expected that Stadler will gain access to the worldwide network and know-how of the Ceratizit Group and can use this as the basis for developing new business models.

The company will continue its operations as before, but in future will benefit from the full support of Ceratizit. "We are firmly convinced that as part of the Ceratizit Group we can grow faster," commented Gabriele Stadler, Managing Director and Owner of Stadler Metalle.



The processing of tungsten carbide inserts (Courtesy Stadler Metalle)

Ceratizit has over 9,000 employees at thirty-four production sites and operates a sales network of over seventy branch offices. The two private companies have agreed not to disclose the financial details of the transaction, which is still subject to the approval of the anti-trust authorities.

www.ceratizit.com
www.stadler-metalle.de

Global automotive industries see mixed results in 2018

The automotive industries in the main global regions showed significant variations in performance in 2018 with growth coming to a halt in Europe and North America, and China experiencing a slowdown in vehicle production and sales.

Asia

According to the China Association of Automobile Manufacturers, automobile production totalled 27,809 million units (down 4.2% on 2017) with sales of all vehicles falling to 28,081 million units (-2.8%). Passenger car sales in China declined by 3.8% in 2018 to 23.256 million units. The main factor behind the decline was said to be the trade conflict with the USA. However, new energy vehicles (NEVs) continued to achieve rapid growth in China in 2018, with production of 1.27 million units - an increase of 60% year-on-year.

Korea saw a 2.1% decline in light vehicle production in 2018 to 4.02 million units, whilst Japan vehicle production decreased by 0.5% year-on-year to 9.234 million units, of which 4.4 million were for domestic sales and the balance exported. India in contrast saw total sales for vehicles increase by 5% in 2018 with 3.4 million units sold.

Europe

In Europe (EU + EFTA) a total of 15.6 million passenger cars were registered in 2018 which equalled the total registered in the previous year. There were increases in some of the high volume sales countries – France (+3%), Spain (+7%) – with Germany matching its 2017 levels but Italy down 3% and the UK down 7%. European Union car and light vehicle production was almost unchanged compared with 2017 at 18.906 million units.

Russia continues to defy market trends and continued its recovery in 2018 with car sales up 13% to 1.8 million units. Turkey's car market slumped by a further 38% in 2018 to 641,541 units and total vehicle production was down 8.5% to 1.550 million units.

Americas

In North America the US market remained flat, with 17.2 million vehicle sales. Passenger car sales slumped 13% whilst the light truck segment added 8%. Canada recorded its first drop in vehicle sales in nearly a decade with a drop of 1.9% to 2.03 million units. Mexico light vehicles sales dropped by 7% to 1.421 million units in 2018. Total car and light truck production in NAFTA dropped from 17.02 million in 2017 to 16.98 million units last year.

The Brazilian market for light vehicles continues to rebound with light vehicle (including cars) sales rising by 14% to nearly 2.5 million units in 2018. Production of all vehicle types in Brazil reached 2.880 million in 2018 – an increase of 6.7% compared with the same period in 2017.

Changes in the management of SMS group

SMS group GmbH, headquartered in Düsseldorf, Germany, has announced the expansion of its management team. The company stated that Prof Dr Hans Ferkel will become Chief Technology Officer, Michael Rzepczyk will become Chief Operating Officer and Dr Guido Kleinschmidt will leave the Management Board.

Ferkel currently serves as Head of Technology and Innovation at thyssenkrupp Steel Europe AG. Previously, he held senior management R&D positions at Volkswagen. Rzepczyk, who currently serves as Executive Vice President of the Business Unit Metallurgy and is mainly responsible for the execution of major projects, will take on the role of Chief Operating Officer.

In addition to Ferkel and Rzepczyk, the five-member management team consists of Torsten Heising (Finance) and Prof Dr Katja Windt (Digitalisation), headed by long-standing chairman Burkhard Dahmen.

"I am delighted to welcome Prof Dr Ferkel and Mr Rzepczyk to our management team. They are experienced industry experts and will support SMS in further expanding its market leadership in metallurgical plant construction," stated Burkhard Dahmen, CEO. "The Management Board is now perfectly positioned to implement our growth strategy and to remain a key partner for our most sophisticated customers."

www.sms-group.com

EPMA appoints new Technical Manager

The European Powder Metallurgy Association (EPMA) has announced that Bruno Vicenzi has been appointed as the association's new Technical Manager. The move follows the announcement last year that Dr Olivier Coube would step down as EPMA Technical Director in February 2019.

Vicenzi received a Master's Degree in Physics from the University of Genova in 1988, and a Diploma in Material Science and Technology in 1993. He worked from 1990 to 2002 as a researcher in Powder Technology, Materials and Applications at Centro Sviluppo Materiali SpA in Genova. Vicenzi was a founding partner of MIMITALIA Srl (now Clayver Srl), and worked from 2002 to 2019 as Production Manager.

Vicenzi was Co-Chairman of the EuroMIM group from 2003 to 2017, and a member of the EPMA Council from 2005 to 2017. In his new role he will be actively working with the EPMA's sectoral groups, as well as analysing industry statistics, organising research projects and working on the development of new research programmes. He will also be responsible for coordinating the EPMA's training and education activities.

www.epma.com

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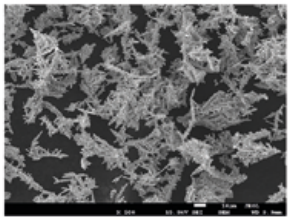
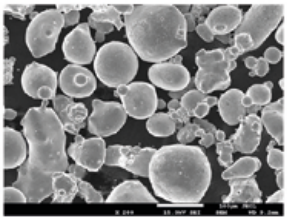
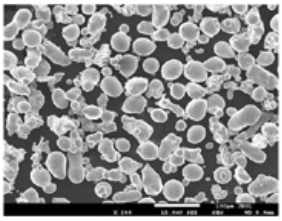
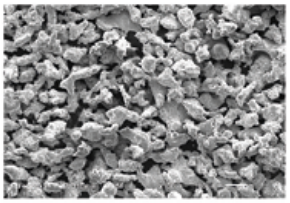
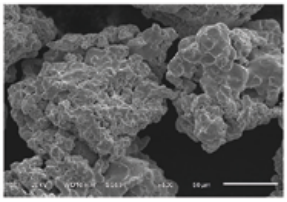
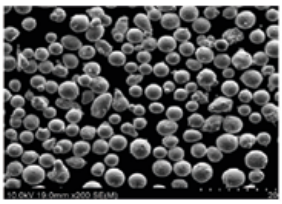

Electrolytic Copper Powder


Atomized Copper Powder


Tin Powder


Copper Alloy Powder


Diffusion Powder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Henrik Ager appointed President of Sandvik Mining & Rock Technology

Sandvik has announced that Henrik Ager, currently President of the Rock Tools division in Sandvik, is to be appointed President of the business area Sandvik Mining and Rock Technology and member of the Sandvik Group Executive Management as of April 1, 2019. Ager succeeds Lars Engström, who will leave Sandvik.

"I'm convinced that Henrik Ager with his experience, already proven leadership skills and excellent performance in Sandvik has the right capabilities to lead Sandvik Mining and Rock Technology going forward," stated Björn Rosengren, Sandvik's President and CEO. "Henrik is committed to further strengthening Sandvik Mining and Rock Technology's market position, reinforcing customer relations, driving aftermarket sales, leveraging further on a decentralised way of working and ensuring our forefront position within automation, electrification and sustainability."

Ager has more than sixteen years' experience in the mining industry, out of which an extended period has been spent living in South Africa. Additionally, he has worked in Australia, South America, India and other important mining markets.

Ager's previous experience at Sandvik includes the role of President of the Global Equipment division and Vice President for Strategy within Sandvik Mining and Rock Technology. He has also held leading positions at McKinsey, Ericsson and several high-tech start-ups prior to joining Sandvik in 2014.

www.sandvik.com

ALD expanding Hanau plant

ALD Vacuum Technologies is to expand its plant site in Hanau, Germany, with a new office building and technical centre. The move into the new buildings has been planned for the end of 2019.

In 2016, ALD moved to the Fraunhofer Science Park in Hanau, where it now employs five-hundred staff. "Currently we have to move closer together and even create interim solutions in order to find a place for all employees. We are therefore very much looking forward to moving into the new buildings this year," stated Markus Holz, ALD's CEO.

The ALD R&D Centre, previously located in one of ALD's assembly halls, will be located in the new technical centre.

www.ald-vt.com

Capstan introduces robots to boost Powder Metallurgy production

Capstan Inc., a producer of structural Powder Metallurgy components and porous metal filters, has introduced Epson 6-Axis C4L robots into its production line in Los Angeles, California, USA. The company expects the new technology to enable it to streamline its manufacturing lines and reduce the high wage costs associated with its location.

The company reported that it had built two press cells with dual C4L robots mounted centrally for dual cavity compaction robotic removal. The dual robot, dual cavity combination was said to have increased manufacturing capacity significantly.

This increase is partly because human operators can have difficulty removing two parts from a machine at one time. The stated increase in production is expected to allow Capstan to enter new markets and bring on higher volume applications.

Custom cells to house the robots and part trays were produced for Capstan by automation specialist Vast-Ex, Murrieta, California, USA. Each work cell also incorporates custom robot grippers, HMI programming, tray sensors, and check lasers, designed to eliminate the risk of operator error.

"Our customers require a hands-off approach to manufacturing which reduces the amount of human error," stated Capstan. "We know that not all programmes require robots and that the upfront investment to introduce this technology might not work for certain applications. We're thankful to be working with new companies that are excited to be growing with us."

This first set of four Epson robots marks a step toward further automation for Capstan, which had previously only used small pneumatic grippers on its production lines. The company expressed its hope that the implementation of its first robots will also lead to future endeavours.

www.capstan.com

Epson 6-Axis C4L robots installed at Capstan's facility in Los Angeles, California (Courtesy Capstan Inc.)

Submitting news..

To submit news to *PM Review* please contact Paul Whittaker: paul@inovar-communications.com

Obituary: Dr Leo Prakash, a renowned authority in the PM industry

Dr Leo Prakash

It is with much sadness that we report the death of Dr Leo Prakash. A renowned authority in the field of cemented carbides and other hard materials, Leo died at age sixty-nine on February 16, 2019, in Rottenburg am Neckar, Germany. A modest man with a contagious smile, he often understated his wealth of knowledge on the subject, which is widely acknowledged within both academic and industrial circles.

His pioneering work in the late 1970s and early 1980s on iron-based binders for hardmetals led to the commercialisation of several alternatives to pure cobalt and laid the foundation for the wave of recent research and development into low cobalt and cobalt-free hardmetals, an important topic considering the status of cobalt as a critical raw materal as well as the current strict classification issues.

Following on, from the mid-late 1980s and into the 1990s, his fundamental studies into the mechanisms of grain growth inhibition and sintering of the very finest grained tungsten carbide hardmetals at the time were also of great significance for the industry, as were his studies of material properties and performance in both laboratory tests and practical applications. He authored or co-authored over forty publications in international journals, conferences and textbooks, and many are still regularly cited today.

Based on his many decades of international industrial experience in R&D, production and general management within the hardmetal industry, even after reaching the stage in his career at which most people enjoy a comfortable retirement, he continued practising his art and supporting academia and industry through his global consultancy activities and participation in many national and international bodies.

For the last ten years, he was co-chairman of EuroHM, the European hard materials group within the European Powder Metallurgy Association (EPMA). In this role, he originated and initiated a series of 'Club Projects', bringing together RTOs and industrial companies from across Europe to perform pre-competitive basic research on a range of topics related to cemented carbides. This collaborative model has now been adopted by other sectoral groups within the EPMA and has proven to be one of its success stories of recent years.

He was central to fostering a true hard materials community within Europe and is an iconic and highly respected figure within the field. One lasting contribution will be the 'Vision2025' EPMA roadmap document for hard materials he co-authored, defining the future strategy and R&D focus of the European hard materials community and how it should address the major challenges of low-cost competition from outside Europe and potential raw material supply chain disruption.

His funeral took place on March 1 in Rottenburg am Neckar. He is survived by his wife Lydia, his four children, Rebecca, Deborah, Sarah and David, and four grandchildren. He will be sorely missed.

Eisenmann showcases new One Solution sintering furnace

Eisenmann SE, Böblingen, Germany, recently showcased its new One Solution high-temperature roller-hearth furnace at a special event at its facility in Bovenden, Germany. A number of guests from the Powder Metallurgy and sintering industries viewed the complete system, which included a return conveyer, in the company's preassembly hall at Bovenden.

The One Solution furnace allows the roller-drive speed to be seamlessly and precisely adjusted to the specific needs of the product, and companies operating this furnace are said to be able to achieve substantially lower energy and industrial gas consumption. It also offers all the advantages of high-temperature sintering with rapid cooling and exact management of the atmosphere, while delivering theoretically ideal sintering conditions of 1,400°C in conjunction with cooling rates of up to 8 K/s.

During the event, Peter Vervoort, Eisenmann's Vice President, Product Development & Technology, spoke about the European Powder Metallurgy Association (EPMA)'s 'Vision 2025', a publication designed to serve as a roadmap for the future of the PM industry. Martin Creutziger, Eisenmann's Head of Test Center, provided visitors with an overview of the potential, security and technological possibilities of 'future-oriented' sintering technology.

Vervoort and Creutziger presented the key components and features of the new furnace and explained some of the ways in which Eisenmann has addressed the market need for highly efficient and flexible production. The One Solution high-temperature roller hearth sintering furnace range was said to offer outstanding advantages in terms of product quality, flexibility and operating costs.

Eisenmann SE employs a workforce of over 3,000 staff worldwide, operating at twenty-seven sites in fifteen countries across Europe, the Americas and the BRIC nations (Brazil, Russia, India and China). In 2017, the company reported annual revenues of €723 million.

www.eisenmann.com

The One Solution high-temperature sintering furnace at Eisenmann's facility in Bovenden, Germany (Courtesy Eisenmann SE)

PyroGenesis to partner with Aubert & Duval on titanium powder supply

Aubert & Duval, Paris, France, a subsidiary of Eramet Group's Alloys division which specialises in high-performance metallurgy, and PyroGenesis, Montreal, Canada, a provider of plasma atomised spherical metallic powders for the Additive Manufacturing and Metal Injection Moulding (MIM) industries, have entered into a partnership agreement for the supply of titanium powders in Europe.

To extend its current portfolio of metal powders for the AM market, Aubert & Duval will partner with PyroGenesis to manufacture and distribute plasma atomised titanium powder, allowing the company to ensure the exclusive distribution of these powders in Europe, its primary market. Under this agreement, the new titanium offering from Aubert & Duval will be marketed under the Pearl® Micro brand.

Eramet Group's Alloys division reported that it expects the partnership to allow Eramet to reach a 15% market share of titanium powders in Europe by 2022. The group presently produces superalloy metal powders, notably for aircraft engines and land turbines in the energy sector, as well as stainless steel powders for various markets including defence and automotive.

Jérôme Fabre, Eramet Group's Deputy CEO in charge of the Alloys division, commented, "With our metallurgical expertise for demanding markets such as aeronautics and energy, this partnership with PyroGenesis allows us to complete our offer of metal powders for Additive Manufacturing, including 3D printing, a growing market of the industry of the future."

www.eramet.com
www.aubertduval.com
www.pyrogenesis.com

ADDITIVE MANUFACTURING

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POWDER ATOMIZATION PLANT FOR ADDITIVE MANUFACTURING

With the launch of the Demo Center for additive manufacturing, SMS group is showcasing its know-how in powder metallurgy and additive manufacturing processes.

The newly developed type of metal powder atomization plant, which includes downstream process stages such as screening, classification and packing, as well as an SLM 3D printer, serves to guarantee the cost-effective production and application of high-purity metal powders made from a range of different metals and alloys.

Today we are already using additive manufacturing to improve and optimize plant components and spare parts.

So you as our customer reap the benefits of our expertise for your powder atomization plants.

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Ford invests $1 billion in its Chicago auto plants

Ford Motor Company is investing $1 billion in its Chicago, Illinois, Assembly and Stamping Plants and adding a reported five-hundred jobs as it prepares to launch three new SUVs, going on sale later this year. The transformation at the plant was set to begin in March and will expand capacity for the production of the new Ford Explorer, including the Explorer ST and Explorer Hybrid, the new Police Interceptor Utility and the new Lincoln Aviator.

The work is expected to be completed by Spring 2019, and includes the addition of an all-new body shop and paint shop at Chicago Assembly, plus major modifications to the final assembly area. At Chicago Stamping, the company will add new stamping lines in preparation for production of the 2020 Ford Explorer, Police Interceptor Utility and Lincoln Aviator. Further, advanced manufacturing technologies will be added including additively manufactured tools and a collaborative robot with a camera for the inspection of electrical connections during the manufacturing process.

Chicago Assembly, located on the city's south side, is Ford's longest continually operating vehicle assembly plan. The factory began producing the Model T in 1924 and was converted to war production during World War II. In 2018, Ford was the No. 1 producer of vehicles in the US and the leading exporter of vehicles from the US, producing nearly 2.4 million vehicles over the course of the year.

Joe Hinrichs, president of Ford's Global Operations, stated, "We are proud to be America's top producer of automobiles. Today, we are furthering our commitment to America with this billion dollar manufacturing investment in Chicago and five-hundred more good-paying jobs. We reinvented the Explorer from the ground up, and this investment will further strengthen Ford's SUV market leadership."

A worker at Ford's Chicago Assembly and Stamping Plants (Courtesy Ford Motor Company)

"Ford's announcement of five-hundred additional jobs and over $1 billion in plant investments is a testament to the quality and hard work of UAW Ford members," added Rory Gamble, Vice President of the UAW Ford Department. "Every day, UAW Ford members head to work, proud of the products they build and the craftsmanship required in vehicles like the Explorer, Aviator and Police Interceptor. Ford's investment announcement demonstrates a commitment to the dedication of UAW members in Chicago."

www.corporate.ford.com

Atlas Pressed Metals receives certification in TMAP Testing

Atlas Pressed Metals, DuBois, Pennsylvania, USA, has announced the successful completion of an industry-sponsored voluntary testing programme, the Test Method Assurance Program. Each year, Atlas Pressed Metals' in-house materials laboratory participates in the programme, which demonstrates proficiency in performing various test methods as outlined in the Metal Powder Industries Federation (MPIF)'s material standard.

The MPIF manages the distribution of the samples and the evaluation of a series of metallurgical lab tests, designed to qualify the proficiency of lab personnel and equipment within the metal powder industry. Atlas participates in the sintered density, apparent hardness, transverse rupture strength, micro-indentation hardness, and total carbon content portion of the programme.

Once completed, the data are returned for statistical analysis to the MPIF. Each company is given a summary report containing the statistical summary with a data table and graphical representation for each test method. The results are benchmarked against other participating companies. For confidentiality purposes, companies are assigned a unique lab code identification number. The data tables contain the specific test method, results for all labs, data mean, grand mean, deviation from grand mean, and comparative performance value (CPV). The graphical analysis compares the individual lab results to the grand mean within a 99.5% confidence limit for the respective test.

"I enjoy the advantages of participating in the TMAP program because we can compare our lab measurement capabilities with other companies in the powder metal industry," stated Christina Mahlon, Materials Engineering Technician at Atlas. "We are proud to meet this achievement each year."

TMAP is designed to compare the laboratory staff's ability to achieve accurate, reliable and consistent results while following the MPIF standard test methods. According to the MPIF, material and testing standards are established to "aid in the conduct of business," and help to clarify and promote the advancement of Powder Metallurgy and associated metal powder industries through well-established material standards and test methods.

www.atlaspressedmetals.com
www.mpif.org

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ZF invests €800 million at transmission plant to meet electrification demand, expands powertrain capacity in India

ZF Friedrichshafen AG, Germany, has announced plans to invest €800 million in its plant at Saarbrücken over the next four years. The plant is the lead location for ZF's transmission technology, and the investment is expected to add production plants, systems and infrastructure and expand its supplier network to make the facility fit for the transition from conventional to electric car drives.

Wolf-Henning Scheider, CEO of ZF Friedrichshafen AG, stated, "The share of hybrid drives in production will increase tenfold over the next few years – from 5 to 50%." The ongoing electrification of the powertrain is both an opportunity and a challenge for the plant, Scheider added. "We see the increasing market penetration of advanced hybrid drives as an opportunity, which in our view is much more than just a bridge technology. With longer ranges between 80 and 100 kilometers, they can complete the majority of all journeys electrically and thus help e-mobility to achieve a breakthrough more quickly."

ZF stated that its order books show hybrid technology to be in great demand. The company is responding to this boom in demand with an investment programme worth more than €3 billion for the further development and sustainability of these products. However, if the development towards pure electromobility progresses as is currently forecast in several studies, ZF predicts that sales for Saarbrücken will decline in the longterm, resulting in a decreasing workforce.

In view of this development, ZF has launched a number of activities in Saarbrücken that are intended to significantly increase the plant's international competitiveness. These include, for example, a series of projects relating to the Internet of Things (IoT). These initiatives will also make use of artificial intelligence to provide quick and valuable decision-making aids for employees and thus increase efficiency.

"The fact that these effects will only occur in a few years' time gives us the opportunity to prepare for them today," explained Stephan von Schuckmann, Head of ZF's Car Powertrain Technology Division. "We want to prepare our employees for the mobility of the future with a wide range of training and qualification opportunities and more agile work structures."

ZF's Saarbrücken plant currently produces 8-speed hybrid transmissions (Courtesy ZF)

ZF expands powertrain production capacity at its Indian facility

ZF Friedrichshafen also announced it has broken ground for the extension of its Indian regional headquarters in Chakan, Pune. With the expansion, the company expects to produce more truck and van drivelines, powertrain and chassis modules from 2020 onward.

The Pune facility was inaugurated in 2015, and its 16,770 m^2 of space is now fully utilised with the commercial vehicle, car powertrain and aftermarket business. The new production complex is expected to be completed by the end of 2019 and offer an additional 4,000 m^2 of space to accommodate further production and warehousing activities.

www.zf.com

Carpenter Technology adds two new directors to its board

Carpenter Technology Corporation, headquartered in Philadelphia, Pennsylvania, USA, has announced the appointment of Viola L Acoff and John Hart to its Board of Directors. Carpenter's board now consists of twelve members, eleven of whom are independent directors.

Dr Acoff is currently the Associate Dean for Undergraduate and Graduate Programs at The University of Alabama's College of Engineering, a position she has held since 2014. For the last fifteen years, she has been a professor in the University's Department of Metallurgical and Materials Engineering, where she also served as Department Head from 2009-2014. Her areas of expertise include Additive Manufacturing, welding metallurgy, physical metallurgy, titanium and nickel alloys, and materials characterisation using electron microscopy.

Dr Hart is an Associate Professor of Mechanical Engineering at the Massachusetts Institute of Technology (MIT). He is also the Director of the MIT Laboratory for Manufacturing and Productivity, and the Center for Additive and Digital Advanced Production Technologies. Prior to joining the MIT faculty in 2013, Hart was Assistant Professor of Mechanical Engineering, Chemical Engineering, and Art and Design at the University of Michigan.

"We welcome both Viola and John to Carpenter Technology's Board of Directors. Their expertise in the materials, engineering, and Additive Manufacturing space further supports Carpenter Technology's strategic objective to be a leading solutions provider across all the markets we serve," stated Gregory A Pratt, Chairman of the Board.

www.cartech.com

2019 Wards 10 Best Engines awards announced

WardsAuto has announced the 2019 recipients of its 10 Best Engines awards. For the first time ever, three pick-up truck engines appear on the list, while four electrified powertrains make the cut for the second consecutive year as well. Completing the line up in this 25th year of the competition is a muscle-car V-8, a German luxury turbocharged inline 6-cyl. and a groundbreaking turbocharged 4-cyl. with variable compression ratio.

WardsAuto editors chose the winners after spending October and November evaluating thirty-four engines and electric propulsion systems. "I never thought I'd live to see the day when a fuel cell car and a battery EV would make the list the same year as two burly V-8s and a sophisticated 4-cyl. engine with variable compression," stated Drew Winter, *WardsAuto* editor.

Cutaway of Chevrolet Silverado 6.2L small-block V-8 (Courtesy WardsAuto)

Other notable trends for the year included Ford winning two trophies for the second year in a row and Hyundai winning two awards in the same year for the first time ever. A hydrogen-powered fuel cell vehicle also made the cut for the third time, and two V-8s earned trophies in the same year for the first time since 2015.

"Automakers and their powertrain engineers are being pushed in different directions: Governments around the world want low emissions and electrification, while customers want vehicles that meet their every need without compromise. We believe this year's list represents the industry's ability to deftly satisfy both demands," added Winter.

This year's winners:

- 3.0L (B58) DOHC Turbocharged I-6 (BMW X5)
- 6.2L OHV V-8 with DFM (Chevrolet Silverado)
- 5.0L DOHC V-8 (Ford Mustang GT/Bullitt)
- 3.0L DOHC TurboDiesel V-6 (Ford F-150)
- 2.0L DOHC Atkinson i-VTEC 4-Cyl./HEV (Honda Accord Hybrid)
- 120-kW Fuel Cell/Electric Propulsion System (Hyundai Nexo)
- 150-kW Propulsion System (Hyundai Kona EV)
- 2.0L DOHC VC-Turbo 4-Cyl. (Infiniti QX50)
- 2.0L DOHC Atkinson 4-Cyl./HEV (Lexus UX 250h)
- 3.6L DOHC Pentastar eTorque V-6 (Ram 1500)

A change of name

Following the news of the winning engines, it was also announced that *WardsAuto* is to rename its Wards 10 Best Engines competition to Wards 10 Best Engines & Propulsion Systems, to reflect the increasing diversity in automotive powertrains. Today, electrified powertrains account for about 40% of the annual awards.

"We've been thinking about a name change for many years because we need to better reflect the growing variety of engines and propulsion systems in the automotive market," stated Tom Murphy, Managing Editor at *WardsAuto*.

"We've been recognising electrified powertrains since the Toyota Prius made our list in 2001. We look forward to a future filled with engines and propulsion systems that thrill us with outstanding performance and groundbreaking technology," he added.

www.wardsauto.com

Furnace and heat treat specialist Ipsen appoints Geoffrey Somary as group CEO

Ipsen International Holding GmbH, Kleve, Germany, has announced the appointment of Geoffrey Somary as CEO of Ipsen Group worldwide. Somary succeeds Thorsten Krüger, who served as CEO from 2013-2019 and who has now moved to the company's Advisory Board.

Since 2005, Somary has held various senior positions within Ipsen and was said to have been closely involved with customers and with team members of the company. He has reportedly demonstrated the ability to bring together employees of different cultures in a way that delivers the best possible solutions to Ipsen customers.

The Advisory Board expressed its thanks to Krüger for his contributions to the company since his appointment in 2013. It was stated that, in shifting his role from operational to advisory, he will continue to support the further development of the company.

Ipsen designs and manufactures industrial vacuum and atmosphere heat-treating systems, supervisory control systems and predictive maintenance platforms for a wide variety of industries, including aerospace, automotive, commercial heat treating, energy and medical. The group has production locations in Europe, North America and Asia, along with representation in thirty-four countries.

www.ipsenUSA.com

Mahle expands powertrain expertise with acquisition of transmission specialist ZG

Mahle Group, Stuttgart, Germany, one of the world's largest automotive suppliers, has announced its acquisition of transmission specialist ZG-Zahnräder und Getriebe GmbH, Eching, Germany. Through this acquisition, the group stated that it hopes to expand its powertrain expertise to include the transmission, a decision driven by the trend in electric vehicles toward integrated drive systems.

The expansion of its powertrain expertise is expected to allow Mahle to tap into additional development competence in this field, putting it in a position to offer its customers integrated systems solutions for the powertrain from a single source, including transmission design. Dr Jörg Stratmann, Chairman of the Management Board and CEO of Mahle, stated, "The acquisition is another important step in the expansion of Mahle's product portfolio and on its path to become a systems provider for all powertrain technologies."

Integrated drive systems are said to offer some advantages over individual modules, such as the drive motor, transmission, or power electronics. Their components are reported to be better coordinated, their construction can be more compact, and they can also be used more flexibly in different vehicle types. ZG-Zahnräder und Getriebe, which was founded in 2008 as a spin-off from the Technical University of Munich, offers particular expertise in state-of-the-art gearing technology, with its approximately forty employees supporting auto manufacturers and suppliers throughout the development process.

The Mahle Group's product portfolio addresses crucial issues relating to powertrain and air conditioning technology, both for drives with combustion engines and for e-mobility, and the company states that its products are fitted in at least every second vehicle worldwide. In 2017, the group generated sales of approximately €12.8 billion and employed roughly 78,000 in more than thirty countries across 170 production locations, as well as sixteen major research and development centres.

www.mahle.com
www.zg-gmbh.de

Fiat Chrysler Automobiles hosts its first PM Industry Day

Over 800 employees attended from Fiat Chrysler Automobiles (Courtesy MPIF)

The Metal Powder Industries Federation (MPIF) has reported that a Powder Metallurgy Industry Day took place at Fiat Chrysler Automobiles (FCA)'s North American headquarters in Auburn Hills, Michigan, USA, on February 14, 2019. PM parts makers and powder producing member companies of the MPIF were invited to the event, coordinated by FCA and the MPIF, to showcase PM technology to FCA's in-house design and engineering teams.

In total, some thirty-five PM parts and powder producers, representing such technologies as conventional PM, Metal Injection Moulding (MIM), and metal Additive Manufacturing (AM), exhibited their products and showcased their capabilities. Thousands of parts were available to the 800+ FCA employees who attended, representing various departments such as powertrain, chassis, body, electronics, controls, engineering systems, sensors, computer-aided engineering, materials, chemistry, safety, quality, MOPAR, and more.

The event was said to be well received and an educational experience for the FCA employees who attended. Event attendees were excited to learn more about the PM industry, and some stated that they were previously unaware of the value and innovation available from PM technologies. Attendees were able to ask questions of PM experts and had a chance to see and touch parts that they had not seen before.

www.mpif.org

Bodycote holds official opening for new UK facility

Heat treatment and thermal processing services provider Bodycote has officially opened its new facility at the Advanced Manufacturing Park (AMP) in Rotherham, Yorkshire, UK. At an official opening event, the facility was ceremonially opened by Andy Greasley, Executive Vice President of Rolls-Royce's Turbines Supply Chain Unit, in recognition of the partnership between Bodycote and Rolls-Royce.

The new advanced heat treatment centre, now fully operational and serving customer requirements, offers a range of heat treatment services and has been established to support the aerospace and power generation markets in the UK and Europe. Greasley commented, "Heat treatment and processing is a vital part of our supply chain and Rolls-Royce are delighted to be supported by Bodycote on the Advanced Manufacturing Park in Rotherham. Close coupling of this capability to our own Rolls-Royce business is critical for our future success and our relationship with Bodycote is one that we truly value."

Bodycote held an official opening for its new facility in Rotherham, Yorkshire, UK (Courtesy Bodycote)

Also speaking at the event, Colin Sirett, CEO of the UK's Advanced Manufacturing Research Centre, located at the AMP, stated, "We've got everything from aircraft parts through to carbon fibre chassis for supercars all being manufactured on this site, the one piece of the process that was missing was materials processing. We can cast, we can forge, we can assemble, we can machine, but the one key element that was missing is exactly what Bodycote brings to the park. So it's great to welcome the Bodycote team here and we are looking forward to working with them for many years to come."

Tom Gibbons, President of Bodycote's Aerospace, Defence & Energy division, told visitors at the opening, "Due to customer demand and interest since the announcement of this new plant in July, we are investing in further capacity and technology. The additional space we secured here at Rotherham is nearly three times the size of our existing unit. We are committed to ensuring we are able to meet our customers' demand in the years ahead."

www.bodycote.com

POWDERMET2019 and AMPM2019: Full conference programmes now available

The MPIF has released the full conference programmes for POWDERMET2019: the North American Conference on Powder Metallurgy and Particulate Materials, and AMPM2019: Additive Manufacturing with Powder Metallurgy, set to run concurrently at the Sheraton Grand in Phoenix, Arizona, USA, from June 23–26, 2019.

POWDERMET2019 will feature more than two-hundred technical presentations from global industry experts presenting on PM, particulate materials, and metal Additive Manufacturing. In addition, 100+ exhibitors will showcase their technologies and services in the co-located POWDERMET exhibition, and a number of industry networking events such as the 'PM Evening Alehouse' will offer visitors and exhibitors the chance to make contacts within a diverse range of PM fields.

"POWDERMET conferences provide attendees with the opportunity to learn best practices, new solutions, and the latest R&D," stated Blaine Stebick, MPIF Technical Board Chairman. "Powder Metallurgy continues to be an innovative technology that inspires the next generation of engineers, especially with the rising influence and interest in metal Additive Manufacturing."

AMPM2019's conference programme will focus on the latest innovations while attempting to filter commercial content. Attendees to AMPM will also have full access to all POWDERMET events including the conference programme, exhibition and networking sessions.

The full technical programmes and further details on POWDERMET and AMPM are available via the conference websites. Registration is available at early-bird discounted rates until May 10, 2019.

www.powdermet2019.org
www.ampm2019.org

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Major global auto producers to present at Dritev 2019

A number of OEM presentations by key global automotive producers have been announced for the Dritev – Drivetrain for Vehicles congress, organised by VDI Wissenforum, which will run in Bonn, Germany, from July 10–11, 2019. The congress addresses current developments and challenges in the vehicle drivetrain industry, from electrification to Noise Vibration Harshness (NVH).

The congress schedule comprises a programme of lectures, presentations and parallel events, and is expected to host more than 1,500 developers, around 100 international exhibitors and 80 specialist speakers, making it what is believed to be one of the largest networking platforms for automotive powertrain and transmission development.

Included in the programme will be presentations from Toyota, Audi, Volvo, Volkswagen, Ford, Daimler and Porsche. At the accompanying VDI specialist conference 'Powertrain Solutions for Commercial Vehicles', numerous powertrain development experts from Germany and abroad will discuss drive and transmission concepts, market development and possible operating strategies. In addition, the EDrive conference will also run parallel to Dritev, providing an in-depth look at the systems and development of electrified powertrains.

www.vdi-wissensforum.de

New ceramitec conference on industrial use of ceramics

Messe München has announced the launch of the ceramitec conference, a new event in the ceramitec series to be held at Messe München, Munich, Germany, September 19–20, 2019. The focus of the event will be on the industrial use of ceramic materials, and it will also include sessions covering Powder Metallurgy and Additive Manufacturing.

Ceramitec is an international ceramics trade fair held every three years in Munich, with the most recent exhibition taking place in April 2018 attended by 15,000 visitors. By creating the ceramitec conference, the organisers aim to shorten the time between the trade fairs.

Today, the ceramic industry is highly innovative due to new manufacturing processes and changed raw material qualities. According to the organisers, shorter innovation cycles make ceramics increasingly attractive for a great number of industrial uses in the automotive and chemical industries, electrical engineering, the health sector, biotechnology, aerospace, mechanical engineering, the pharmaceutical industry, and in the world of design.

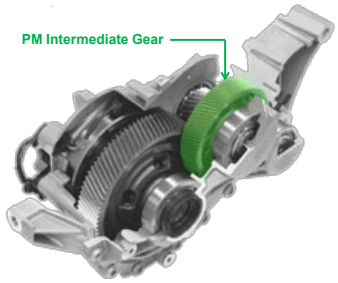
www.ceramitec.com/conference

EPMA launches Functional Materials Sectoral Group

The European Powder Metallurgy Association (EPMA) has established a new Functional Materials Sectoral Group (EuroFM) with the objective of increasing awareness of the sector, promoting discussion and improving understanding amongst end users, designers, mechanical engineers, metallurgists and students. Formed following the EPMA's 2018 Functional Materials Seminar in Jülich, Germany, the EuroFM sectoral group is open to members of the trade association who have an interest in this category of materials.

Functional materials can be defined in a number of different ways, but EuroFM's definition denotes materials which make use of a distinct physical property that they bring to a component, such as magnetism, caloric effects, or electronic conductivity, for varying functions. Whatever functionality they provide, these materials are key components with regard to targeted applications.

The EPMA stated that with a growing understanding of powder-based processes comes an increased desire to implement functionality into components, making functional materials an important aspect of current and future applications and developments. "The creation of the Functional Materials Sectoral Group is a positive step for the EPMA, as these types of components and the applications they are used in could show us what to expect from components of the future," explained Dr Lionel Aboussouan, the EPMA's Executive Director and group facilitator.



PM could offer solutions in electric-drive gear boxes (Courtesy GKN Powder Metallurgy)

"When we think of future components made by using the PM process, functional, maybe even adaptive materials, where the component has the ability to change a property, such as internal structure, will help to keep PM at the cutting edge of industrial applications," he added.

A second Functional Materials Seminar will take place April 3-4, 2019, in Bremen, Germany.

www.epma.com

TAT Technologies announces May dates for its popular sintering courses

TAT Technologies has announced May 2019 dates for its sintering courses, held at the company's training centre in St. Mary's, Pennsylvania, USA. The courses are aimed at employees in the PM industry who want to learn more about the necessary fundamentals of the sintering process.

The hands-on training encourages interaction between lecturers and students and, with class sizes typically between 6-10 students, there is the opportunity to tailor experiments to student needs.

Course 1:
Preparation for Better Sintering
May 14-27, 2019
Covering all aspects of preparation of parts and the furnace before sintering, this course will give attendees a clear understanding of what is needed to ensure parts will be properly and thoroughly delubed, oxide reduced and graphite diffused before proceeding to the sintering section of the furnace.

Course 2:
Sintering-Ferrous PM
May 20-23, 2019
Building off the knowledge and skills gained in Preparation, this second course will teach students how to guide their well-prepared part through the furnace and achieve a quality sintered result with the least property variation and at higher production rates. Course one is a prerequisite for this course.

www.tat-tech.com

Poudres2019 symposium heads to Grenoble

Poudres2019, organised by Société Française de Métallurgie et de Matériaux (SF2M) and Groupe français de la céramique (GFC), will be held in Grenoble, France, May 22-24, 2019. The symposium programme will highlight themes that are of common interest to the two organising communities: the development and characterisation of powder, its functionalisation, its role in the shaping, sintering and melting processes, microstructural characterisation, powders and final materials, and the numerical simulation of processes.

Both oral and poster presentations will be supported with an exhibition of relevant scientific and technical interest.

www.sf2m.fr

Zeiss to build new Industrial Quality and Research customer centre in Detroit

Zeiss, Oberkochen, Germany, has begun construction of a new facility for its Industrial Quality and Research (IQR) segment, represented in the USA by Carl Zeiss Industrial Metrology, LLC. Situated near Detroit, Michigan, USA, the new facility will consolidate the company's four existing Michigan facilities into one location and provide room for business growth.

With almost 170 employees, the centre will span over 82,800 ft² (7,700 m²) over two floors and is expected to open in 2020. It will contain a customer demonstration area with new technologies and systems, offer training, support and metrology services, and house fixture system production and assembly.

It is expected to provide a broad portfolio of dimensional metrology and inspection equipment and services to a wide variety of industries, including: automotive, medical, aerospace, defence, machine tools and more. Measuring specialists will be able to perform proof-of-capability demonstrations for multidimensional measurement equipment, surface form and geometry equipment, and non-destructive testing and surface defect detection equipment.

It will also serve as a centre for aftermarket sales support. Here, customers will receive training on how to use Zeiss software and systems and software help desk services will operate out of the facility.

Dr Jochen Peter, Member of the Executive Board of the Zeiss Group and Head of the Industrial Quality and Research segment, commented, "We are investing over $45 million in the Detroit metro region to strengthen and increase our engagement in this global automotive and smart factory hot spot."

"This will not only have a strong, positive impact for our customers and partners in North America, but will also generate new momentum for the whole Industrial Quality and Research segment of Zeiss worldwide," he concluded.

"With the new Zeiss Center in Michigan, we aim to assure a higher level of satisfaction with our solutions for our customers and provide a more attractive working environment for our team," added Michael Kirchner, Zeiss Industrial Quality Solutions and head of its business in North America.

www.zeiss.com

APMI International names 2019 Fellow Award recipients

Joseph T Strauss (Courtesy MPIF)

John L Johnson (Courtesy MPIF)

APMI International has named Joseph Tunick Strauss and John L Johnson as the recipients of its Fellow Award 2019. Established in 1998, the award recognises APMI members for significant contributions to the goals, purpose and mission of the organisation, as well as for a high level of expertise in the technology, practice or business of the industry.

Joseph Tunick Strauss

Joseph Tunick Strauss, Engineer, President, HJE Company, Inc, has worked to advance the PM industry through engineering and ingenuity for over 30 years. He was the first to commercially offer turn-key small-scale high-performance gas atomisers and publish on the use of elevated temperature gas for atomisation.

Strauss formally introduced PM to the jewellery industry, and continues to develop press & sinter and Metal Injection Moulding technologies for this market. He has been influential in uniting the PM and Additive Manufacturing communities, and assisted in the formation of the MPIF's AMPM conference.

Strauss has served on the APMI Board of Directors and has been on the MPIF Conference Committee for a number of years. He has received many awards including the MPIF Distinguished Service award in 2013.

John L Johnson

John L Johnson, VP Technology, Elmet Technologies, has dedicated over 20 years to research and development of processes and products for the PM industry. Prior to joining Elmet, Johnson was Director of Powder Sales for Kennametal Firth Sterling. Before moving to sales, he held various R&D positions at ATI Firth Sterling, Kennametal, Alcoa Howmet, AMTellect (a US subsidiary of Singapore Technologies) and Penn State University.

Johnson has authored or co-authored more than one hundred technical papers and, as an editorial committee member, reviewed over two hundred technical articles for various technical journals. Johnson has served on many committees and association boards including the APMI Board of Directors and the MPIF Technical Board.

He has been a co-chairman of the Tungsten, Refractory and Hard Materials Conference and continues to organise numerous Special Interest Programs for the annual POWDERMET conferences. While completing his PhD at The Pennsylvania State University, Johnson was a recipient of the 1993 CPMT/Axel Madsen Conference Grant.

www.apmiinternational.org

MPIF's 2019 Distinguished Service to Powder Metallurgy Awards announced

The Metal Powder Industries Federation (MPIF) Awards Committee has announced the recipients of the 2019 MPIF Distinguished Service to Powder Metallurgy Award, which recognises individuals who have actively served the North American PM industry for at least twenty-five years and whose peers believe they deserve special recognition.

The awards ceremony will take place during POWDERMET2019 and AMPM2019 on June 25, 2019, at the Industry Luncheon in Phoenix, Arizona, USA.

The 2019 award recipients are as follows:

- Denis Christopherson, PMT, Federal-Mogul Powertrain
- Zhigang (Zak) Fang, FAPMI, University of Utah
- Robert M Gasior, Arconic Technical Center
- Ryuichiro Goto, Engineered Sintered Components
- William A Heath, PMT, MPP
- Stephen J Lanzel, Catalus Corporation
- Deepak Madan, Luxfer Magtech
- David Milligan, North American Höganäs
- Thomas Pfingstler, Atlas Pressed Metals
- Daniel P Reardon, Abbott Furnace Company
- Christopher T Schade, Hoeganaes Corporation
- Michael Stucky, Norwood Injection Technologies
- C James Trombino, MPIF (retired)

www.mpif.org

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(6) Metal or ceramic injection mould (MIM、CIM);
(7) Precision plastic or die casting mould;
(8) Cold forging mould;
(9) CNC powder molding press;
(10) Rotary type powder molding press;
(11) Upright type powder molding press;
(12) DR、square machining machine;
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(17) Auto parts and other precision parts processing.

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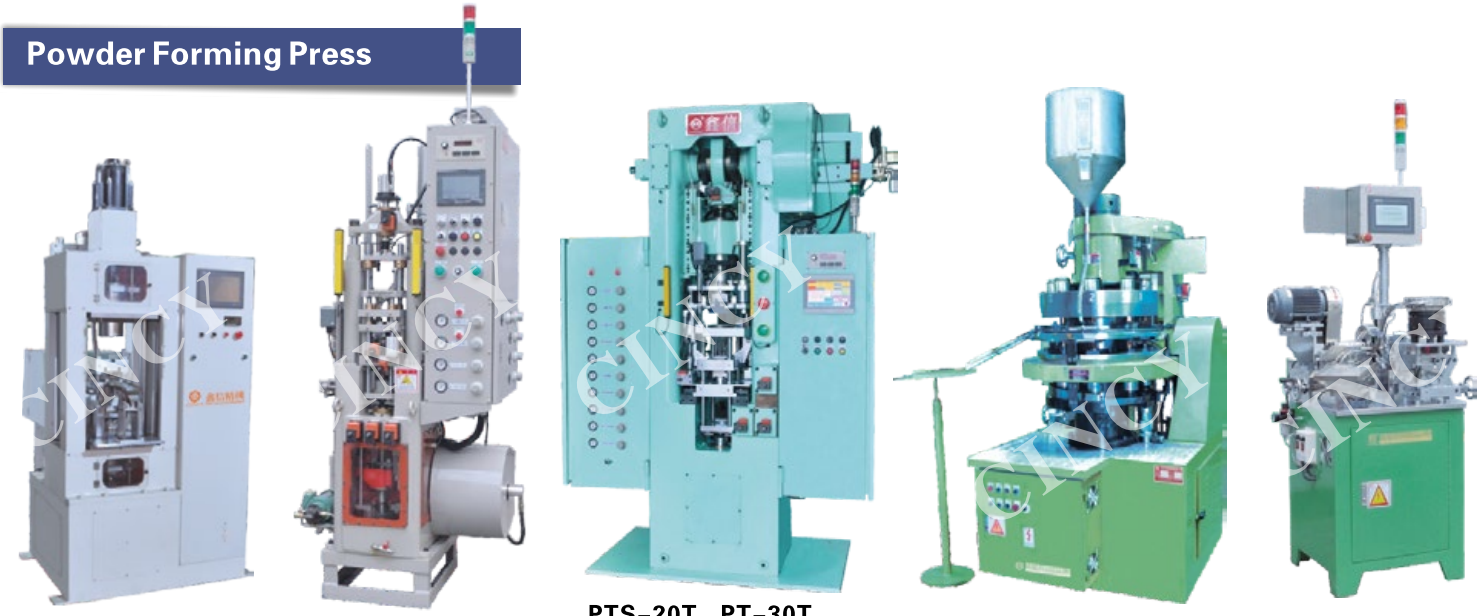

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Mobile: +86-13549366908 Mr Wilson
E-mail: cincy@cincy.com.cn
Website: http://www.cincy.com.cn

DeburringEXPO trade fair to highlight precision surface finishing

DeburringEXPO, the only trade fair to deal exclusively with the removal of burrs and the production of precision surface finishes, will be held at the Karlsruhe Exhibition Centre, Karlsruhe, Germany, from October 8-10, 2019. The event is expected to provide a complete overview of current and new solutions and development trends.

In addition to the trade fair, a supplementary programme of 'Theme Parks' covering the special issues 'AM Parts Finishing', 'Cleaning After Deburring' and 'Sheet Metal Deburring Process Sequence', as well as a bilingual expert forum, will offer specialised knowledge to attendees.

"As of mid-January 2019, more than 100 exhibitors from ten countries had already made firm bookings for the exhibition. The solutions offered by the exhibiting companies are designed to efficiently and reproducibly fulfil current and future requirements for deburring, rounding and precision surface finishing in a great variety of industry sectors," reported Hartmut Herdin, Managing Director of fairXperts GmbH & Co KG, promoters of DeburringEXPO.

www.deburring-expo.com

AIMS appoints Dr Bernie Rickinson its Director of Business Development

Advanced Interactive Materials Science Limited (AIMS), Peterborough, Cambridgeshire, UK, has appointed Dr Bernie Rickinson its Director of Business Development. Rickinson formerly served as Chief Executive of The Institute of Materials Minerals and Mining (IOM3), and is a materials technologist with an extensive global network and significant experience in Powder Metallurgy and Hot Isostatic Pressing (HIP).

Rod Tompsett, Chairman and Chief Executive of AIMS' parent company, Alycidon Capital Group, commented on the appointment, "Bernie has a unique combination of skills and knowledge to assist with our innovation and market development for the business, so we are very happy he has agreed to join us."

"I am delighted to be joining AIMS, an established leader in high-integrity Powder Metallurgy surfacing for improved product performance," stated Rickinson. "I'm looking forward to applying my expertise to the business and supporting AIMS in developing its innovative processing technology and materials for demanding environments, and to improve manufacturing productivity."

www.aimsltd.com

ASTM to host workshop on metal powder characterisation

The ASTM International committee on metal powders and metal powder products (B09) is holding a workshop on powder characterisation in Fernandina Beach, Florida, USA, on April 16, 2019. Taking place at the Hampton Inn & Suites Amelia Island Historic Harbor Front, the workshop will run in conjunction with the standards development meetings of the ASTM committee.

Workshop organiser and ASTM International member W. Brian James noted that new powder characterisation tests have been developed but not yet standardised for use specifically with metal powders.

In anticipation of the meeting, workshop presenters were supplied two sets of metal powders (titanium alloy and ferrous-based) with a particle size suitable for Powder Bed Fusion processing. Each set contained virgin powder plus powders that had been through the process multiple times. Participants were asked to characterise the powders using either a Freeman rheometer or a rotating drum tester. Then, they recorded results for three test repetitions on a fresh test portion of powder from each process condition.

The results of these tests will be presented at the workshop and will form the basis for deciding whether the committee should develop standard guides or test methods for these new metal powder characterisation techniques.

www.astm.org

MPIF Digital Library contains thousands of PM manuscripts

The Metal Powder Industries Federation (MPIF) has announced the launch of the MPIF Digital Library, an online database reported to contain thousands of technical manuscripts from MPIF technical conferences. Manuscripts dating as far back as 1946, can be bought and downloaded individually, rather than requiring the purchase of the entire proceedings.

The MPIF Digital Library includes a fully searchable listing of abstracts, with the option to search by title, author, keyword, publication type, category, keyword, or year. Discounted rates are available for MPIF and APMI members.

www.mpiflibrary.org

AAM Co-founder to be inducted into Automotive Hall of Fame

Richard E 'Dick' Dauch, Co-founder of American Axle & Manufacturing, Inc. (AAM), is to be inducted into the Automotive Hall of Fame. Dauch is being honoured for his manufacturing expertise, strategic vision, bold leadership and business success.

"After retiring from Chrysler Corporation as Executive Vice President of Worldwide Manufacturing, Dauch formed a small investment team to create AAM," a statement from the Automotive Hall of Fame reads. "Under his bold and steady leadership, AAM has become a multi-billion-dollar global company that is one of the largest and most respected Tier One automotive suppliers in the world."

The Automotive Hall of Fame is now in its eightieth year, and recognises individuals across the world who have significantly impacted the automotive industry and the world of mobility. In 1986, Dauch was named Industry Leader of the Year 1985 by the Automotive Hall of Fame for his manufacturing leadership at Chrysler Corp and Volkswagen of American.

Also set to be inducted into the Hall of Fame will be Janet Gutherie, the first woman to qualify for the Indianapolis 500; Sergio Marchionne, former CEO of Fiat Chrysler Automobiles; and Patrick Ryan, creator of the first auto dealership finance and insurance department.

www.automotivehalloffame.org
www.aam.com

Dick Dauch, Co-founder of AAM (Courtesy Automotive Hall of Fame)

Ametek SMP appoints Marucci and expands team

Ametek Specialty Metal Products (SMP), a division of Ametek, Inc., has appointed Michael Marucci as its Vice President Sales and Marketing for Powders. The division, which includes Reading Alloys, Hamilton Precision Metals, Superior Tube, Fine Tubes, SMP Eighty Four and SMP Wallingford, manufactures high purity alloy powders and master alloys, as well as precision metal tubes, strip and foil at six manufacturing facilities in the USA and UK, with sales offices across the globe.

Marucci will be responsible for sales and marketing activities related to titanium master alloys, titanium powders and water and gas atomised powders. Prior to joining Ametek, he was Vice President, Commercial and Strategy, at GKN Hoeganaes.

In the US, Ametek also announced the appointment of Regional Sales Managers Ryan Cicciu and Andrew Blankemeier. Cicciu will identify and develop new customers and product applications for the division's tube, strip and powder products, covering the New England region. Blankemeier will cover the North Central region with a focus on the division's powder, tube and strip products for medical and industrial applications.

Marucci has been appointed Ametek SMP's new VP Sales and Marketing for Powders (Photo via LinkedIn)

The company also announced Pierpaolo Pigliacelli as its new Regional Sales Manager, Western Europe. Responsible for sales and business development in France, Italy, Switzerland, Spain and Portugal, Pigliacelli represents the SMP Division across the board.

In China, Michael Zhu has been appointed as Regional Sales Manager for SMP. Working from the AMETEK Shanghai office, Zhu will be responsible for sales and business development across the SMP portfolio throughout China.

www.ametekmetals.com

Comprehensive view of lightweighting technologies to feature at Hannover Messe 2019

This year's Hannover Messe, taking place in Hannover, Germany, from April 1–5, 2019, will include a comprehensive look at what lightweighting has to offer industrial manufacturing and other disciplines, and what makes it a key technology for the future. The show will feature a high-level conference, applications of lightweight solutions and explore strategies to raise awareness of this important multidisciplinary technology.

Lightweight construction reduces product weight, saves on materials and reduces production costs, as well as having the potential to make products and components better by enhancing durability, improving efficiency and paving the way to better design. What's more, lightweight design makes for more efficient use of resources and materials and reduces energy consumption and thus emissions.

"Lightweight construction will be a very important topic at Hannover Messe 2019," commented Olaf Daebler, Deutsche Messe's Global Director Industrial Supply for Hannover Messe. "Users from all industries will find experts who will show them how they can use lightweight construction to enhance their products."

www.hannovermesse.de

Industry 4.0 and the Powder Metallurgy industry: Challenges and opportunities ahead

Computers and the internet affect all sectors of our lives and have led to profound changes in industrial production. Through growing digitalisation and the integration of ever more advanced artificial intelligence, the ability for systems to respond to external circumstances without human intervention is just one aspect of what has come to be known as the fourth industrial revolution, or 'Industry 4.0'. Just how and to what degree this could affect the Powder Metallurgy industry has been the subject of several recent presentations at technical conferences. In this article, Dr Georg Schlieper offers a look at the challenges that Industry 4.0 brings to the PM industry, and highlights the opportunities that could lie ahead.

The fusion of advanced technologies and rapid adoption of digital systems has the potential to transform the way industry works. From automated process controls to self learning robots, digitalisation is changing how machines operate and how businesses are managed. Keywords such as the Internet of Things (IoT), Smart Factory, Big Data, Virtual Reality and Artificial Intelligence are often used in the context of the fourth Industrial Revolution, or Industry 4.0 (Fig. 1).

An important feature of digitalisation is the generation of data in large quantities. Computers are no longer firmly tied to a specific location, but mobile and wirelessly networked worldwide. In his keynote speech at Euro PM2018, Bilbao, Spain, organised by the EPMA, Borja Arenaza Latorre, of Spanish consulting firm Sisteplant, addressed 'Big Data in Industry 4.0', explaining how this data could be managed in a smart factory.

Latorre highlighted some of the innovations that can be expected in the near future, with specific reference to the real opportunities they can offer when applied to Powder Metallurgy. A growing number of tasks in industrial manufacturing are now being taken over by computers due to their ability to work twenty-four hours a day, more reliably than humans, and while demanding no salary. Manufacturing robots,

The four industrial revolutions

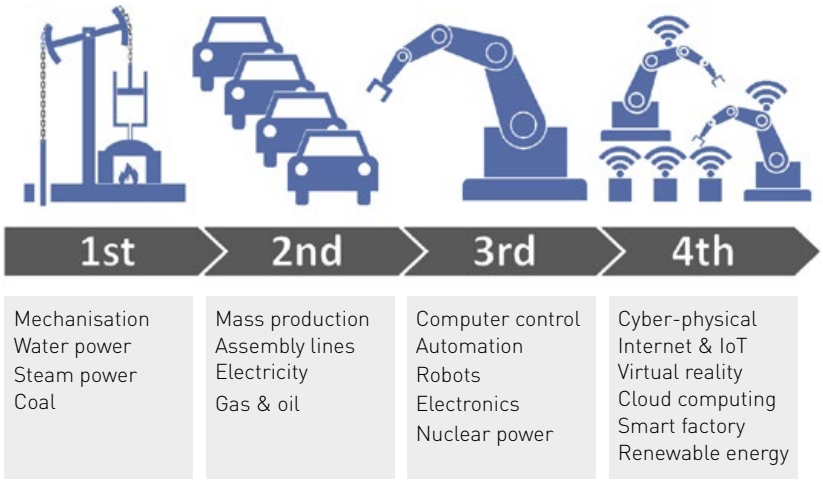

Fig. 1 Defining technologies of the industrial revolutions

Fig. 2 Integrating Industry 4.0 in advanced manufacturing is more than digital (Courtesy Sisteplant)

production processes, the acquisition and documentation of production parameters are just a few of the tasks that computers are now taking over. Computers offer the potential for substantial productivity increases.

According to Latorre, core technologies in this process are sensors, communication, connectivity, data storage, human-machine interfaces and more. A computer simulation that is close to reality provides a realistic insight into the respective technical process. It can be used to optimise procedures and monitor processes in real time, immediately identify deviations and take corrective action. In product development, many iterative steps are taken over by the computer; the time and cost required are thus reduced, manufacturers can react more flexibly to customer requests, and it is possible to efficiently produce small quantities of products.

Integrating Industry 4.0 into a smart factory is far more than just a digital process; it affects all areas of an enterprise (Fig. 2). Digitalisation enables a deeper understanding of core processes that can be used to optimise them and make them more reliable. The agility and flexibility to react on changes in the marketplace can be improved. Enhanced internal logistics can make the supply chain more efficient and cost-effective. Employees have the chance to develop new skills and improve their labour situation. A fundamental shift is said to be taking place, away from the control of end products to a comprehensive understanding and mastery of manufacturing processes (Fig. 3).

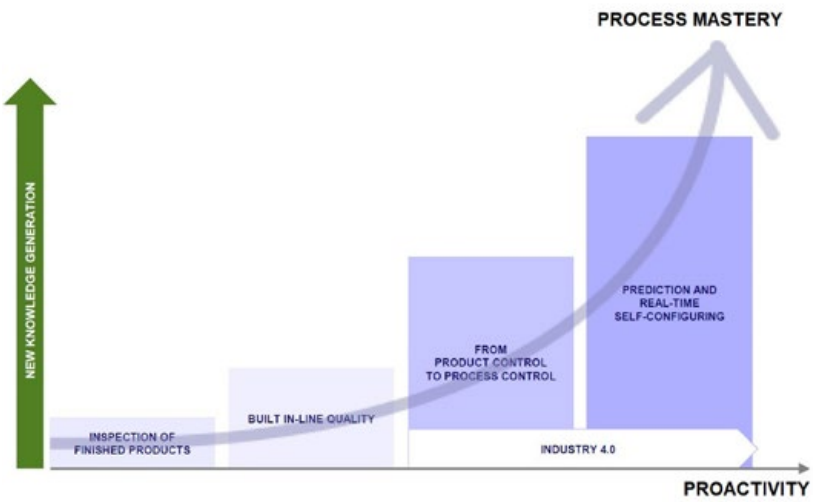

Fig. 3 From product control to process control (Courtesy Sisteplant)

Establishing an Internet of Production

At the Hagen Symposium 2018, Hagen, Germany, organised by the Fachverband Pulvermetallurgie, Günther Schuh, Director of the Laboratory for Machine Tools and Production Engineering WZL at RWTH Aachen University, discussed his work to create an 'Internet of Production' (IoP) designed to test the transfer of significant aspects of Industry 4.0 to a manufacturing company based on the university campus. The overall objective of an IoP is to provide an infrastructure that supports decisions at all stages of the product lifecycle. It is intended to enable data-based, interdiscipli-

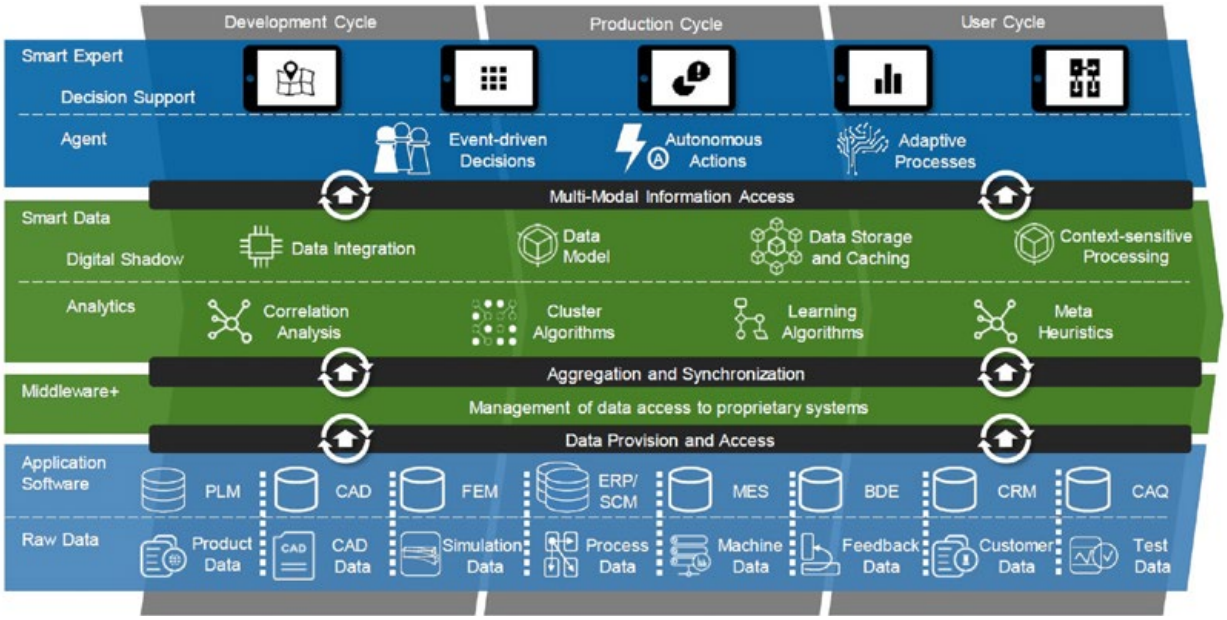

Fig. 4 Infrastructure of Internet of Production (Courtesy WZL)

nary collaboration in manufacturing companies in order to solve overarching technical problems.

Schuh divided the IoP into three main categories horizontally along a product's lifecycle, highlighting the Development Cycle, Production Cycle and User Cycle (Fig. 4). Within these three sections, proprietary data systems such as Product Lifecycle Management (PLM), Computer Aided Design (CAD), Finite Element Method (FEM), Enterprise Resource Planning (ERP), Manufacturing Execution System (MES), Customer Relationship Management (CRM), and more are applied. These software tools can often only be used by experts who have the necessary understanding within their domain. For an overall analysis of the data, an intermediate layer is therefore required that filters and links the data. Without an automated solution, such a process is time consuming. In IoP, this process step is managed by Middleware+ software. The data linked in this way are processed according to need and relevance by analytical algorithms.

A digital shadow

The Smart Data layer creates a digital shadow that represents a real-time image of all production-related processes. The availability of relevant data in real time minimises the time spent by employees searching for needed information. In addition, both historical and real-time analyses can be performed, hidden optimisation potential can be identified, and hypotheses based on experience verified. This leads to a more comprehensive understanding of the system and enables predictions and, consequently, proactive measures to be taken.

Even after data processing, there is still a high complexity of smart data and, to handle these, digital support systems are needed. Their task is to assist the user in decision-making processes by reducing the complexity to the essentials, without eliminating it altogether. This requires the design of intuitive user interfaces which could, for example, be similar in design and operation to those used on smartphone apps. In addition, it would be conceivable to run automated agents in the background without user interfaces. These have the function to save decisions made by the user and to learn from them. As a result, better options can be offered to solve future problems. On the other hand, recurrent problem situations can be identified and decisions made automatically. Digital support systems aim to empower people, despite their high complexity, to make smart, intelligent decisions.

The data exchange

The infrastructure of IoP, and in particular the Middleware+ software contained therein, enable a data exchange between various systems. While Middleware+ filters and connects information from individual software solutions, the resulting smart data can be accessed by apps that support decisions in an intuitive, user-friendly manner. It is therefore possible to use product data via mobile terminals on the shop floor, and to enter found errors directly into the PLM system. All product changes and their processing status can be tracked transparently with such a web-based system.

App-based interface

A respective app has already been developed at WZL and is being used successfully for the assembly of the e.GO Kart in the demonstration factory in Aachen. Real-time transparency becomes more important the higher the complexity of production. As previously mentioned, smart

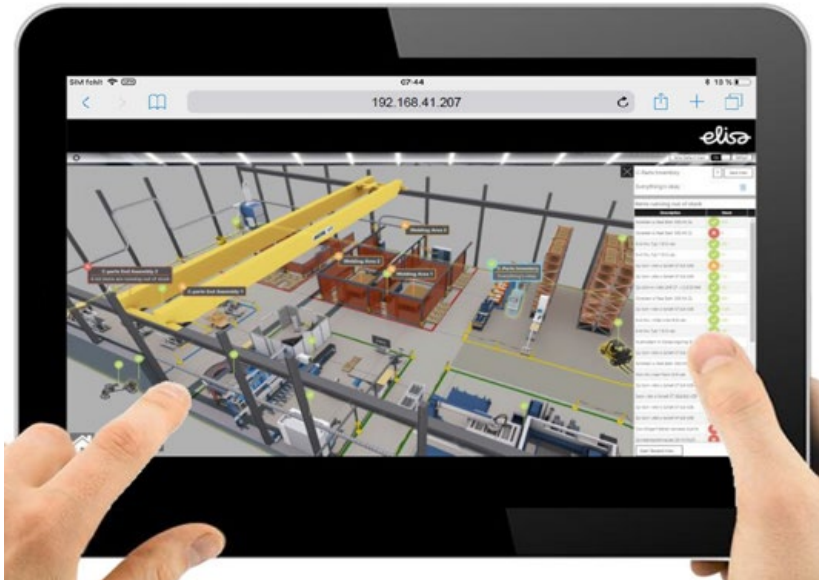

Fig. 5 Visual representation of a digital shadow (Courtesy WZL)

data can be used to create a digital shadow that represents a real-time image of all production processes to provide this kind of transparency. On this basis, significantly higher agility and productivity can be achieved in the company. Fig. 5 shows an example of the visual representation of a prototypically implemented digital shadow of the e.GO Mobile AG. This not only shows current order information (quantity, delivery date, etc.), but also the status of all production machines, such as their temperature, energy consumption, and more. In addition, location data and the status of logistics resources such as forklift trucks, picking trolleys and Automated Guided Vehicles (AGV) can be retrieved. The data of an intelligent small parts storage system are also displayed in the digital shadow. The linking of the different data systems is taken over by the Middleware+ software, which harmonises the different data structures, semantics and granularities. The visualised digital shadow is web-based and presented in a user-friendly manner on mobile devices.

Possible examples of future applications based on this are apps that, in the event of a disruption in the production process, offer suggestions for changing the order sequence to be processed, or that show the impact on the adherence to deadlines of other open orders and possible options for action in the event of a delayed production order. However, the full benefit of a digital shadow goes far beyond providing information about the production cycle. It is the prerequisite for a holistic understanding of the system for all relevant business processes. Only then can hidden potentials for optimisation be identified, complex processes automated and proactive measures introduced.

The changing relationship with the customer

Customer relations are also being challenged in Industry 4.0, according to Schuh, with the actual behaviour of customers expected to change over time. For this reason, it is crucial to continuously compare the expected and actual usage behaviour of customers in order to ensure sustainable customer orientation, and thus a sustainable competitive advantage. IoP is said to provide the necessary infrastructure for this because it understands the customer and the product as components of the infrastructure. Using modern sensors and communication technologies, customer usage patterns can be recorded and transmitted to a raw data system.

The smart data generated in this way can be directly translated into product specifications, by means of a horizontal feedback to the development cycle, and compared with the existing ones. On this basis, the product design can be adapted to meet the new specifications. Continuous repetition of this process will ensure ongoing product adaptation to actual customer requirements.

Creating a new product

In a further presentation at the Hagen Symposium 2018, Christian Dennert of PMG Füssen, a powder metal parts producer in Germany, outlined the steps required to produce a new Powder Metallurgy component in an Industry 4.0 environment. The process is structured in three phases, that of the enquiry phase, procurement phase and manufacturing phase, each with its own set of requirements and input from different departments across the company (Fig. 6).

Enquiry phase

The first phase begins with the customer request, an exchange of relevant data in order to submit an offer that is tailored to the customer's needs. The very intensive exchange of information at this stage, he stated, carries a high risk of losing the chronological flow of information, therefore the use of CRM software is advised.
For a smooth internal process, it is important that the product-specific data that are relevant for the feasibility analysis are available, such as manufacturing processes, including post processing and quality parameters, customer specifications and the current customer design.
Here, the interfaces between the systems ERP - PLM - CAQ - CAD are of crucial importance. The feasibility analysis thus forms the central element of the bidding phase.
In order to improve its quality, a standardisation of the manufacturing processes, including the qualitative requirements, is a necessity that should not be underestimated.

Procurement phase
The second phase is characterised by an active exchange of information between customer and supplier regarding the quotation submitted and, in the event of a change in the request conditions, the timely updating of the offer. This generally requires a short reaction time, which is only possible if the feasibility analysis and the cost framework derived from it have a high degree of accuracy. Of essential importance here are the interfaces between the CRM - PLM - ERP systems.

Manufacturing phase
When the order has been placed by the customer, the manufacturing / development phase follows. It begins with the phase of simultaneous engineering by customer and manufacturer, the production of the first tool-dropping samples, and the final product release process, at the end of which follows the approval of component and process by the customer. In order to ensure a smooth procedure, an intensive coordination between the individual internal and external parties involved, such as suppliers, quality departments and production, is necessary.

An ongoing data exchange, in particular between ERP and PLM systems, is absolutely required, said Dennert. Without an exchange of the necessary documents, such as component drawings, working instructions, etc., as well as relevant production parameters, a timely introduction of the product is very difficult.

The complexity of the data from external and internal sources that are required to perform the feasibility analysis gives an idea of the challenges that can be expected in the course of vertical integration. In addition to the product-specific standardised processing sequences and the associated high-quality data for the calculation of the cost structure, the parameters required for the definition of the manufacturing process, such as press force or material specification, are indispensable. The basis for this is the customer's drawing, followed by an electronically editable 3D model and the supplementary customer standards and specifications.

When an integrated system engineering across the entire value chain has been realised, it will lead to a proactive integration of the customer. At the end of this development, the automatic offer in real time could be imagined. The customer designs his individual product on the basis of the information provided to him, submits the requirement profile to the supplier and receives an offer tailored to his needs. If we continue this mental game, it is possible for the customer to virtually accompany the production of the component and to co-ordinate the optimal project sequence in cooperation with the supplier.

In addition to the challenges already mentioned, such as product-specific, standardised process flow and real-time data exchange across the entire vertical/horizontal value chain, the legal, organisational and IT security requirements must be taken into account.

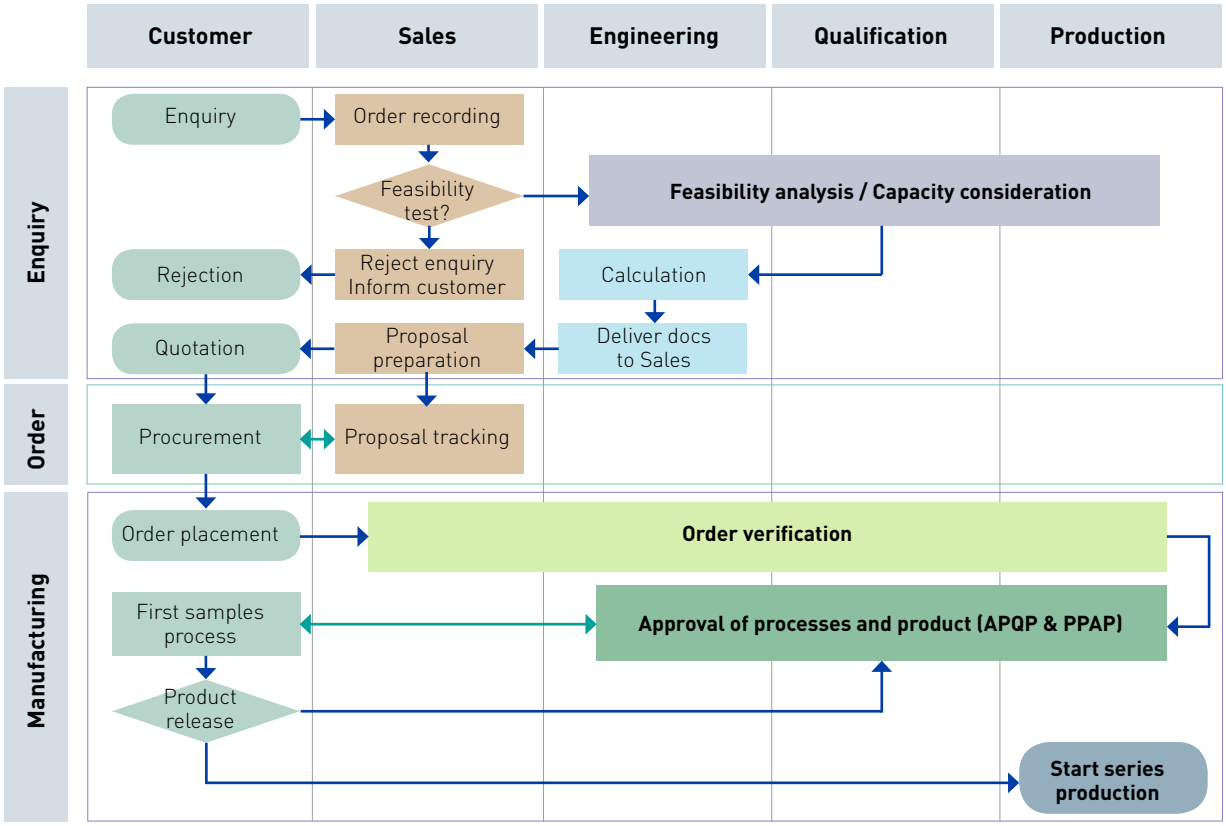

Fig. 6 The steps required in the production of a PM component in an Industry 4.0 environment (based on Dennert)

Business intelligence systems and processes

GKN Powder Metallurgy has already implemented a wide variety of data acquisition and processing systems across the global group, as presented by Gerd Kotthoff and his co-author Paul Mairl at the 2018 Hagen Symposium. A cornerstone for the effective use of such systems is the application of Business Intelligence (BI) systems and processes. In a competitive marketplace, BI has been on GKN's agenda for more than fifteen years and is said to make a significant contribution to efficient work and economic success. BI tools, according to Kotthoff, have also proven to be a useful factor in the development and implementation of a data-driven culture of decision-making. Ideally, the chosen system can seamlessly manage the data of all business processes, from purchasing through production to sales and financial management.

Development of iDash

GKN developed a proprietary BI solution called iDash. This application marks a significant milestone on GKN's route to digital processes and Industry 4.0 manufacturing. Unlike many commercial reporting and visualisation systems, iDash has been geared to process-oriented rather than functional reporting. Great emphasis was placed on the consistent visualisation of daily reports at both global and local levels.

GKN's iDash provides information in a standardised and transparent manner to all levels of the organisation. It supports the execution of global business processes such as budget planning, monthly reports, investment planning and approval, tax audit and much more. iDash can also be transferred to other companies due to its flexible and modular structure with complementary modules that can be adapted to existing customer databases and requirements. Based on the most important business processes, data is automatically loaded from different sources, thus avoiding manual data entry. The tool provides and visualises reliable controlling and management information for GKN employees and management, updated automatically, every day, anytime, anywhere. Since all data is stored in the same database, setting filters and creating new feature-based reports is greatly simplified.

A catalyst for the development of a digital culture

The iDash tool has been, and still is, a key factor for GKN Powder Metallurgy and a catalyst for the development of a digital culture. The system and its modules are used for daily operational tasks and make them much more transparent. The confidence in the quality of the data has grown steadily and these contribute to more qualified decisions.

The integrated presentation mode is a feature that allows users to directly apply the digital dashboards for their reports. It is not necessary to enter data into presentation slides because the data is automatically loaded and transferred to a standard visualisation template. Creating a presentation requires no further data manipulation or visualisation. Since all data is stored in the same database, users can also access all historical presentations with a simple filter selection. Online meetings are also carried out from the system. Again, the data is loaded automatically from the source.

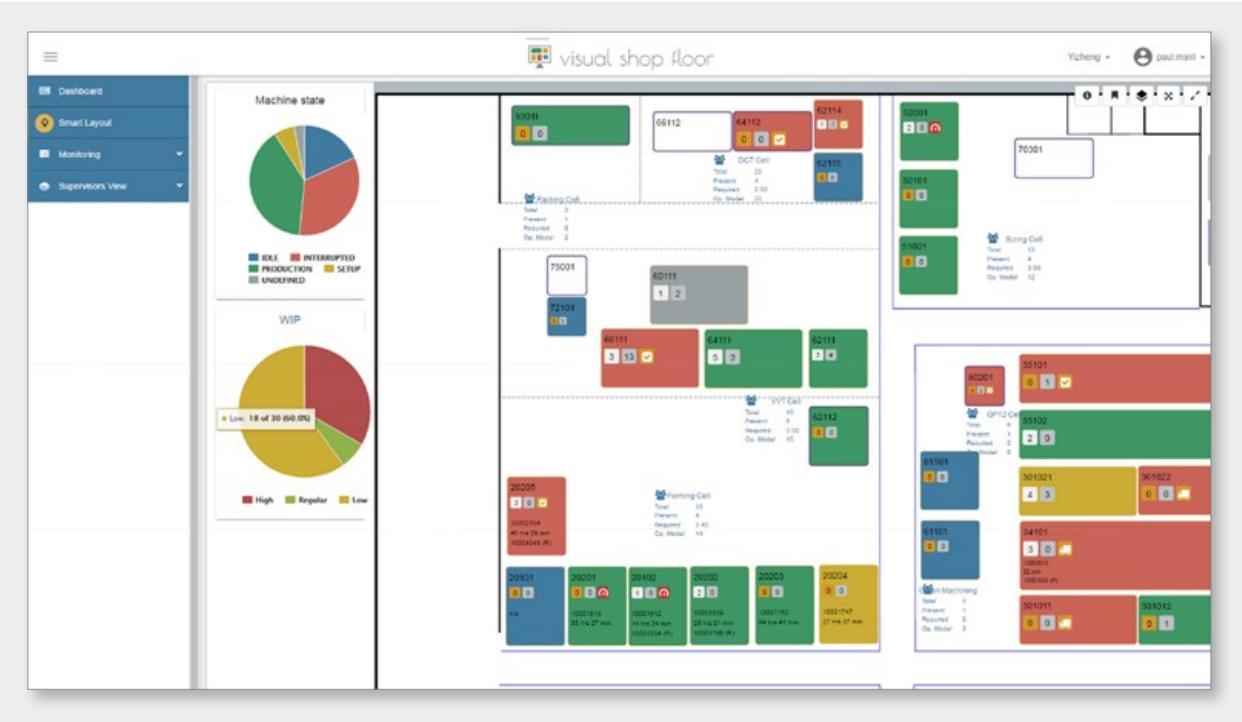

Fig. 7 Remote monitoring of the production area with Visual Shop Floor (Courtesy GKN Powder Metallurgy)

Fig. 8 Daily Startup Meetings at GKN are based on iDSM (Courtesy GKN Powder Metallurgy)

Visual Shop Floor

Visual Shop Floor is one of the applications in iDash (Fig. 7). It is used for remote monitoring of all sites and production areas in the company and enables detailed online analysis down to the individual machine in the GKN production network.

With the availability and automatic delivery of information, regular meetings are no longer dependent on individuals. Every employee can always access the latest information when needed. Yammer, an in-house chat and communication platform, has been integrated directly into the system for the direct documentation of comments, tasks and best practices. As a result, employees now evidently spend more time analysing the data and sharing data-based discussions of improvement plans rather than discussing the origin and reliability of the data.

The module iDSM (stands for (digital) Daily Start-up Meeting) is a good example (Fig. 8). This application is used daily in all locations and production areas of GKN Powder Metallurgy. With the help of iDSM, digitalisation has been recognised as a supportive feature and it is even favoured as a means for data-driven decision-making at all levels of the organisation.

GKN Powder Metallurgy's roadmap to Industry 4.0

A high level of digitalisation of machine and process data is the basis and the starting point of the Industry 4.0 strategy at GKN Powder Metallurgy. Operational and strategic processes have to be mapped digitally and used globally. This results in transparent processes that can be reproduced consistently and reliably with high data quality. Decisions along strategic organisational guidelines, based on reliable and constantly updated data, can be made and also be automated. Data is often worthless

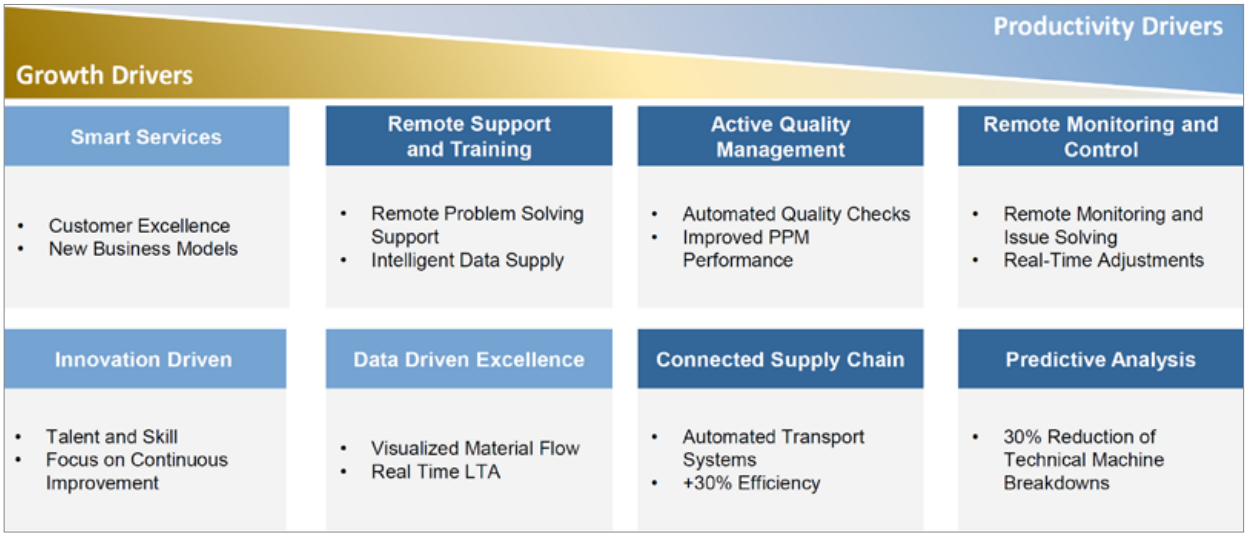

Fig. 9 Issues to be tackled on the road to Industry 4.0 (Courtesy GKN Powder Metallurgy)

if it is not edited and prepared for decision-making; it must be related to the task and, ideally, displayed in a visualised form.

The GKN strategy pursues two types of projects, increasing operational excellence (productivity drivers) and accelerating time to market (growth drivers). The complexity of tasks on the road to Industry 4.0 makes it necessary to tackle many issues at the same time (Fig. 9). The challenge lies in setting priorities and in defining the added value that should result from each project. When deciding which projects to prioritize, considerations such as availability of data, maturity of the technology, and the number of potential users should be considered.

Considering the technologies and action fields in relation to the processes in the company has led to the vision of two focal points, "operational excellence" and "time to market". The digital business model in conjunction with the two target visions are the cornerstones of GKN's digital roadmap (Fig. 10). The implementation of this roadmap requires a balanced approach between medium to long-term goals and short-term business objectives.

Implementing a digital culture

A successful implementation of Industry 4.0 requires a living digital culture in the company, said Kotthoff. Employees must be open-minded to embrace, accept, and integrate data into their decision-making processes. This includes the openness to digital communication platforms as well as the introduction of digital, cloud-based collaboration tools. Every decision is based on data, is transparent and traceable. The consequence of implementing a digital culture is crucial to the success or failure of digitalisation. Very often data is accepted when it supports the user's opinion, but ignored if not. These impediments must be overcome with the help of a digital culture.

There are many ways of dealing with new technologies and working with start-ups is one area that can be tapped in different ways. One way is to participate in an innovation incubator. For example, GKN Powder Metallurgy has logged into an incubator programme in Silicon Valley named RocketSpace in order to deal with new, agile organisational forms, working models and IoT technologies. There, groups of employees have got to know and internalised the methods, procedures and thus the start-up mentality in different projects and in close cooperation with start-ups. With this knowledge and spirit, they have become ambassadors for an accelerated journey into the digital world, even in a traditional manufacturing company in the automotive environment that is accustomed to pursue long-term product programmes and detailed development processes.

Employees and management at GKN have recognised cooperatively how the great digital ideas are created today and with how much energy they are driven forward by the founders of start-ups. No challenge seems impossible, and the dreaming of great things is encouraged at every step. The important thing is to change the world instead of thinking about why an idea might fail. The focus is on things functioning despite all the obstacles. At the same time, start-ups need to deliver quickly to prove themselves and survive in a highly competitive environment. GKN's ambassadors bring this idea back to their respective operations and functions worldwide, thereby shaping a new era of entrepreneurial action, willingness to take risks and to accept the failure of an idea and learn from it.

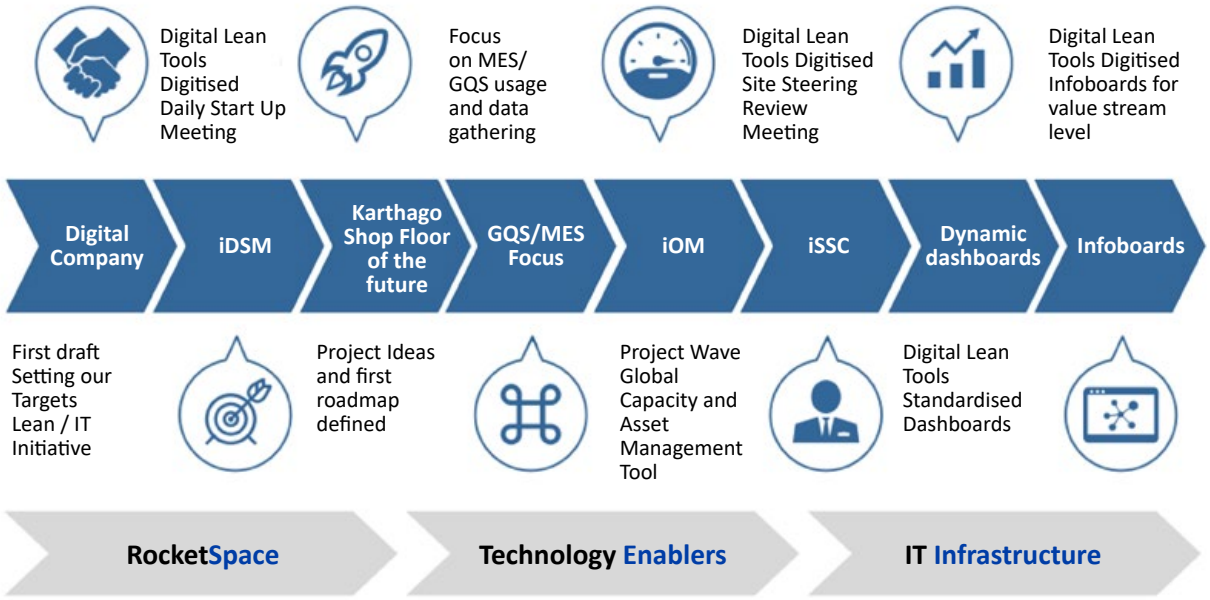

Fig. 10 GKN's digital roadmap to Industry 4.0 (Courtesy GKN Powder Metallurgy)

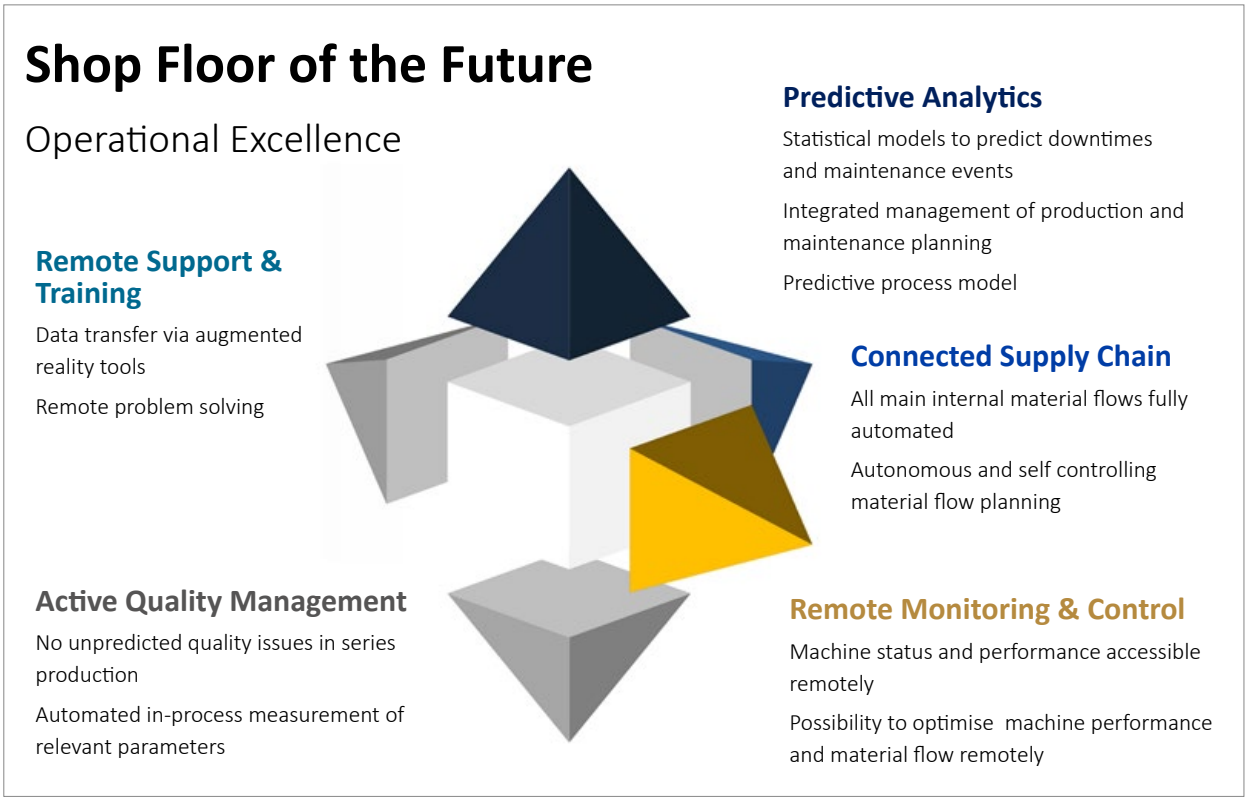

Fig. 11 The envisioned shop floor of the future (Courtesy GKN Powder Metallurgy)

The vision of GKN at the end of the process of digitalizing the processes in the company is the "shop floor of the future" (Fig. 11). The PM production will then be fully networked. An active communication will be realised between machinery, equipment, products and workforce and all data will be recorded. Machine learning and artificial intelligence contribute to improving resource efficiency, safety and risk management and competitiveness. Highly skilled workers act as needed and are agile problem solvers.

Summary

Although Powder Metallurgy is already a lean technology in terms of material usage and environmental impact, the PM industry can still benefit from improved monitoring and better utilisation of the many process steps that lead to the finished part.

The challenge, of course, is not just in the collation of data or the physical infrastructure required to transmit and hold data. The challenge is in how data is interpreted, the building of software systems that can react and intelligently interact with physical process steps, and the communication of relevant data along the entire supply chain.

In an ever more connected world, working closer with customers and suppliers, streamlining processes and improving performance will clearly have mutual benefits for all.

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New opportunities for master alloys: Ultra-high pressure water atomised powders

Research began on the development of master alloys (MAs) for PM steels some fifty years ago. Over the years, a number of master alloys have shown promise, but the wide adoption of these was prevented due to the need for high sintering temperatures and the excessive tool wear caused by the very hard and angular MA powder particles. In this article, Dr Raquel de Oro Calderon of the Institute of Chemical Technologies and Analytics at TU Wien, Austria, reports on work that makes use of ultra-high pressure water atomised master alloy powders and could significantly increase the hardenability of commercial steel powders at a very low alloying cost.

Opening new markets for Powder Metallurgy steels in the automotive sector is often only possible if three requirements are met: 1) Price: cost-effectiveness compared to competing technologies, 2) Properties: a competitive level of material performance and 3) Precision: achievement of close dimensional tolerances and consistent quality with large production volumes. Finding more efficient alloying alternatives that offer cost-reduction and a higher level of performance is surely a very attractive route, but care must be taken that all the requirements of precision, price and properties are met. It is often for this reason that a change in the alloying system and/or the alloying route is not readily accepted by the industry, and in fact Fe-Cu-C PM steels are still by far the biggest players nowadays. However, with the noticeable impact of electrification on the global automotive industry, PM parts producers are facing lots of new challenges, and one of the keys to success will be their ability to develop innovative and unique PM tailored solutions. Here, new alloying approaches might provide interesting possibilities.

PM steels are typically produced by mixing a plain (or pre-alloyed) iron base powder with graphite. Further alloying elements are introduced by admixing or bonding elemental alloying particles (typically Cu, Ni and Mo) While the use of pre-alloyed powders provides homogeneous microstructures, the admixed approaches (i.e., powder mixes, diffusion bonded, hybrids and master alloys, Fig. 1) give the possibility to obtain microstructures with defined heterogeneity that can

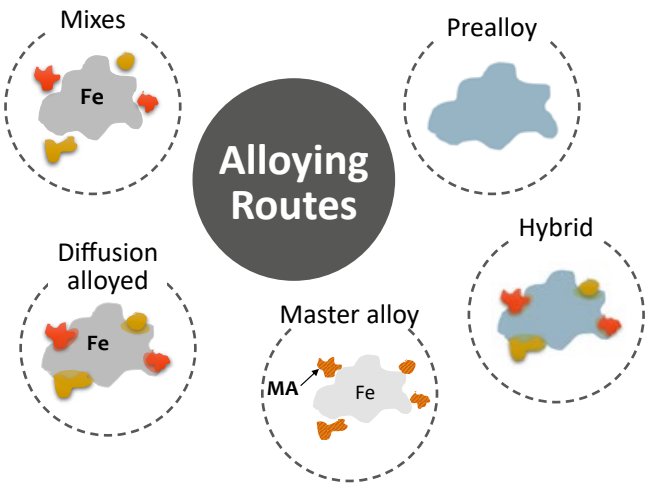

Fig. 1 Possible alloying routes for producing sintered steel parts

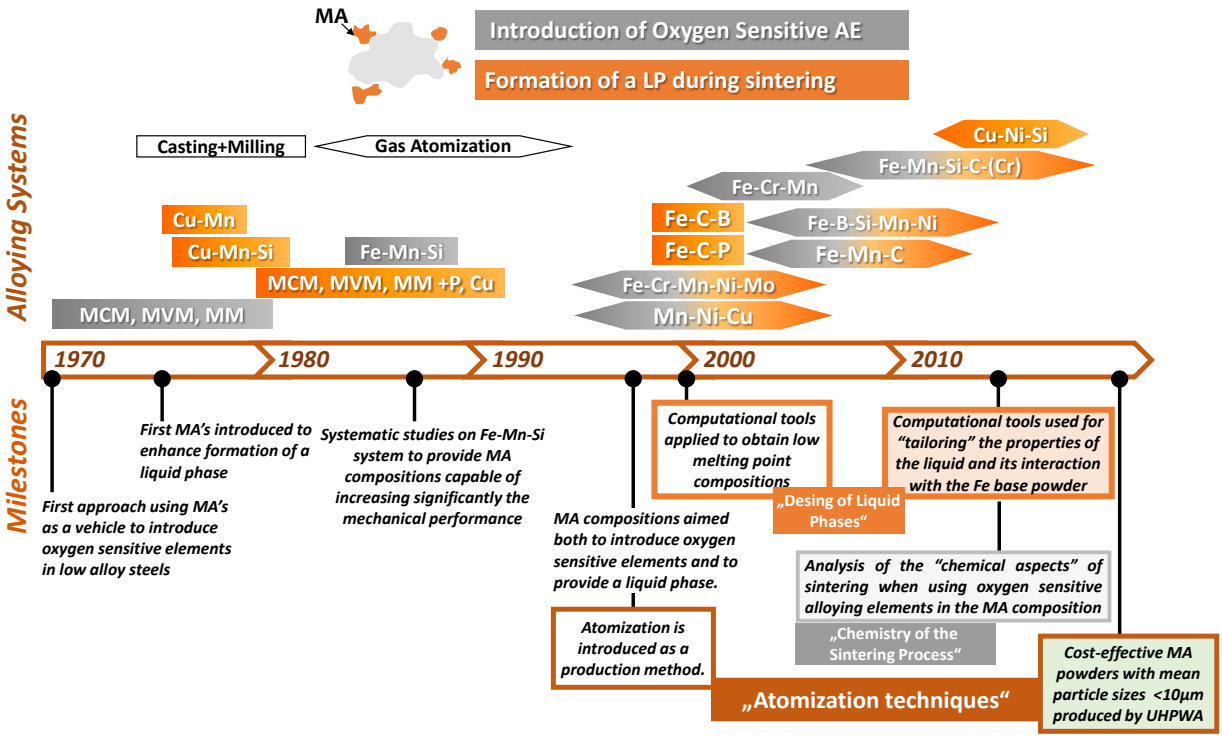

Fig. 2 Outstanding developments in the field of MA. Grey colour is related to the compositions exclusively developed for introducing oxidation sensitive elements, and orange to compositions aimed to form a liquid phase

offer combinations of mechanical properties not attainable by any other method (due to the special combinations of hard and ductile phases). This is a unique feature of PM steels that is not yet being fully exploited.

In this regard, the use of master alloys offers a singular opportunity, as their compositions can be specifically tailored to form a transient liquid phase with defined characteristics. For instance, master alloys forming liquids with low infiltration capacity (non-infiltrating liquids) give rise to heterogeneous microstructures comparable to those obtained with diffusion bonded powders, with the peculiarity of presenting – in a single powder particle – a tailored combination of different alloying elements. On the other hand, homogeneous microstructures can be obtained when using infiltrating liquids (Cu-like). Such infiltrating liquids can be used to homogeneously distribute alloying elements that otherwise would require unrealistic sintering times/temperatures. As an example, a Cu-based master alloy can be used to take advantage of the ability of Cu to penetrate inter-particle contacts and grain boundaries. Thus, Cu acts as a vehicle to distribute other alloying elements with a low diffusion rate in Fe (e.g., Ni) within the grain boundaries of the base iron powder, by which the diffusion distances needed to achieve microstructural homogeneity are smaller.

Both with infiltrating or non-infiltrating liquids, the master alloy approach always offers the possibility to introduce several alloying elements simultaneously, and thus take advantage of the synergistic effects of combining alloying elements instead of introducing them individually (thus also at least alleviating mixing problems). Besides, using the MA route, the compressibility of the base powder can be preserved, and there is a high flexibility in the selection of the steel composition, i.e., the final properties can be 'tailored' by using different MA additions or by combining the MA powder with different base powders.

Developments in the master alloy field

The development of master alloys for PM steels has been a topic of research since the early 70s. At that time, some very interesting master alloys named MCM (Mn-Cr-Mo), MVM (Mn-V-Mo) and MM (Mn-Mo) were thoroughly studied for almost two decades with the aim of using them in the production of highly loaded PM parts [1–3]. However, the idea was eventually abandoned in the 90s for two reasons: 1) the need for high sintering temperatures (around 1280°C) to dissolve the carbide phases present in the master alloy particles, and 2) the excessive tool wear caused by the very hard and angular MA powder particles (at that time produced by melting, casting and then milling the ingots). Since then, different master alloy compositions have been developed pursuing the introduction of oxygen-sensitive elements [1–5], or the formation of a liquid phase [6–9], or both aspects at the same time [10–21] (Fig. 2). But the main boost of this research area

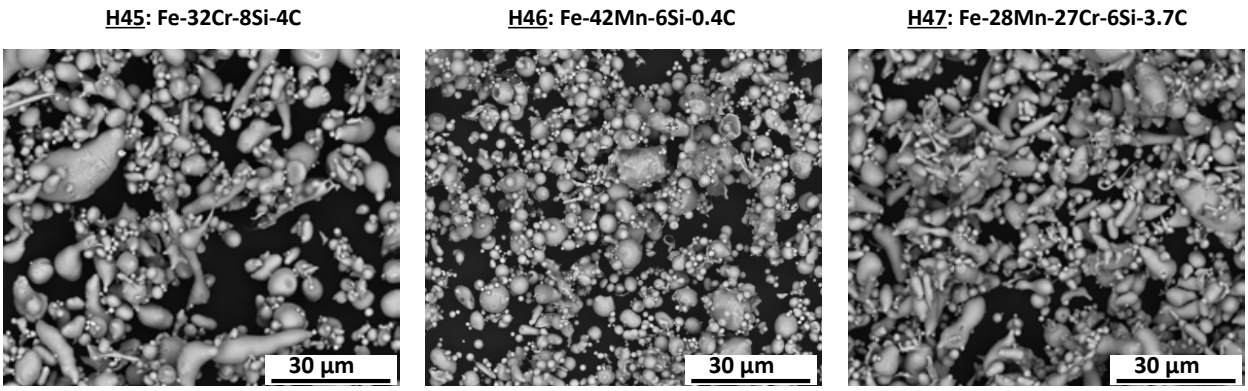

Fig. 3 Three UHPWA master alloys with different compositions

Name	Nominal Composition	d_{10}	d_{50}	d_{90}	O (%)	C (%)	Melting range
H45	Fe-32Cr-8Si-4C	3.21	7.84	18.4	0.14	4.01	1150–1220ºC
H46	Fe-42Mn-6Si-0.4C	2.33	6.7	16.1	0.10	0.54	1120–1200ºC
H47	Fe-28Mn-27Cr-6Si-3.7C	2.92	8.09	22.6	0.12	3.61	1095–1310ºC

Table 1 Characteristics of the master alloy powders used in this study

did not occur until the end of the 90s, with two parallel developments: firstly, the use of inert gas atomisation as a production method allowing the obtainment of increasingly fine MA powder particles with rounded morphologies that minimised the damage to the compacting tool, and secondly, the use of computational tools to systematically search compositions with adequate melting points below the usual sintering temperatures [22–23].

Moreover, during the last few years, very important advances in the MA field have provided key scientific knowledge that gives a glimpse on how the MA route can be used to take full advantage of PM capabilities:

- The detailed study of the chemical processes that take place when sintering steels containing master alloys with oxygen-sensitive elements in their composition [24–26]. This contributes to increasing the robustness of the sintering process.
- The implementation of a scientific methodology that allows the design of liquid phases with special features [27–29]. This opens the possibility to create 'tailored' PM solutions in terms of microstructure and dimensional behaviour.
- The development of a new atomisation technique - Ultra-High Pressure Water Atomisation (UHPWA) that allows cost-effective production of MA powders with rounded morphologies, low oxygen contents and small particle sizes [30]. This overcomes the main handicaps of the master alloy route: obtaining powders with suitable particle sizes at high yield and a reasonable cost.

This paper will present some extended information about the microstructures and properties of PM steels produced from UHPWA master alloy powders.

Ultra-high pressure water atomised powders

UHPWA is a newly developed atomisation technique that operates with induction melted batches of molten alloy, utilising water pressures of 60-200 MPa. Atomisation is followed by dewatering and vacuum drying. This technique allows economic production of master alloy powders with low oxygen contents (~0.1 wt.%), low particle sizes (d_{50}< 8 µm, d_{90}< 20 µm) and rounded morphologies (see Fig. 3), which can be made available at very convenient costs (~8 €/kg). The characteristics of three prototype powders obtained with this technique can be observed in Table 1 and the morphology of the powder particles in the Scanning Electron Microscope (SEM) images from Fig. 3.

The melting range of these alloys was measured using Differential Thermal Analysis (DTA). These prototype compositions were not yet optimised for liquid phase

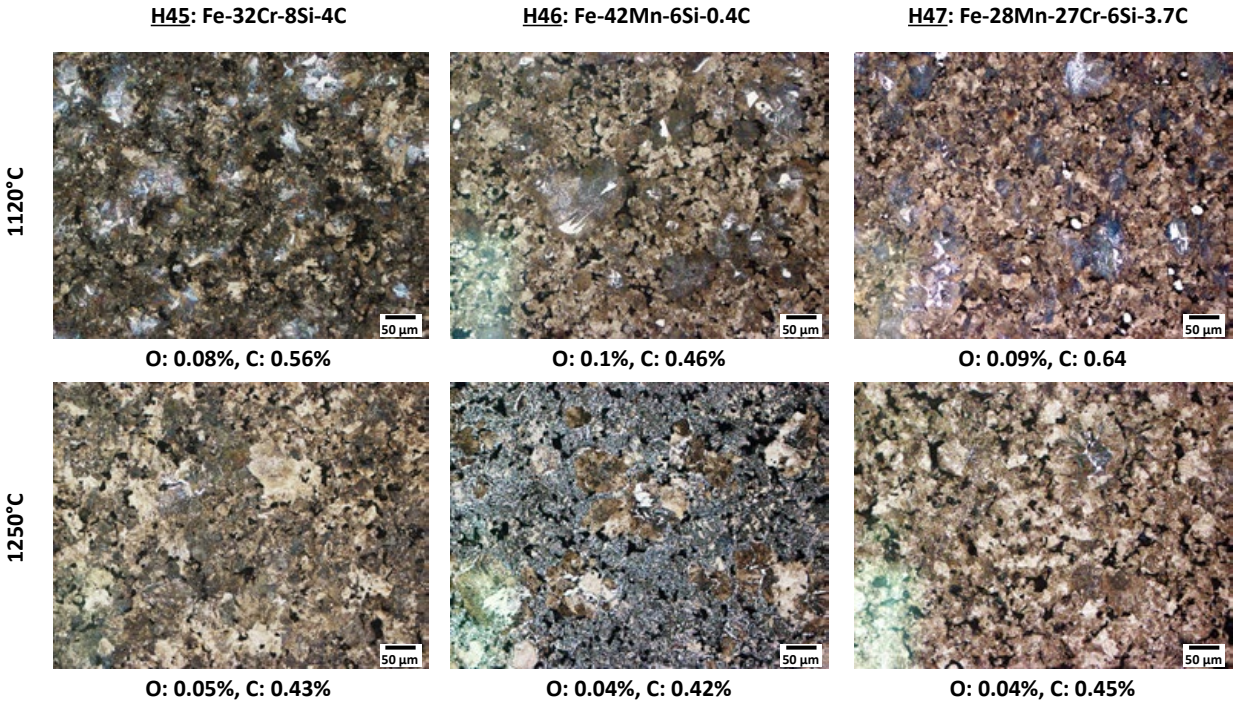

Fig. 4 Microstructures and interstitial contents in steels containing master alloys (Fe-0.5C-4MA) sintered at 1120°C and 1250°C for 30 min in N_2-5H_2. Linearised cooling rate ~0.75°C/s

sintering. In those powders batches with higher 'as-received' oxygen contents, thermal analyses with coupled DTA and mass spectrometry (to study the de-gassing process) suggested that these oxygen could easily be removed through a heat treatment in inert atmosphere at approximately 300°C.

Preliminary studies on microstructure and properties

Sintered steels were prepared from mixes of plain iron powders, graphite and 4 wt.% UHPWA master alloy and sintered at 1120°C or 1250°C for 30 min in N_2-5H_2. The typical microstructure consists of fine pearlitic phases in the cores of the Fe base powder particles, surrounded by areas with a higher amount of alloying elements in which harder microstructures are developed (Fig. 4). The homogeneous distribution of these phases within the sample suggests a fairly good distribution of the alloying particles in the mix. At high sintering temperatures the porosity is more rounded, and the diffusion of alloying elements is improved, which is evidenced by the decrease in the amount of ferritic/pearlitic areas. Undissolved master alloy particles are in some cases clearly discernible when sintering at 1120°C, which suggests that the sintering temperature/time has been insufficient to efficiently distribute the alloying elements present in the master alloy. This could be avoided by further sieving of the master alloy powders to remove the coarser fractions. A redesign of the masteraloy composition to ensure its melting at lower temperatures could be another way of improving the homogenisation at low temperatures.

The properties of these steels are shown in Fig. 5 together with the properties of steels produced using commercial powders (data obtained from [31, 32]). As can be observed in Fig. 5 - top, steels obtained using UHPWA - master alloys present very competitive Ultimate Tensile Strength (UTS) values with a very low content (below 3 wt.%) of inexpensive alloying elements (Cr, Mn, Si). In the graph from Fig. 5 (top), the positioning of steels containing UHPWA master alloys is similar to those obtained with Cr-prealloyed powders with a similar amount of alloying elements (both for 1120°C and 1250°C sintering temperature).

A similar comparison is presented in Fig. 5 (bottom), but in this case UTS is depicted against elongation

" At high sintering temperatures the porosity is more rounded, and the diffusion of alloying elements is improved..."

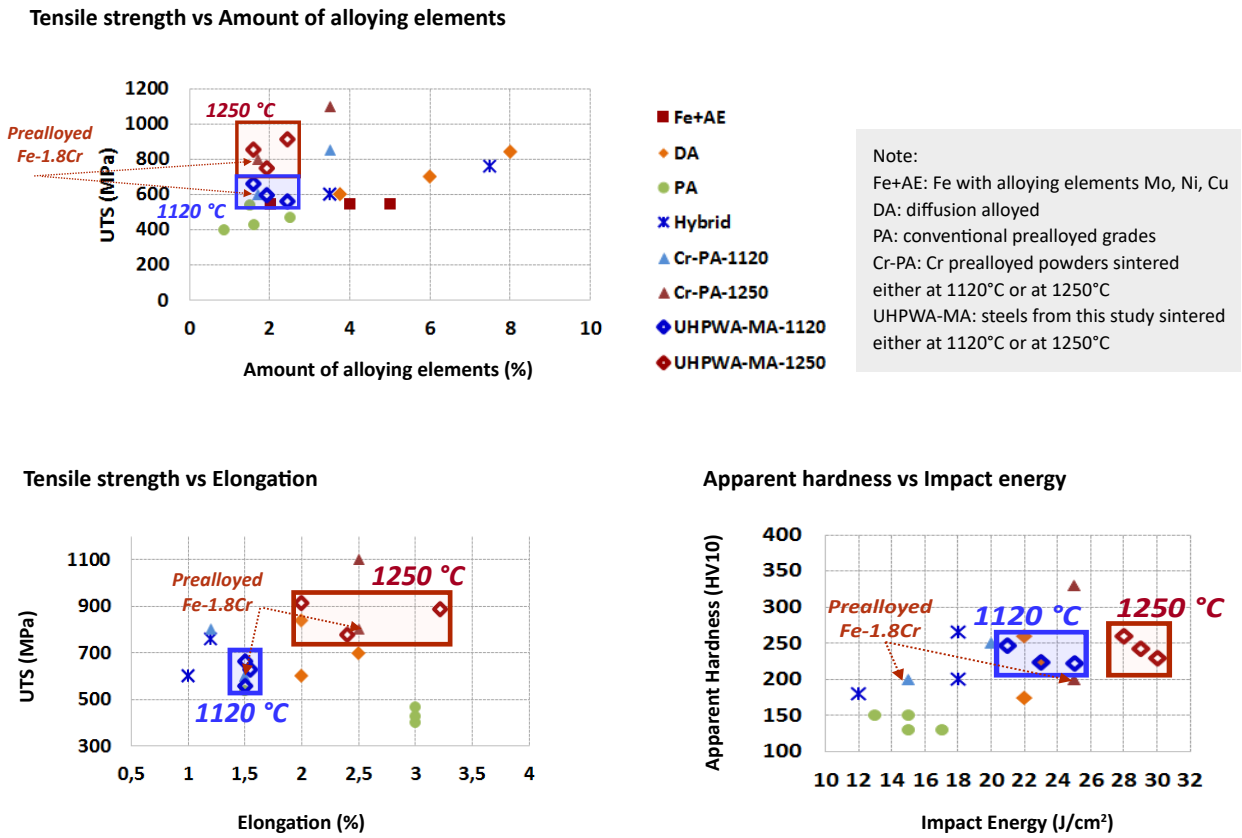

Fig. 5 Comparison of properties of steels obtained using UHPWA master alloys with steels produced under similar conditions using commercial powder grades (data on commercial grades were retrieved from the powder manufacturer)

and apparent hardness is plotted against impact energy.

Excellent combinations of properties are observed in steels containing UHPWA master alloys, even when sintering at 1120°C, very competitive with those obtained with commercial powders and again comparable with Cr - prealloyed grades. At high sintering temperature (1250°C), the properties of steels containing master alloys are boosted, presenting very interesting combinations of strength and ductility.

The fact that some master alloy particles were not dissolved completely at 1120°C leaves some room for improvement. By working on the design of the master alloy composition, it might be possible to obtain a better distribution of alloying elements at lower sintering temperatures, thus positioning the steels obtained following the master alloy route even better on the property map.

Are high sintering temperatures a must?

High sintering temperatures provide a significant increase in the mechanical performance of low-alloy sintered steels, particularly for those containing elements such as Cr, Mn and Si, with a high affinity for oxygen (both in pre-alloyed and master alloy approaches). However, such high temperatures are often less attractive for industrial production. In the particular case of steels produced through the master alloy route, the differences in properties can be attributed to various phenomena: enhanced reduction of oxides at high temperature, changes in the morphology of the pores, improved dissolution of master alloy particles and thus better distribution of alloying elements, etc.

The effect of the sintering temperature has been evaluated in hybrid PM steels prepared from Cr - pre-alloyed base powder (Fe-1.8Cr) with small additions of UHPWA master alloy. From a green density of ~6.92 g/cm^3, the sintered densities obtained at different temperatures range between 6.98 and 7.02 g/cm^3 (Fig. 6, top left), which suggests that the sintering temperature mainly affects the size and shape of the pores, but the total density is not influenced significantly. This is also reflected in the rather low dimensional changes (Fig. 6, top right).

The evolution of the oxygen and carbon contents is represented in Fig. 6 (bottom). The amount of oxygen after sintering at 1120°C and 1180°C is approximately that of the starting powder mix, which suggests that hardly any removal of oxygen from the sample has taken place. Most likely only a transformation of the oxides carried on the starting powders

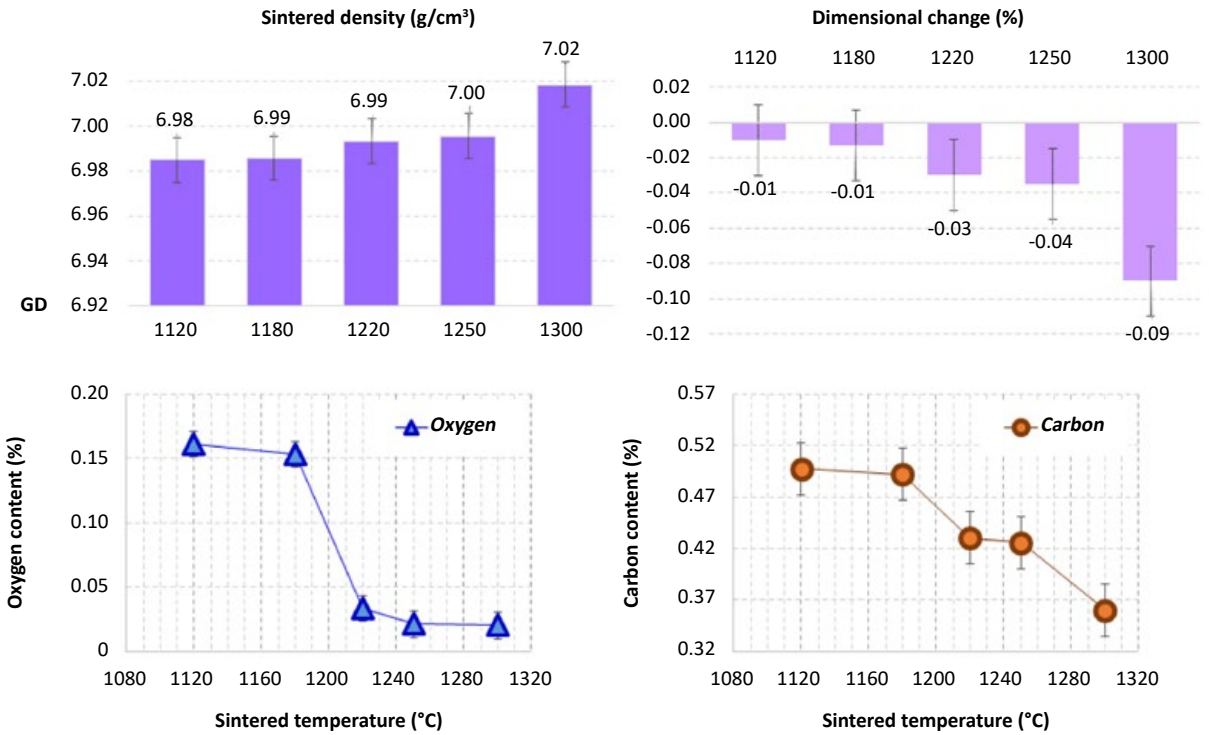

Fig. 6 Sintered density, dimensional change and interstitial content in steels prepared from Fe-1.8Cr base powder and 4 wt.% UHPWA master alloy, sintered at different temperatures

(mainly Fe-oxides) into more stable ones (Cr, Mn, Si containing oxides) took place (internal getter effect, see [25, 26]). A marked decrease in the oxygen content is observed after sintering at 1220°C (~0.03 %O at 1220°C vs ~0.16 %O at 1120°C), which indicates that at this temperature a significant reduction of the oxides is attainable under the sintering conditions used. The carbon content decreases at temperatures above 1220°C, as corresponds to the consumption of carbon required for the reduction of the oxides. However, a significant decarburisation is observed when sintering at 1300°C that cannot be attributed exclusively to the reduction of oxides (for the oxygen loss registered a carbon loss of around 0.1 wt.% would be expected), but is most likely related to the conditions in the furnace during these runs.

Fig. 7 shows the microstructures of the steels sintered at different temperatures. A significant amount of less-alloyed pearlite areas (darker) are observed when sintering at 1120°C. By increasing the sintering temperature to 1180°C, better distribution of the alloying elements is evidenced by the bainitic cores (instead of pearlitic), and especially by the considerably broader martensitic areas. As the

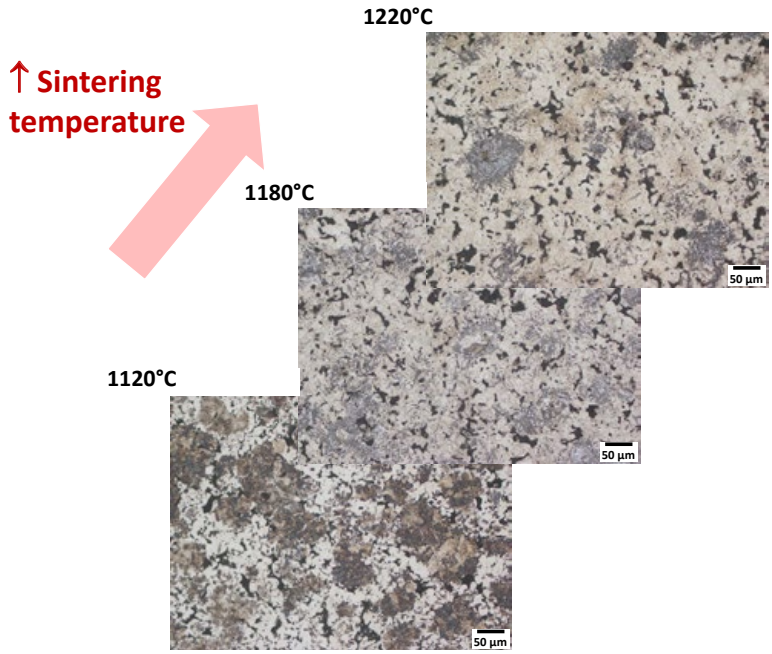

Fig. 7 Microstructure of steels prepared from Fe-1.8Cr base powder and 4 wt.% UHPWA master alloy, sintered at different temperatures. Linearised cooling rate ~0.75°C/s

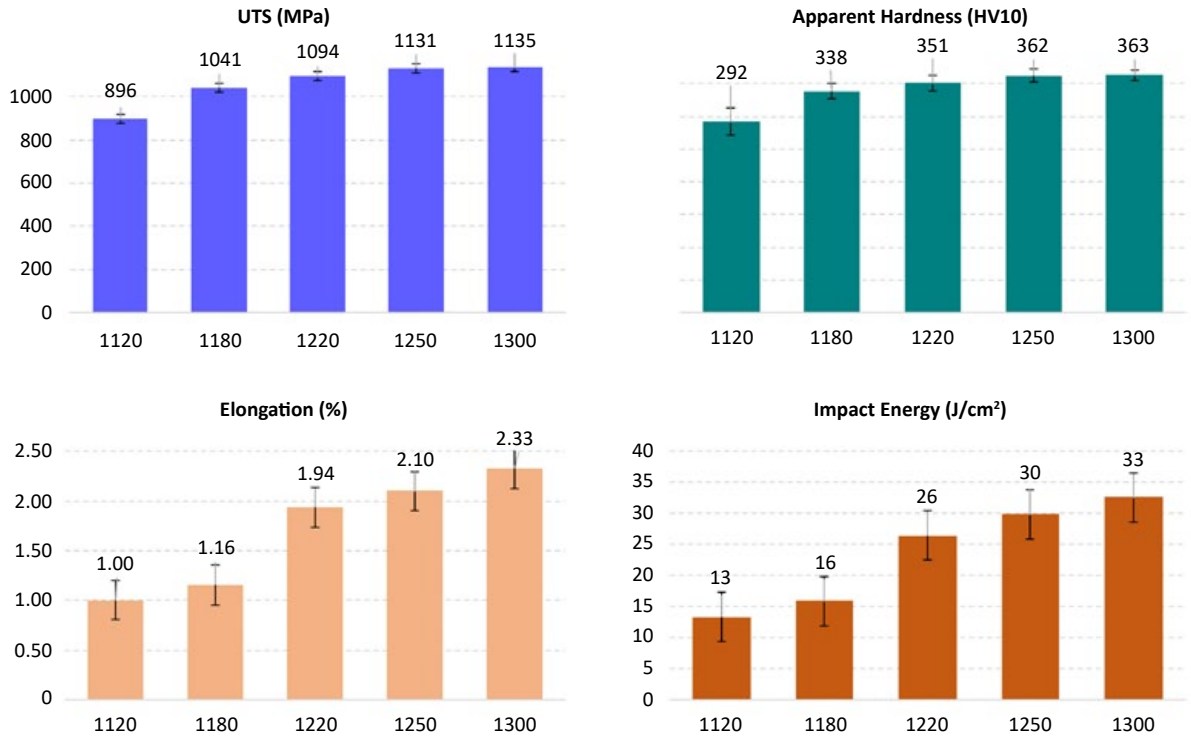

Fig. 8 Mechanical Properties of steels prepared from Fe-1.8Cr base powder and 4 wt.% UHPWA master alloy, sintered at different temperatures

sintering temperature increases, the size and amount of the bainitic areas decreases (due to the enhanced diffusion of alloying elements), and the pores become smaller and more rounded.

The 'hybrid alloying approach' considered in this study (combination of an Fe-1.8Cr pre-alloyed base powder with 4 wt.% UHPWA master alloy) can be used to obtain materials with impressive mechanical properties in the as-sintered condition, even when using low sintering temperatures (Fig. 8). As-sintered samples processed at 1120°C exhibited apparent hardness ~292 HV10 and UTS~ 896 MPa combined with reasonable impact energies ~13 J/cm^2 and elongations ~1%. When using only a slightly higher sintering temperature (1180°C), the homogenisation of the alloying elements is improved and excellent apparent hardness and UTS values are obtained (~338 HV10 and ~1041 MPa respectively), for similar impact energies and elongations (~16 J/cm^2 and ~1.2%).

When sintering at or above 1220°C, a significant improvement in elongation and impact energy values is achieved. At this temperature a reduction of the oxygen content is registered (~0.03 %O at 1220°C vs ~0.16 %O at 1120°C). The oxygen-sensitive alloying elements present both in the base powder (Cr) and in the master alloy (Mn and Si) form stable oxides that require high sintering temperatures to be reduced. For the specific combination of base powder and master alloy used in this study, the sintering conditions 1220°C and N_2-5H_2 atmosphere seem to be sufficient to ensure a significant reduction of the oxides. This enhances the quality of the sintering contacts, thus providing better impact energy and elongation values (~26 J/cm^2 and 1.9%) at slightly higher apparent hardness and UTS (~351 HV10 and ~1094 MPa). Further increase of the sintering temperature (to 1250°C or 1300°C) does not seem to provide any significant advantage, at least for the monotonic properties.

As a summary it can be stated that the very competitive properties observed at low sintering temperatures are mainly a consequence of the positive effect of the alloying elements used on the hardenability of the material, which allows high values of hardness and tensile strength to be obtained. By increasing the sintering temperature above 1220°C, it is possible to promote a reduction of the more stable oxides, which play a very important role in improving the quality of the sintering contacts. Thus, both the impact energy and the elongation are significantly improved at this temperature, which shows that the full potential of these materials is only obtained when the sintering temperatures required for the reduction of the oxides are reached. In this sense, understanding the reduction/oxidation phenomena characteristic of the combination of master alloy and base powder is critical for optimising the parameters of the sintering cycle.

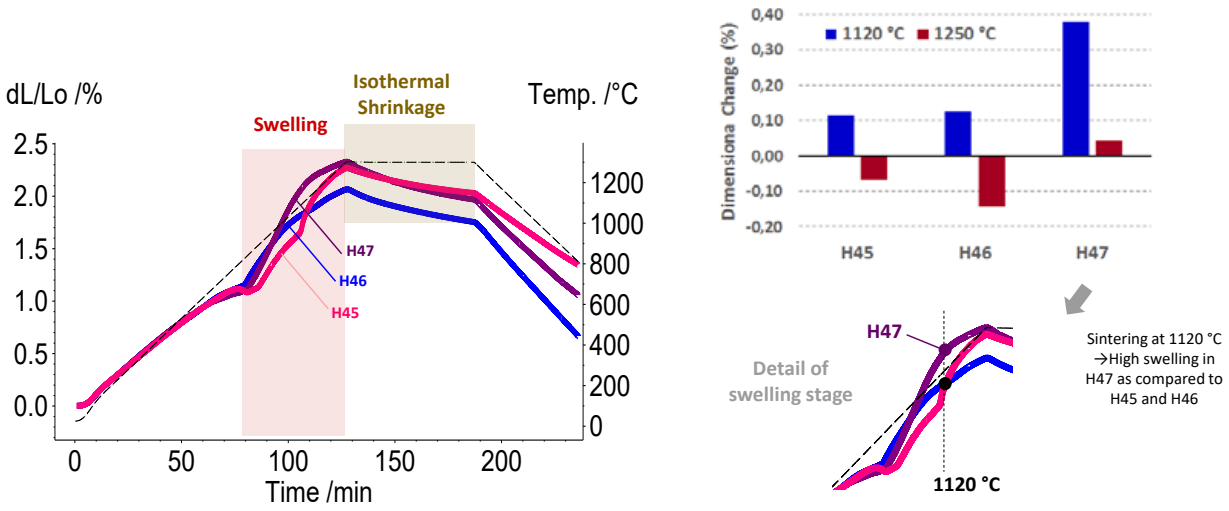

Fig. 9 Dimensional variations in steels containing different UHPWA master alloys. Dilatometry curves (left) show the different swelling phenomena occurring during heating depending on the alloy composition. On the right are the dimensional changes after sintering at 1120°C and 1250°C. The final dimensional change depends on the ability to compensate the swelling effect (taking place on liquid phase formation) by the isothermal shrinkage

Dimensional stability of steels containing master alloys

In general, steels containing Fe-based master alloys can give rise to swelling or shrinkage phenomena, depending on whether the swelling effect produced during the diffusion of alloying elements – or the melting of the master alloy particles – can be or cannot be compensated by the shrinkage that takes place in the isothermal region (Fig. 9). Since the sintering phenomena are activated more at high temperatures, higher shrinkage effects (or lower swelling) are observed when increasing the sintering temperature. Dimensional changes – measured on the length of impact test bars – in steels containing H45 and H46 are around 0.1% or below. With these two master alloys, swelling is observed when sintering at 1120°C, while shrinkage takes place when sintering at 1250°C. Consequently, the density increases with higher sintering temperature, because the sintering phenomena are enhanced at higher temperatures. The densities of steels containing H45 and H46 are in the range of 7.02–7.07 g/cm^3.

Swelling is observed in samples containing master alloy H47 both at 1120 °C and – to a lower extent – at 1250°C. As a consequence, the sintered densities achieved are below 7 g/cm^3. In general, the dimensional changes obtained in steels containing master alloys are strongly dependent on the composition of the master alloy and particularly on the interaction between the liquid phase formed and the base powder. This opens up the possibility of playing with the design of the master alloy composition in order to tailor the dimensional performance.

> *"In general, steels containing Fe-based master alloys can give rise to swelling or shrinkage phenomena."*

Master alloys: A key to tailor hardenability

A very remarkable advantage of the master alloy route for introducing metallic alloy elements is the flexibility in the selection of compositions. Different amounts of master alloy can be admixed to different types of base powder, giving a wide portfolio of microstructures and properties.

An example of the variety of different microstructures attainable is presented in Fig. 10. In this study, three different base powders (plain iron, Fe-0.85Mo and Fe-1.8Cr) were combined with two different amounts of UHPWA master alloy powder (4 wt.% and 6 wt.%). Small additions of MA to an Fe base powder provides bainitic areas surrounding the pearlitic/ferritic microstructures present in the core of the iron base powders. When increasing the addition of

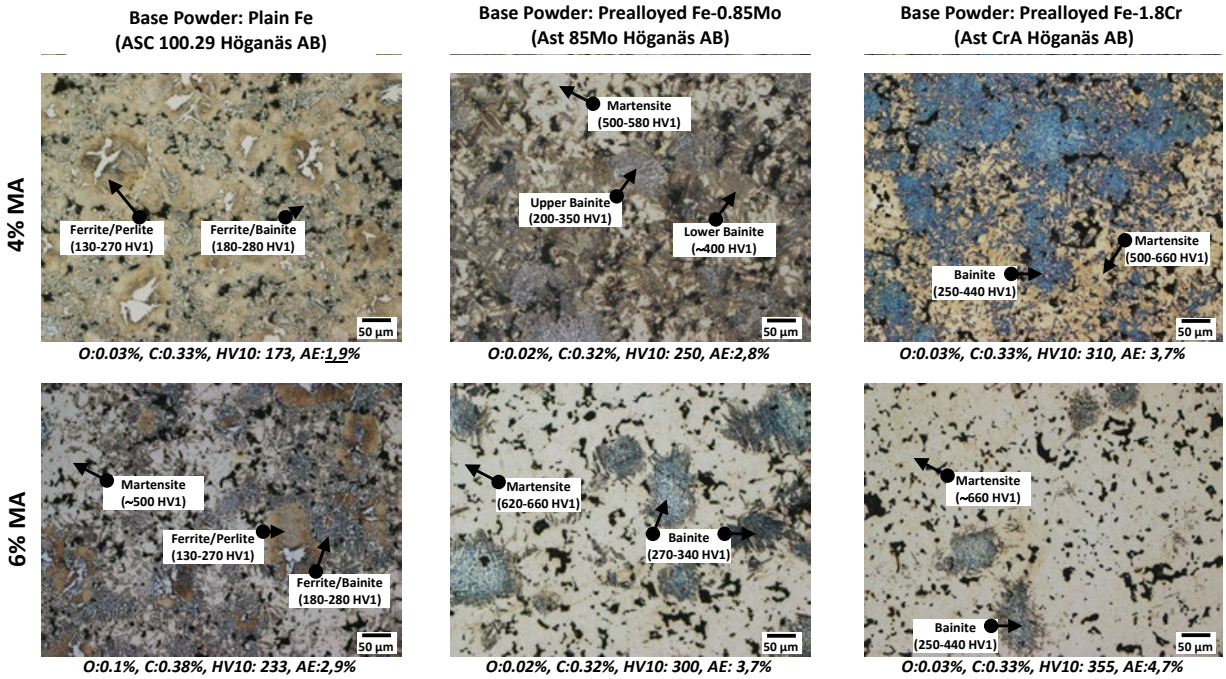

Fig. 10 Microstructure (including the micro-hardness ranges registered on the different phases), oxygen and carbon content and apparent hardness of steels prepared from different base powders, with two different additions of UHPWA master alloy (4 wt.%top and 6 wt.% bottom). Sintering temperature 1250°C. Linearised cooling rate ~0.75°C/s.

MA to 6 wt.%, martensitic areas are observed in the highly-alloyed regions.

In case of combinations with Fe-0.85Mo pre-alloyed powders, quite significant effects are observed with the addition of only 4 wt.% MA, which provides microstructures consisting of small upper bainite cores surrounded by areas of lower bainite and martensite with considerably higher hardness. When the addition of MA is increased to 6 wt.%, the upper bainite disappears and the lower bainite cores are surrounded by broad martensitic areas. If only a 4 wt.% MA are added, it results in an increase of the apparent hardness to 250 HV10 (from 156 HV10 in the Fe.0.85Mo base powder), for similar carbon contents (~0.35%C)

But the most significant increase in apparent hardness is observed when using Fe-1.8Cr pre-alloyed powder: 4 wt.% addition of MA provide an apparent hardness of ~310 HV10 in the as-sintered condition, and ~355 HV10 is obtained with 6%MA (from 141 HV10 in the base powder). In both cases, the microstructure consists of bainitic cores surrounded by martensitic areas that are broader when increasing the addition of MA.

Fig. 11 shows a comparison of properties (apparent hardness plotted vs impact energy) for different commercial powders with or without additions of master alloys. In this case all the powders were processed under the same laboratory conditions (pressed at 600 MPa and sintered in N_2-5H_2 at 1120 or 1250°C).

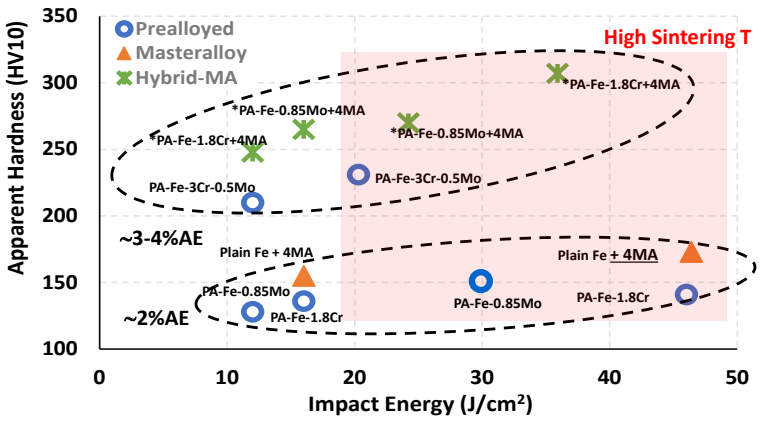

Fig. 11 Apparent hardness (HV10) vs Impact energy (J/cm²) in different as-sintered steels processed at 1120°C and 1250°C in N_2-5H_2, 30 min with cooling rate ~0.75°C/s. In the legend: Master alloy represents steels prepared from plain iron powders with 4 wt.% UHPWA master alloy additions, Hybrid-MA represents steel prepared from prealloyed base powders with 4 wt.% UHPWA. Shaded area: values for 1250°C (all steels were simultaneously processed under the same lab conditions)

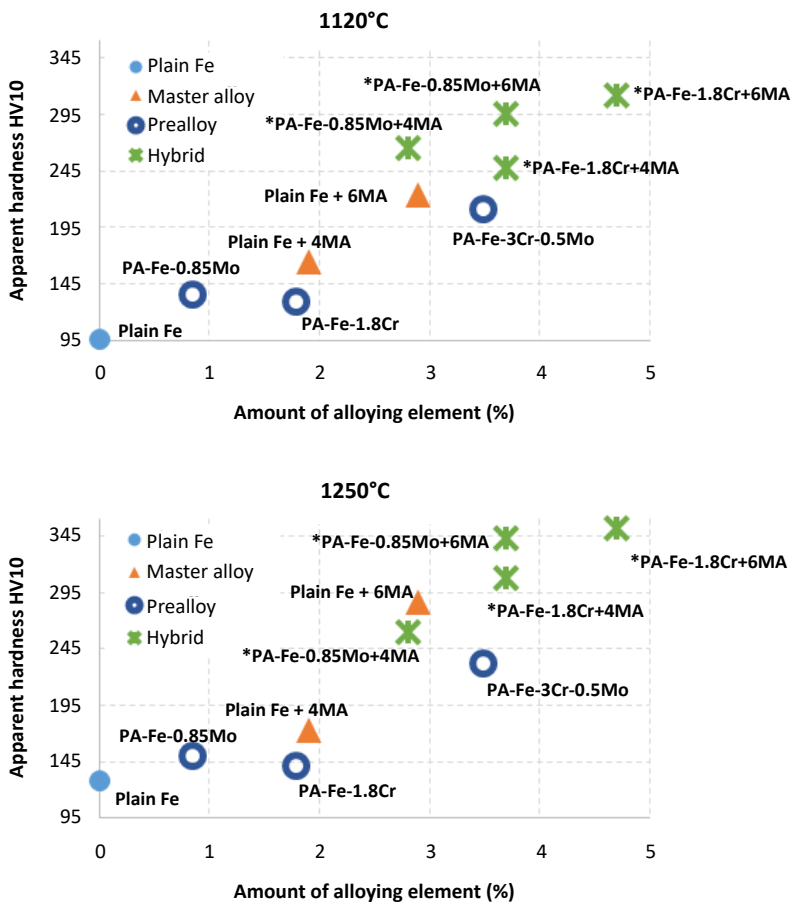

Fig. 12 Apparent hardness (HV10) vs amount of alloying elements (wt. %) in different as-sintered steels processed at 1120°C and 1250°C in N_2-5H_2, 30 min with cooling rate ~0.75°C/s. In the legend: Master alloy represents steels prepared from plain iron powders with 4 wt.% UHPWA master alloy additions, Hybrid-MA represents steel prepared from pre-alloyed base powders with 4 wt.% UHPWA (all steels were simultaneously processed under the same lab conditions)

The materials can be divided in two groups depending on the total amount of alloying elements added to the steel (without considering carbon). The dashed circles outline these two families of materials: one with alloying contents below 2 wt.%, and another one with alloying contents around 3–4 wt.%. The data highlighted in the box (High Sintering T) correspond to the samples sintered at 1250°C, while the remaining data corresponds to the sintering runs at 1120°C. The same data are represented in Fig. 12, but in this case the UTS values are plotted vs the amount of alloying elements, and two different graphs are given for the sintering runs at 1120 and 1250°C.

In the group of steels containing alloying contents below 2 wt.% it is possible to compare the introduction of alloying elements by using either a fully pre-alloyed approach (PA Fe-1,8Cr or PA Fe-0.85Mo), or by using a master alloy (Plain Fe + 4MA). For a similar alloying content, the properties in steels containing master alloy are always slightly superior to those obtained with the pre-alloyed approach.

The group with the higher total amount of alloying elements (~3 - 4 wt.%) shows considerably higher apparent hardness values. This group contains the pre-alloyed grade Fe-3Cr-0.5Mo, as well as the 'hybrid' combinations which consist on prealloyed powders with small amounts of alloying elements (Fe-0.85Mo and Fe-1.8Cr) mixed with small additions of master alloy (4wt.%). For a similar total amount of alloying elements, the 'hybrid' approaches seem to provide the most advantageous combinations of properties at both sintering temperatures. Using the hybrid combinations, apparent hardness values around 250-350 HV10 are obtained in the as-sintered condition for steels with final carbon contents around 0.30-0.35 %.

The experiments at low sintering temperatures show the fairly high apparent hardness values that can be obtained by adding MA to pre-alloyed powders such as PA Fe-0,85Mo and PA Fe-1,8Cr, with very reasonable values of impact energy.

The results obtained at high sintering temperature allow the comparison between a fully prealloyed approach (PA Fe-3Cr-0,5Mo) and a hybrid approach (combination of MA with two prealloyed powders with low alloying content: PA Fe-0,85Mo and PA Fe-1,8Cr). The properties obtained with the fully pre-alloyed grade are slightly exceeded by the hybrid combinations based on PA Fe-0,85Mo, but the most significant improvement in properties is observed by using combinations of MA powders with PA Fe-1,8Cr. This latter case shows how the very good properties of PA Fe-3Cr-0,5Mo can still be considerably improved if using hybrid combinations of low-Cr pre-alloyed powders and master alloys.

Summary

The use of Ultra-High Pressure Water Atomisation technologies brings the opportunity to produce master alloy powders with low oxygen contents (~0.1 wt.%), low particle sizes (d_{50}< 8 µm, d_{90}< 20 µm) and rounded morphologies, at very attractive costs (~8 €/kg). This opens a completely new frame of possibilities for the master alloy concept, because it overcomes one of the main handicaps of this alloying

route: the necessity to obtain MA powders with suitable morphologies and particle sizes (~20 µm) at a reasonable cost (which typically involves obtaining a high yield of the fine fractions). This work presents an overview on the properties that can be obtained when adding small amounts of such master alloy powders to different iron base powders (plain or pre-alloyed). With less than 3 wt.% of inexpensive alloying elements these steels present combinations of properties that reach or even surpass the properties of steels obtained with commercial powders. In some of the steels produced, the master alloy particles were not completely dissolved when sintering at 1120°C, which indicates that an optimised design of the alloying composition could promote the homogenisation of alloying elements at lower temperatures (by, e.g., the formation of a liquid phase), resulting in an even better combination of properties for low-temperature sintering cycles.

Even though the use of master alloys is not a common practice in the industry, nowadays the advances in the research areas and in the atomisation technologies bring very interesting opportunities for this alloying route. Some challenges that may still be on the table are:

- Homogeneous admixing of such small MA powder particles. Avoiding agglomerations and ensuring a good distribution of the MA particles in the mix is surely a must. At the laboratory scale this was so far not a big problem, but this needs to be industrially scaled.
- The reproducibility of the dimensional changes. Dimensional stability in steels containing MA that form a liquid phase will depend on the possibility to compensate the swelling obtained upon liquid formation by the isothermal shrinkage (as it is also the case of Fe-Cu-C steels). Here, the master alloy approach opens up many different possibilities. By designing the properties of the liquid phase and its interaction with the Fe base particles it might be possible to 'tailor' the dimensional behaviour of the compact. Of course this needs to be optimised for the particular geometry of the part.
- The risk of oxidation and therefore the robustness of the production processes. Nowadays, thermal analysis techniques can bring up very relevant knowledge on the chemical aspects of the sintering cycle. A proper design of the sintering conditions adapted to the specific combination of master alloy and base powder provides the hints to design robust products and processes.

The use of UHPWA master alloy powders offers the possibility of significantly increasing the hardenability of commercial steel powders at very low alloying cost and with more flexibility to select the final composition of the steel (as compared with the fully pre-alloyed approach). The 'hybrid alloying approach' (e.g., the combination of an Fe-1.8Cr prealloyed base powder with 4 wt.% of an UHPWA master alloy) provided excellent mechanical properties in the as-sintered condition, even when using low sintering temperatures. The master alloy route can thus be used as an effective tool for tailoring the performance of PM materials by simply adapting the amount of MA added, or by combining the MA powder with different base powders (plain iron or pre-alloyed grades).

Acknowledgements

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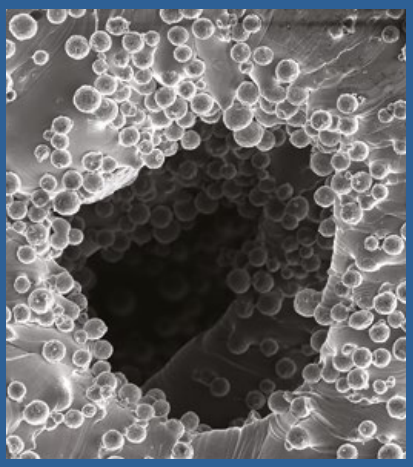

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Euro PM2018: Powder Metallurgy processing by hot pressing technologies

Several papers presented at the Euro PM2018 Congress and Exhibition, organised by the European Powder Metallurgy Association (EPMA) and held in Bilbao, Spain, October 14–18, 2018, addressed developments to enhance the understanding of process control in hot pressing technologies. In this report, Dr David Whittaker discusses two papers focused on the numerical simulation of Hot Isostatic Pressing (HIP) using Finite Element Modelling, and a further paper on the impact of W particle size on the diffusion and porosity of hot pressed chromium-based compounds.

Finite Element Simulation and design optimisation of complex-shaped models of 316L stainless steel powder for Hot Isostatic Pressing

Firstly, Yacine Kchaou, Jean-Philippe Chateau-Cornu, Ludivine Minier and Frederic Bernard (Universite Bourgogne Franche-Comte, France) and Olivier Gyss and Regis Bigot (Manoir Industries, France) considered the Finite Element Modelling (FEM) simulation and design optimisation of complex-shaped models of 316L stainless steel powder for HIP [1].

To predict deformation and final shape, Finite Element Simulation, using an appropriate constitutive model, can be carried out. Several published studies have used numerical simulation to design the initial shape of complex-shaped containers with a combined model, which includes both a time-independent plasticity and a rate-dependent plasticity (creep). These studies have shown that the combined model gives a better prediction than mere plastic or viscoplastic models. For HIP numerical simulation, the model of Abouaf *et al* is the simplest and most commonly used model to describe the densification behaviour of different alloys, as well as the deformation state and final shape, and was used in the numerical simulations of HIP in this reported study.

A gas atomised 316L stainless steel powder was used in the reported experimental investigations. Hot Isostatic Pressing was carried out using a Quintus QIH-15L facility, with a maximum temperature of 2000°C and a maximum pressure of

Fig. 1 Euro PM2018 at the Bilbao Exhibition Centre (Courtesy EPMA)

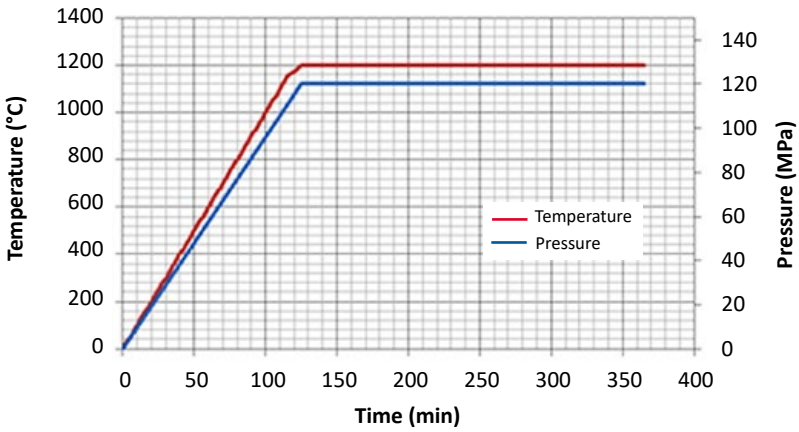


Fig. 2 HIP cycle of temperature and pressure [1]

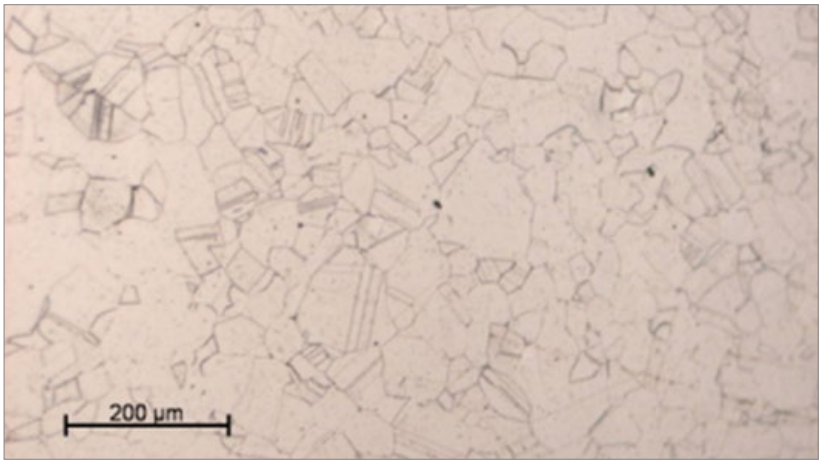


Fig. 3 Optical micrograph of HIPed 316L [1]

Temperature (°C)	25	0	-50	-75	-100	-140	-196
Failure Energy (J)	146	122	118	102	96	90	82

Table 1 Charpy impact energies of HIPed 316L steel at different temperatures [1]

200 MPa. A cylindrical 304L stainless steel container of 2 mm in thickness, 164 mm in height and 80 mm in diameter was first used. The 316L powder was filled in the container using a vibration system in order to reach an initial density of 0.7. The applied HIP cycle consisted of heating at 10°C/min up to 1200°C and 120 MPa, holding for four hours and then naturally cooling (Fig. 2). The densification of more complex-shaped specimens was performed using the same conditions, except at a lower applied pressure (102 MPa).

The powder particle size ranged between 0–500 µm, with a median diameter d(0.5) of 126 µm. After HIPing, the measured relative density reached 100% in all cases. It can be seen in Fig. 3 that the microstructure is fully austenitic, with the presence of some inclusions in the austenitic matrix. The microstructure consisted of equiaxed grains and many twins could be observed. The grains were randomly oriented, with grain sizes ranging between 10–100 µm.

Charpy impact tests were performed on normalised V-notched specimens, with a 10 mm wide square section, at a range of temperatures: room temperature and cooling with liquid nitrogen to 0°C, -50°C, -75°C, -100°C, -150°C and -196°C. The measured fracture energies are shown in Table 1. Charpy impact tests at low temperatures showed lower fracture energies compared with forged 316L steel, due to the presence of trapped oxides.

Numerical simulation of the HIP process used the Abouaf *et al* model to describe the viscoplastic behaviour of the powder during compaction, with the strain rate tensor being expressed as:

$$\dot{\varepsilon}_{ij} = \frac{3}{2} A \sigma_{eq}^{n-1} \left(2 f \sigma_m \delta_{ij} + c S_{ij}\right)$$

where A and n are the parameters of the Norton law for dense 316L creep, S the deviatoric stress tensor, σ_m the hydrostatic stress and σ_{eq} the powder equivalent stress:

$$\sigma_{eq}^2 = 9 f \sigma_m^2 + c \sigma_{vm}^2$$

with $\sigma_{vm} = (1.5\, S_{ij} S_{ij})^{1/2}$ the Von Mises stress. The parameters f and c are the powder rheological parameters and are functions of the relative density D:

$$f(D) = 0.16 \left(\frac{1-D}{D-D_0}\right)^{1.1}$$

$$c(D) = 1 + 5.23 \left(\frac{1-D}{D-D_0}\right)^{0.914}$$

The Abouaf constitutive equation is implemented into the user-defined subroutine CREEP of the finite element software ABAQUS/CAE. A, n, f and c are taken from the results in the published literature. Mechanical and thermal properties, such as Young's modulus and thermal expansion coefficient of 316L and 304 stainless steels, were also taken from the literature. As the specimens were small, heat transfer was not taken into account and the temperature was assumed to be homogeneous and equal to the applied temperature.

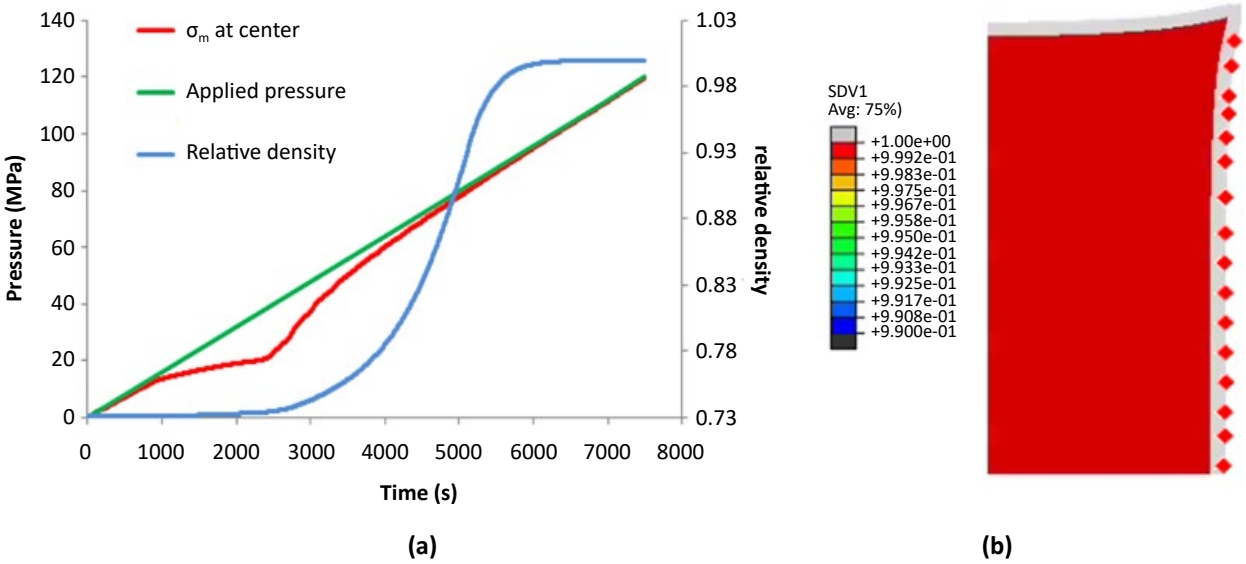


Fig. 3 Finite element simulation of the cylinder. a) hydrostatic stress at the centre of the cylinder and relative density along with time, b) relative density (SDV1) at t = 7500 s (T=1200°C, P=120MPa) and comparison of the external shape with experimental measurements of the diameter along the height (red diamonds) [1]

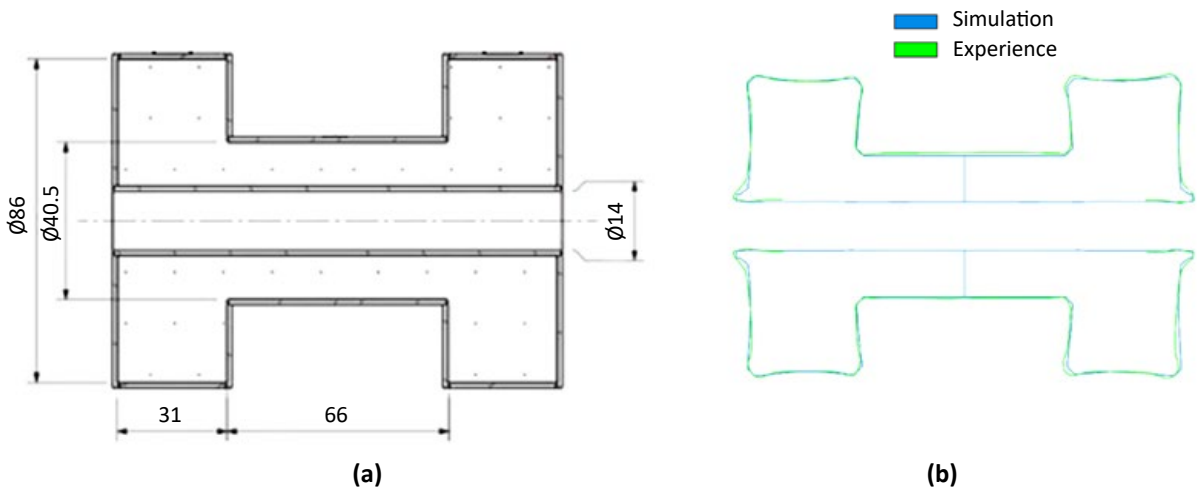
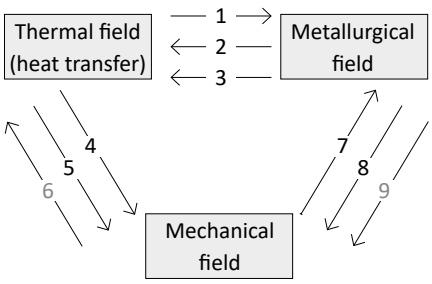


Fig. 5 Double flange part with internal tube. a) shape and dimensions. (The part is rotationally symmetrical around the horizontal axis), b) shape after HIP: comparison between experiment and numerical simulation [1]

2D finite element analysis of the cylindrical specimen was carried out, with the results as shown in Fig. 4. The stress calculation at the centre of the cylinder shows that the presence of the container shields the powder from the applied pressure at the beginning of compaction. The relative density at the end of heating is already uniformly equal to 1, showing that the four hour holding time required to close the final micro-porosity has no influence on the final shape. After the HIP test, the diameter of the capsule was measured throughout the height and compared to the simulation results. This measurement was used to adjust the strain rate of the container (Norton parameter A) in the simulation to fit the experiment.

Numerical simulation of the HIP process, for a more complex-shaped and hollow specimen, was carried out in order to validate the previous calibration on the cylinder. The example shown in Fig. 5 (isolated flanges) was part of a study carried out on a valve for the oil & gas industry. The shape and dimensions of the sample are shown in Fig. 5a. Using a 3D scan of the HIPed specimen, a comparison between the experimental and the numerical results was performed using a superposition between the two final shapes, as shown in Fig. 5b. The agreement between the numerical simulation prediction (shown in blue) and the actual experimental result (shown in green) was excellent, with an error below 0.5 mm.



1: Thermal driving force
2: Phase-dependent thermal properties
3: Latent heat of transformation
4: Thermal strain/stress
5: Temperature-dependent mechanical properties
6: Heat induced by deformation
7: Transformation induced strain/stress
8: Phase-dependent mechanical properties
9: Transformation induced by strain/stress

Fig. 6 Quenching as a multi-physics process [2]

FEM simulation of consolidation and microstructure development during PM-HIP of cold work tool steel D7

Secondly, Carola Birke, Yuanbin Deng, Sebastian Riehm, Ali Rajaei, Anke Kaletsch, Christoph Broeckmann, Stephanie Bohrt and Herbert Pfeiffer (RWTH Aachen, Germany) and Nils Wulbeiter and Werner Theisen (Ruhr-Universitat Bochum, Germany) considered the FEM simulation of consolidation and microstructure development in the combined process of HIP and heat treatment of the cold work tool steel D7 [2].

HIP is usually followed by a heat treatment to adjust the final microstructure. Cooling equipment in the HIP unit enables the combination of HIP and heat treatment in a single step, when the achievable cooling rates are high enough to create a martensitic transformation. In the reported study, a combined simulation of the densification during HIP and the phase transformation during quenching has been carried out to predict the shape of the final component and the achieved phase fractions.

The modelling of the consolidation during HIPing was divided into three stages. Firstly, the particles rearrange. The second stage is dominated by plastic flow with porosity and a relative density below 90%. The porosity is closed in the third stage, which is characterised by creep and diffusion, and the relative density increases beyond 90%. The material behaviour during the densification process can be described using the approach described in the previous paper, which couples a time-independent model of plasticity with the time-dependent model of Abouaf *et al* for viscoplasticity.

The calculation of the total strain increment considered elastic ($\Delta\varepsilon_{ij}$) and inelastic ($\Delta\varepsilon_{ij}^{inel}$) contributions is in the following equation:

$$\Delta\varepsilon_{ij} = \Delta\varepsilon_{ij}^{el} + \Delta\varepsilon_{ij}^{inel}$$

The elastic strain is described by Hooke's law, shown with the inverse stiffness matrix C_{ijkl}^{-1} that depends on temperature and relative density:

$$\Delta\varepsilon_{ij}^{el} = C_{ijkl}^{-1} \cdot \Delta\sigma_{kl}$$

The inelastic strain is composed of plastic ($\Delta\varepsilon_{ij}^{pl}$), viscoplastic ($\Delta\varepsilon_{ij}^{vp}$) and thermal ($\Delta\varepsilon_{ij}^{th}$) strains:

$$\Delta\varepsilon_{ij}^{inel} = \Delta\varepsilon_{ij}^{pl} + \Delta\varepsilon_{ij}^{vp} + \Delta\varepsilon_{ij}^{th}$$

Plasticity is modelled using the approach proposed by Kuhn and Downey, who regarded the powder as a porous medium with a modified flow condition, given by an ellipsoidal yield surface $F(\sigma_{ij}, \rho, p_{eq})$. The plastic strain can be calculated considering the consistency condition, the flow rule and the mass conservation, shown in the following equation, where $\Delta\lambda$ gives the amount of plastic flow and $\left(\frac{\partial F}{\partial \sigma_{ij}}\right)$ the flow direction:

$$\Delta\varepsilon_{ij}^{pl} = \Delta\lambda \cdot \left(\frac{\partial F}{\partial \sigma_{ij}}\right)$$

The strain increment of viscoplasticity in the secondary creep state, considered by the model of Abouaf *et al*, is provided by the following equation where A is the Dorn's constant and N the creep exponent of the fully

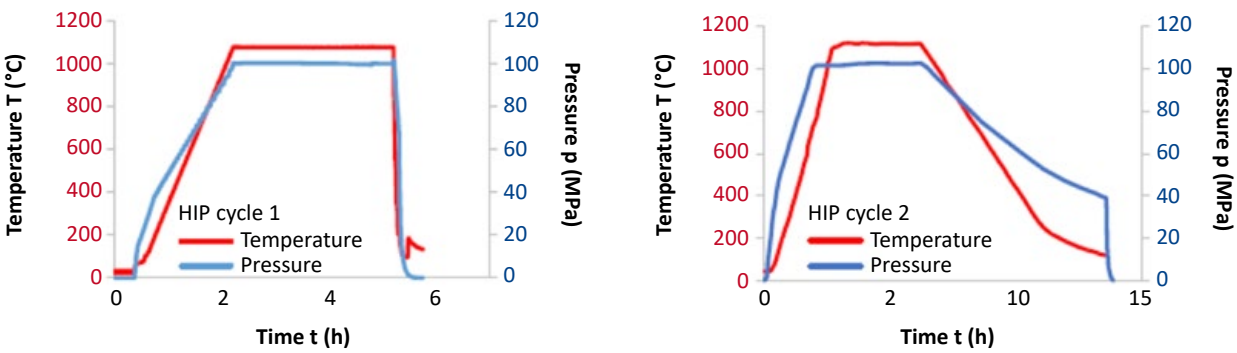


Fig. 7 Temperature and pressure during HIP. HIP cycle 1: HIP + Quenching; HIP cycle 2: HIP + slow cooling [2]

dense material, the σ_{eq} terms in the equivalent stress of creep for a porous material. $c(\rho)$ and $f(\rho)$ are rheological functions:

$$\Delta\varepsilon_{ij}^{vp} = \dot{\varepsilon}_{ij}^{vp} \cdot \Delta t = A \cdot \sigma_{eq2}^{N-1} \cdot \left(\frac{3c(\rho)}{2} \cdot S_{ij} + f(\rho) \cdot I_1 \cdot \delta_{ij}\right) \cdot \Delta t$$

The thermal strain is calculated by using the thermal expansion coefficient α_{th} and the temperature T:

$$\Delta\varepsilon_{ij}^{th} = \alpha_{th} \cdot \Delta T \cdot \delta_{ij}$$

To predict microstructure, deformation and residual stresses during quenching, a thermomechanical-metallurgical coupled model has been used, which considers the interactions between the fields (Fig. 6). The grey marked interactions, with numbers 6 and 9, are neglected in the quenching model. The total strain tensor (ε_{ij}^{ges}) is given by the sum of elastic (ε_{ij}^{el}), plastic (ε_{ij}^{pl}), thermal (ε_{ij}^{th}), transformational strain components (ε_{ij}^{tr}) and transformation-induced plasticity (ε_{ij}^{tp}). Hooke's law describes the elastic strain, plastic strains are available through the yield criterion of von Mises, and the other components are modelled according to dilatometric experiments.

$$\varepsilon_{ij}^{ges} = \varepsilon_{ij}^{el} + \varepsilon_{ij}^{pl} + \varepsilon_{ij}^{th} + \varepsilon_{ij}^{tr} + \varepsilon_{ij}^{tp}$$

Phase transformations are substantially involved in the evolution of deformation and residual stress. The modified Avrami model, as shown in the following equation, describes the diffusion controlled transformations by eliminating the time factor. In this way, the model can be used with non-isothermal conditions:

$$\dot{p} = n(T) \cdot \frac{\tilde{p}(T) - p}{\tau(T)} \cdot \left[\ln\left(\frac{\tilde{p}(T)}{\tilde{p}(T) - p}\right)^{\frac{n(T)-1}{n(T)}}\right] \cdot f_1 \cdot f_2$$

$\dot{p}$ is the transformation rate, p the volume fraction of the formed phase and $\tilde{p}(T)$ the maximal possible volume fraction at temperature T. $n(T)$ and $\tau(T)$ represent kinetic parameters and f_1 and f_2 are correction terms, of which only f_1 is used to include the cooling rate. Displacive transformations, as in the martensitic transformation, are modelled by consideration of the cooling parameter λ through a modification of the Koistinen-Marburger approximation:

$$p_m = \tilde{p}_m \cdot \left[1 - \exp\left\{-\left(\frac{M_s(\lambda) - T}{b(\lambda)}\right)^{n(\lambda,T)}\right\}\right]$$

p_m is the volume fraction of martensite, $\tilde{p}_m$ the maximal possible volume fraction of martensite, M_s the martensite start temperature and T the actual temperature ($T < M_s$). Material parameters are included through n and b.

The reported study then comprised the experimental validation of the predictions from the developed models.

Gas atomised cold work steel D7 powder was filled in two cylindrical capsules of 304 stainless steel (d = 44.5 mm, h = 44.5 mm). The chemical composition of the powder is given in Table 2. The particle size distribution showed particles with a diameter of up to 500 µm. After evacuating and sealing, the capsules were HIPed using HIP cycle 1 and HIP cycle 2 with different cooling rates. The performed HIP cycles are shown in Fig. 7. The capsules were HIPed at 1075°C and 1120°C for 3 h under a pressure of 100 MPa. From the HIP temperature, the quenching was performed with an average cooling rate of –1.27 K/s for HIP cycle 1, whereas the slow cooling rate of the second cycle was –0.05 K/s.

The capsules were simulated as a quarter of a 3D rotationally symmetrical FEM model. The geometry and the combination of consolidation and heat treatment models are presented in Fig. 8. A capsule is divided into two sections: one represents the container (or can) made from SS 304; the other section represents the cold work tool steel D7 powder. Filling of the capsules attained a relative density of 63%, which was used as the initial relative density of the powder in the consolidation model. In relation to the comparison of simulation and experiment, the temperature and pressure profiles of the HIP cycles serve as the boundary conditions of the models.

The simulation was divided into two steps. Firstly, the densification

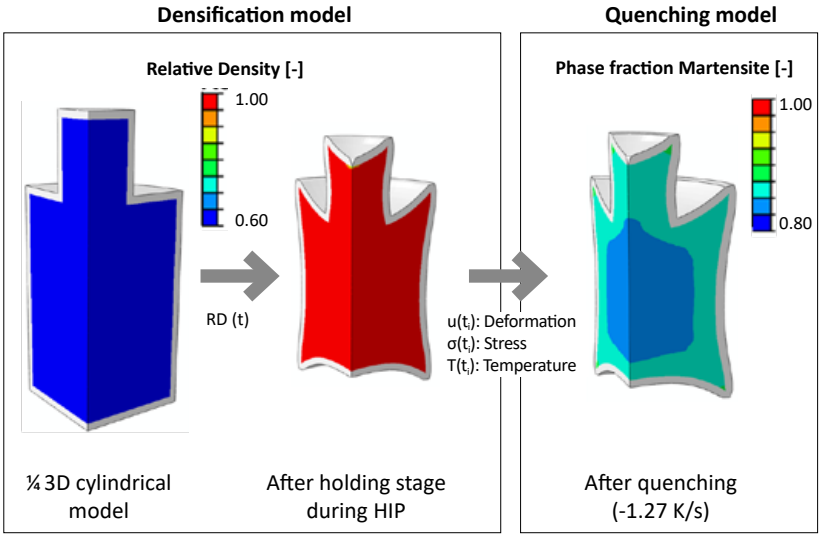


Fig. 8 Simulation model and sequence of simulation (RD: relative density) [2]

C	Si	Mn	P	S	Cr	Mo	V	Ni	N
2.29	0.46	0.34	0.014	0.014	12.3	0.99	4.01	0.106	0.048

Table 2 Chemical composition of the D7 powder [wt.%] [2]

	HIP cycle 1: HIP + Quenching				HIP cycle 2: HIP + Slow cooling			
MP	Initial mm	Experiment mm	Simulation mm	Deviation mm	Initial mm	Experiment mm	Simulation mm	Deviation mm
H1	44.5	41.35	44.09	6.62	44.5	41.31	40.47	-2.04
H2	44.5	35.70	32.95	-7.69	44.5	35.91	32.82	-8.61
H3	44.5	38.51	39.67	3.00	44.5	38.20	39.60	3.65
H4	44.5	35.71	34.75	-2.70	44.5	36.19	34.70	-4.11
D1	44.5	41.80	41.68	-0.28	44.5	41.36	41.46	0.25
D2	44.5	39.60	38.90	-1.77	44.5	40.05	38.66	-3.47
D3	44.5	42.61	42.54	-0.17	44.5	41.80	42.26	1.11

Table 3 Comparison of final geometry taken from experiments and simulation [2]

	HIP cycle 1: HIP + Quenching			HIP cycle 2: HIP + Slow cooling	
	Martensite %	Austenite %	Bainite %	Perlite %	Austenite %
XRD analysis	82.7	17.3 ± 1.4	-	99.4	0.6 ± 0.65
Simulation	83.8	11.4	4.8	-	-

Table 4 Comparison of phase fractions obtained from experiment and simulation [2]

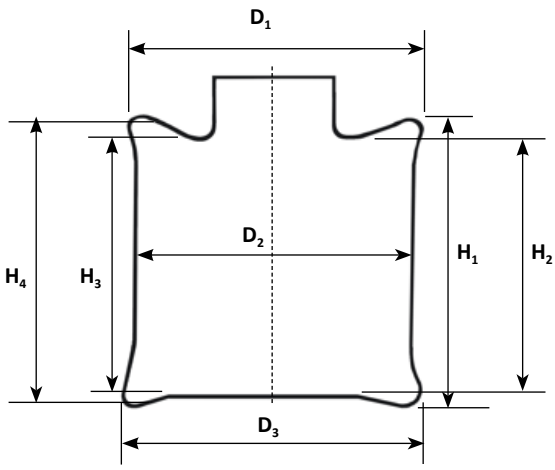


Fig. 9 Measurement points (MP) [2]

model was active until the end of the HIP holding time. Then the relative density was assumed to be 100%, so that capsule and filled powder could be considered as one solid part. The second step was simulated with the quenching model, which calculated the cooling stage down to room temperature. The material properties were taken from published data and from previous studies.

Deformation caused by anisotropic shrinkage was investigated after HIP experimentation and simulation. The results for HIP cycles 1 and 2 are presented in Table 3. Fig. 9 shows the characteristic positions in a schematic sketch. Deviations between simulation and experiment occur especially around the corners due to the welding seams.

The simulation of quenching predicted the phase volume fractions of martensite, retained austenite and bainite obtained after HIP cycle 1 (Table 4). The fraction of martensite was consistent with the results of XRD analysis. However, as the XRD analysis only considered martensite and austenite but not bainite, this explains the differences in austenite and bainite contents. HIP cycle 2 resulted in a purely pearlitic microstructure.

The different phase transformations in HIP cycle 1 and HIP cycle 2 could also be seen in hardness measurements. The primary martensitic microstructure is much harder than the pearlite microstructure of HIP cycle 2. Both hardness profiles showed only minor fluctuations, indicating quite a homogeneous microstructure.

Computational Fluid Dynamics (CFD) simulation was performed to predict the cooling performance of the HIP unit. This was coupled with the quenching model by transferring the sample surface to the FEM simulation as the shell model, which was linked with a contact condition to the part. Then the temperature profile was calculated by considering the heat transfer coefficients of the sample surface and was provided to the quenching model. As a first step, the connection to the submodel was examined by calculating the profile using a constant heat transfer coefficient. The simulation

of the temperature profiles in the FEM model and their transfer to the quenching sub-model resulted in the same temperature distribution (see Fig. 10). On the basis of this simulation, the connection of the two models was successful.

The authors' major conclusion was that the quantitative comparison of the simulated and experimental results showed only small deviations caused by welding seams, friction and inhomogeneous density distribution. In relation to proposed future work, the described model could be complemented by determining creep parameters to specify the viscoplastic model to predict the densification process. In addition, the influence of pressure on phase transformation should be investigated.

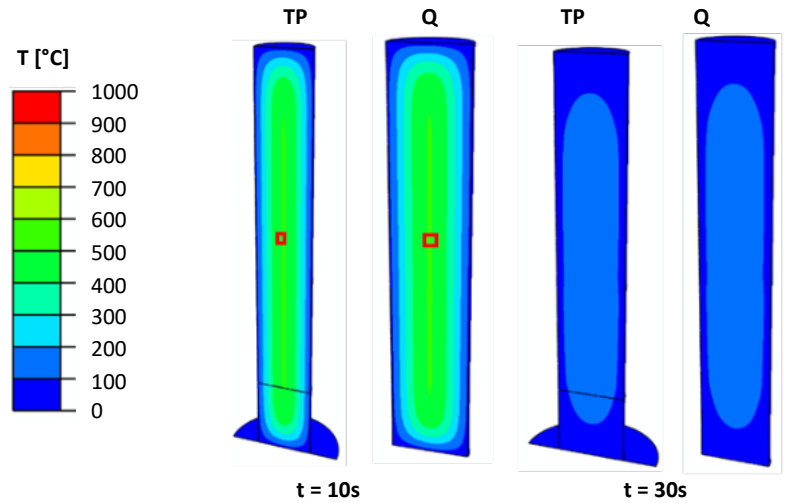


Fig. 10 Temperature distribution calculated by temperature profile (TP) and transferred to the quenching model (Q) [2]

Influence of the W-particle size on the densification and diffusion behaviour of CrSiW

This contribution came from Wolfgang Tillmann, Alexander Fehr and Mark Heringhaus (Technical University of Dortmund, Germany) and addressed the influence of W particle size on the densification and diffusion behaviour of CrSiW [3].

The production of CrSiW systems by conventional processing is restricted by the significantly diverging melting points and the high oxygen affinity of each of the individual elements. Powder metallurgical production therefore offers considerable advantages, such as an implementation of the process under inert atmosphere to avoid oxidation.

This presented paper analysed the influences of two different W particle size modifications (3 and 0.8 µm) on the diffusion and porosity of hot pressed CrSiW, by varying the temperature, pressure and sintering time. Two mixtures of 60Cr10Si30W (wt.%) were prepared by means of high-energy milling. With reference to the sintering mechanisms, the corresponding interface reactions, which take place at the W particle boundaries, are of particular interest. It was therefore the aim of this paper to investigate the diffusion between Cr and W, since these elements tend to form two solid solutions due to a miscibility gap in the binary phase diagram of Cr W for 20 ≤ W ≤ 98 (wt.%).

Elemental powders (Table 5) were used for the high energy milling (HEM) of the two CrSiW systems with different W particle sizes. To identify possible impurities in the elemental powders in advance, the chemical composition was determined by means of energy dispersive X-ray spectroscopy (EDX). Based on the weight percentage ratio of 60Cr10Si30W, the powders were mechanically mixed in a planetary ball mill, using hardened steel vials and Al_2O_3 balls as milling media with a ball-to-powder ratio of 4:1 (wt.%). Two $CrSiW_{coarse}$ and $CrSiW_{fine}$ powder mixtures, each 111 g with differing W particle sizes (Table 5), were mixed in a turbula mixer for 1 h prior to the HEM process, which was set to 2 h. All milling experiments were conducted using 0.5 wt.% n-heptane as a process control agent (PCA) and with a constant milling speed of 200 revs/min.

A graphite die with 16 cylindrical cavities (15 mm diameter each) with upper and lower punches was used for the hot pressing process. Each cavity was filled with 6 g powder. Based on previous hot pressing investigations of CrSiW,

	Particle size	Chem. Composition [wt.-%]				
	[µm]	Cr	Si	W	O	Fe
Cr	< 45	100				
Si	< 10		95.47±0.67		4.5 ± 0.67	
W_{coarse}	3			100		
W_{fine}	0.7-0.9			98.19±0.5	1.4±0.4	0.5±0.07

Table 5 Details of the powders used [3]

Parameter	Pressure [MPa]	Temperature [°C]	Sintering Time [min]
	5.2	1160	20

Table 6 Sintering parameters, each for $CrSiW_{coarse}$ and $CrSiW_{fine}$ [3]

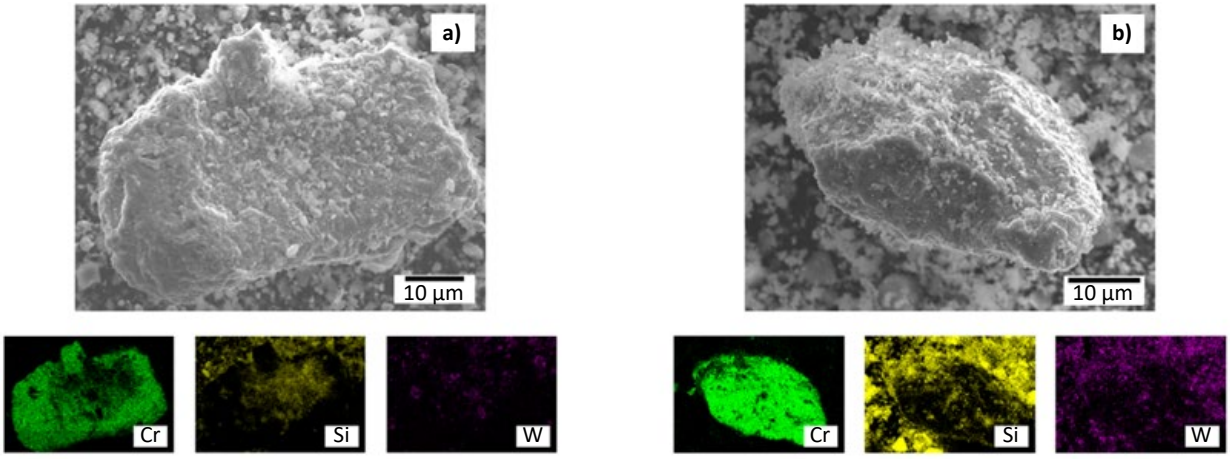
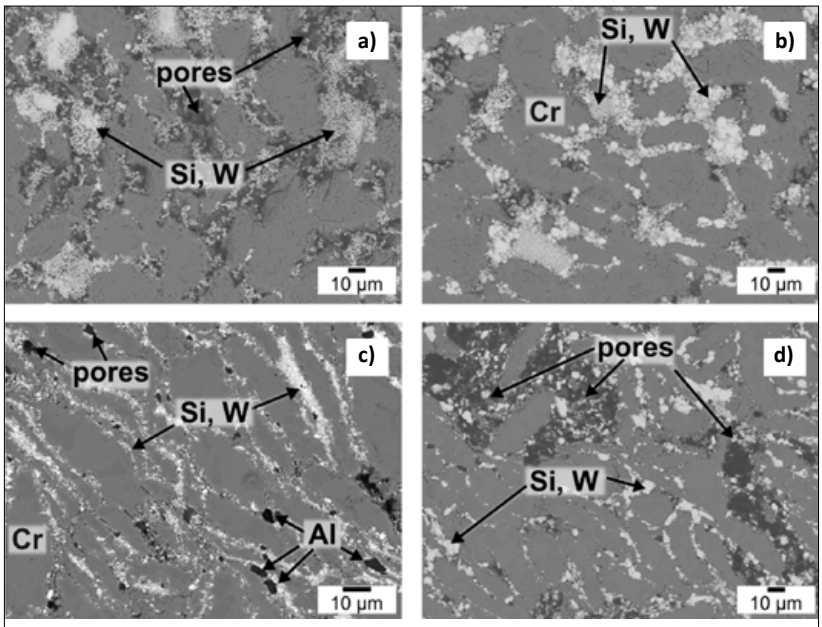


Fig. 11 SEM and EDX images of a) $CrSiW_{coarse}$ and b) $CrSiW_{fine}$ particles, both mechanically milled for 2 h [3]

the experimental setup, summarised in Table 6, was implemented for both $CrSiW_{coarse}$ and $CrSiW_{fine}$, using a sintering press. The HEM powders were analysed using a field emission scanning electron microscope in combination with EDX analyses.

Fig. 11 shows SEM images of the HEM particles of the $CrSiW_{coarse}$ and $CrSiW_{fine}$ powders. Both images show rounded structures of partially alloyed chromium particles. Since the chromium powder has, in general, the largest particle size (see Table 5), silicon and tungsten particles are preferentially cold welded onto the surface of the Cr particles. Furthermore, in the SEM images, some isolated silicon and tungsten powder particles could still be detected around the alloyed chromium particles. Nonetheless, the chromium particles were completely covered with tungsten, this observation being especially clear for CrSiWfine. It was concluded that the PCA partially lowered the impact energy and therefore impeded both cold welding and fracturing of the particles. This becomes more fully obvious when comparing the initial Cr powder particle size (< 45 µm) to the powder particle size after the mechanical milling process. Diameter measurements of the alloyed particles revealed a diameter increase of approximately 16 µm that can be traced back to the milling process with Si and W.

As mechanical milling leads to both a refined particle size and finer particle distributions, the fine tungsten powder in CrSiWfine causes an even finer distribution of tungsten, as already indicated. An analysis of the chemical composition by means of EDX (Table 5) further revealed an increased amount of fine tungsten particles in $CrSiW_{fine}$ compared to the $CrSiW_{coarse}$ powder. In general, the Cr weight percentage is depleted, since the Cr particles are coated with tungsten after HEM. Besides Cr, Si, and W, aluminium and iron impurities were found in the alloyed powders. These impurities were a result of collisions of the Al_2O_3 balls with the hardened steel grinding bowl



Specimen	HEM-time	W-particle size
a)	0 h	0.8 µm
b)	0 h	3 µm
c)	2 h	0.8 µm
d)	2 h	3 µm

Fig. 12 SEM images of sintered powder blends [3]

used that triggered slight particle abrasions. As already indicated in previously reported literature, the milling time plays a decisive role in this context, ensuring that the powder blend is not contaminated by substances abraded from the milling media.

The microstructures of the hot pressed $CrSiW_{fine}$ and $CrSiW_{coarse}$ powders were investigated by means of SEM in combination with EDX (see Fig. 12) to analyse the particle distribution with regard to diffusion behaviour. Depending on the milling time as well as on the tungsten particle size, significant differences in the development of the microstructure could be detected. Compared to the pre-alloyed powders, the solely blended powders exhibited an inhomogeneous distribution of silicon/tungsten agglomerations at the boundaries of the chromium particles. In general, silicon and tungsten both tended to fill the spaces around the chromium grain boundaries.

One reason for this was the larger particle size of chromium particles (see Table 5) in comparison to the silicon and tungsten powders.
The SEM images of sintered HEM powders, however, showed Cr grains that were homogenously enclosed by Si/W. Smaller tungsten particle sizes obviously led to significantly thinner aggregations, which accumulate at the Cr particles. Furthermore, pores could be mainly found next to Si/W agglomerations. Powders, prepared by solely mixing prior to sintering, had a tendency to form sintering necks between Cr and Si/W. These regions, however, were predominantly surrounded by pores, which impeded the formation of solid solutions between Cr and W. In contrast to this, mechanical milling of the 60Cr10Si30W helped to generate sintering necks, contributing to an enhanced grain growth. Additionally, a pressure of 5.2 MPa and a temperature of 1160°C during hot pressing generally contributed to densification.

Fig. 12 c) shows examples of the Al_2O_3 impurities caused by the abrasion of the milling balls. These impurities were already identified in the EDX analyses of mechanically milled powders (see Table 7). In addition, EDX analyses as area scans were conducted on the sintered CrSiW compounds to investigate their chemical composition (Fig. 13) and to compare them to the initial composition. The weight percentage composition of the solely mixed powders after sintering corresponded fairly closely with the initial 60Cr10Si30W composition. The Cr content was almost 60 wt.%, whereas the Si and W contents by differ about ± 6 wt.% compared with the original powder composition.

These deviations can be attributed to segregation effects of Si/W, which were already identified in Figs 11 a) and 10 b).The EDX analyses of specimens that were mechanically milled for 2 h prior to sintering further confirmed the previously found Al_2O_3 impurities of approximately 1.2% (see Table 7). Also, the Cr content of these specimens was slightly above 60 wt.%, although it was depleted after HEM. The tungsten content was about 5 wt.% lower than in the initial composition. Independent of the milling process prior to sintering, the Si content varied by approximately ± 2-5 wt.%, indicating that silicon leads to segregation.
As indicated in the analyses of the mechanically milled powders, HEM contributed to the refinement of particles in general and finely dispersed Si and W particles on the Cr particles; however, Si and W particles still remained in elemental form around the alloyed Cr particles (Fig. 11). These isolated particles generated occasional segregation, which was responsible for the differing silicon and tungsten proportions in Fig. 13 when compared to the initial 60Cr10Si30W composition.

	Cr	Si	W	Al	Fe
$CrSiW_{coarse}$	31.17 ± 14.7	36.57 ± 7.68	24.42 ± 6.82	1.22 ± 0.27	0.6 ± 0.1
$CrSiW_{fine}$	36.5 ± 9.64	19.86 ± 4.85	41.87 ± 5.06	1.14 ± 0.39	0.62 ± 0.17

Table 7 EDX particle analyses of alloyed powders (wt.%) [3]

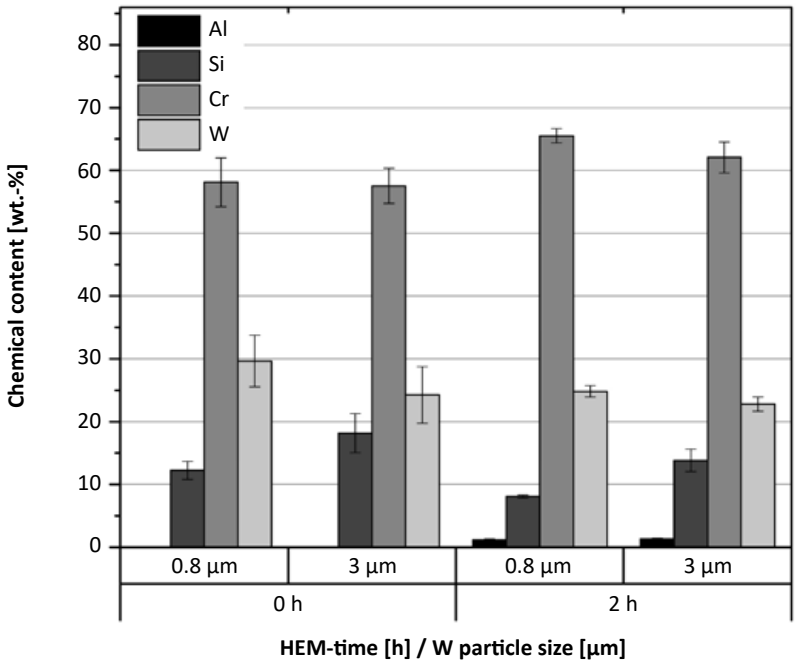


Fig. 13 Chemical composition of sintered 60Cr10Si30W compounds [3]

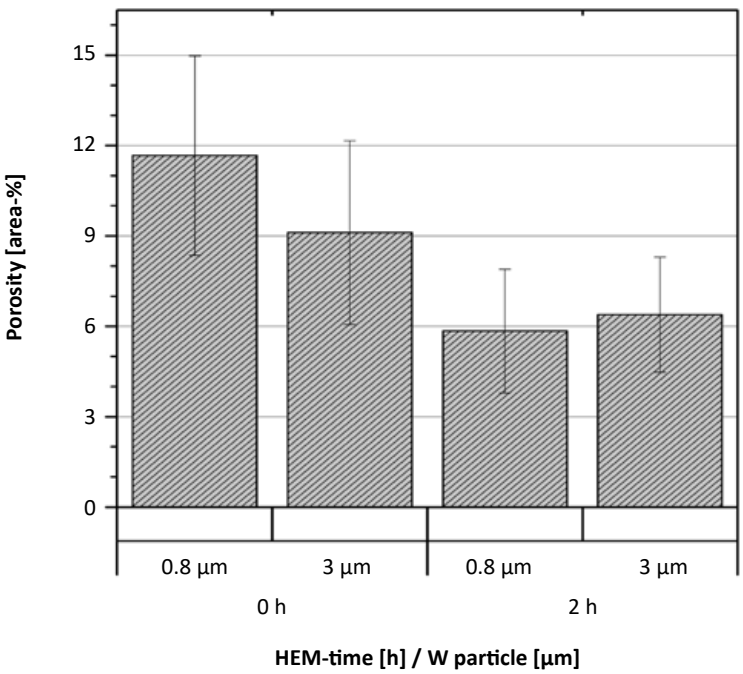


Fig. 14 Porosity of 60Cr10Si30W as a function of the mechanical milling time and tungsten particle size [3]

The densification of 60Cr10Si30W, as a function of the HEM time and the different W particle sizes, was investigated. Fig. 14 shows the resulting porosity values. In general, the porosity ranged from 5.8 to 11.6 area%. In comparison to the solely mixed powders, high energy milling for 2 h helped to reduce porous areas by approximately 3% (see Fig. 14). In general, the tungsten particle size was of significance in relation to agglomeration processes. During mixing, insufficient energy is introduced to distribute the powder particles homogeneously, especially for fine W particles (0.8 µm). On the other hand, after HEM, the fine W powders induced a more homogenous particle distribution and had a greater sintering activity than coarse powders. This fact is consistent with the porosity measurements. The highest densification could be achieved with a tungsten particle size of 0.8 µm and by milling for 2 h. As already revealed in the EDX analyses of the mechanically milled powder particles (Table 7), the finer tungsten particles were distributed more evenly on the surface of the chromium particles. This prevented particle agglomeration at the chromium grain boundaries that were, in turn, surrounded by pores.

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[2] FEM simulation of consolidation and microstructure development during PM-HIP of cold work tool steel D7, Carola Birke, *et al.* As presented at the Euro PM2018 Congress, Bilbao, Spain, October 14-18, 2018, and published in the proceedings by the European Powder Metallurgy Association (EPMA).

[3] Influence of the W-particle size on the densification and diffusion behaviour of CrSiW, Wolfgang Tillmann, *et al.* As presented at the Euro PM2018 Congress, Bilbao, Spain, October 14-18, 2018, and published in the proceedings by the European Powder Metallurgy Association (EPMA).

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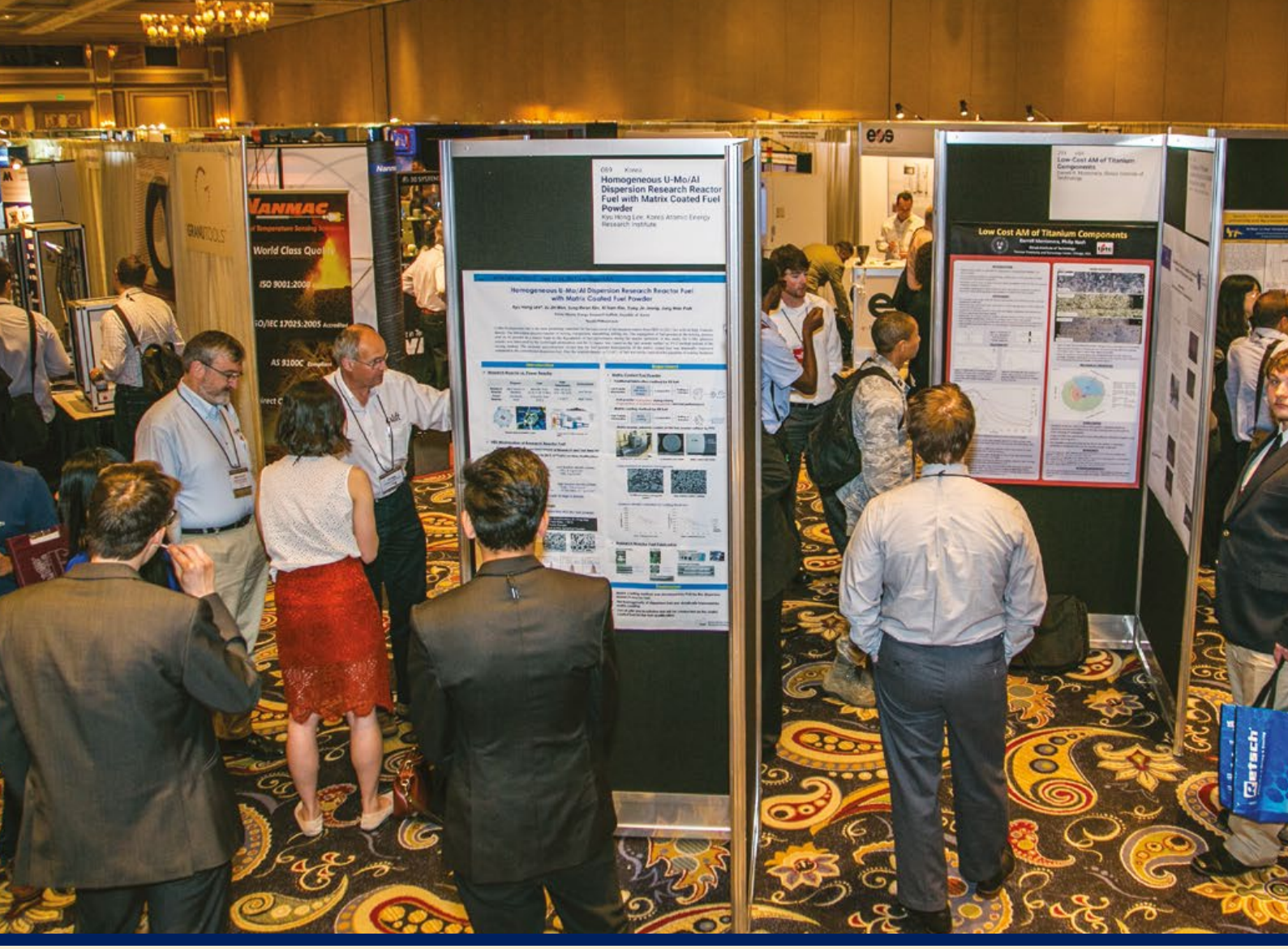

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Hagen Symposium: How Powder Metallurgy can meet the needs of a changing market

The annual PM symposium at Hagen, Germany, organised by Fachverband Pulvermetallurgie, brings together the German-speaking PM community for two days filled with technical presentations on all sectors of PM technology, an accompanying exhibition of PM raw materials and equipment suppliers and a social event on the eve of the conference. This year, the Hagen Symposium welcomed 200 participants and 51 exhibitors, and for the first time, a day of practical training with workshops on compaction, sintering and inspection was offered in conjunction with the symposium programme. Dr Georg Schlieper visited the symposium on behalf of *PM Review*.

Traditionally, the Hagen Symposium opens with the Skaupy lecture. This is an honorary prize awarded by the German Powder Metallurgy Association (Fachverband) to a person specialising in Powder Metallurgy. This year, Dr Thomas Weissgärber was honoured for special merits in his discipline. Presenting the award, Heinrich Kestler of Plansee in Reutte, Austria, paid tribute to the private and professional career of the prize recipient, which began in communist East Germany and, after the collapse of the Eastern Bloc, led to a position at the Fraunhofer Institute IFAM in Dresden, Germany. The Skaupy Certificate was presented to him by Prof Herbert Danninger, Chairman of the PM Committee of the PM Association, in the presence of Heinrich Kestler (Fig. 1).

In his Skaupy presentation, Thomas Weissgärber focused on processes and applications for metal matrix composites (MMC) with functional properties. When manufacturing these materials, PM's ability to combine very different components that cannot be combined in other processes, such as metals and ceramics, is often exploited. In PM technology, material properties can be specifically influenced and adapted to the technical requirements of the application. Excerpts from Weissgärber's paper and other presentations given at the symposium are featured below.

Dispersion-strengthened materials

Metal matrix composites are typically applied at elevated temperatures. Since the deformation behaviour at high temperatures by creep is mainly determined by the migration of dislocations, the most significant

Fig. 1 Thomas Weissgärber (centre) received the Skaupy Certificate from Herbert Danninger (left) and Heinrich Kestler (Courtesy Fachverband)

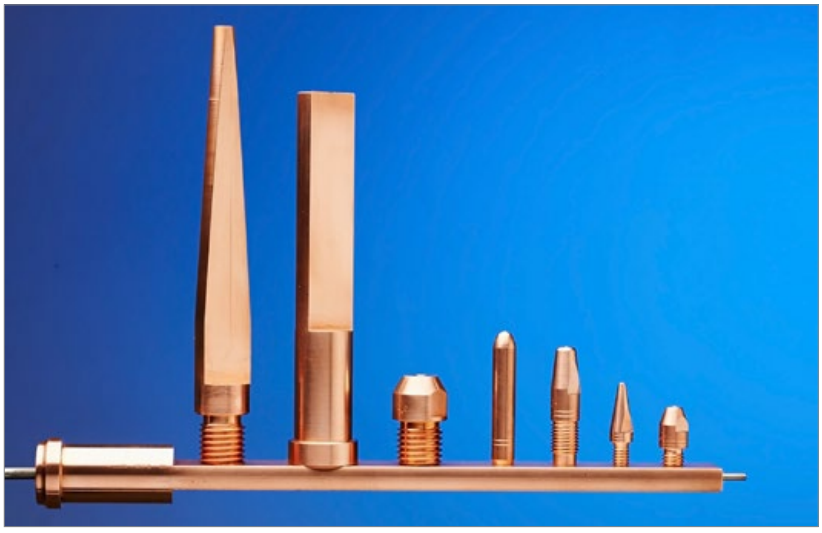

Fig. 2 High-voltage contacts for welding units made from dispersion-strengthened copper (Courtesy CEP - Compound Extrusion Products GmbH)

increase in strength is achieved by second phase particles that are barriers for dislocations, with dispersion-hardened alloys having the highest strengthening potential. The technical route to dispersion-strengthened materials usually involves high-energy milling. For example, dispersion-strengthened nickel, iron, aluminium and copper powders can be produced using this method. The powders are consolidated either by extrusion or plasma spark sintering.

For the production of copper alloys with high heat resistance combined with good electrical and thermal conductivity, the principle of dispersion hardening is of some interest. Today, the process is used for industrial products, such as in welding technology, for profiles in high-field magnets and for high-voltage contacts (Fig. 2). The method of incorporating the dispersoids influences the nature of the dispersoid-matrix interface; high-energy milling of pre-alloyed Cu(Ti) powder and graphite followed by heat treatment leads to a finely dispersed distribution of TiC dispersoids (d_{50} = 10–20 nm) and to the formation of a semi-coherent interface between TiC and Cu. In addition to a comparatively high strength at room temperature, the extruded composite exhibits a significant increase in creep resistance.

Weissgärber continued that dispersion-strengthened ferritic-martensitic steels are of interest for applications in power engineering, especially for nuclear fusion reactors and fourth generation fission reactors. Components in these systems are exposed not only to high temperatures and mechanical loads, but also to neutron irradiation. The interaction of the neutrons with the lattice atoms leads to radiation damage and consequently to changes in the mechanical properties (e.g., embrittlement). The radiation damage itself cannot be prevented; however, certain structural constituents can counteract this damage. Sinks for radiation-induced lattice defects in dispersion-strengthened steels are the grain boundaries and the oxide particles (or particle-matrix interfaces). Since oxide dispersion hardening tends to reduce the matrix grain size, the impact of the two effects is difficult to separate. For the Fe-14Cr alloy dispersion strengthened with Y_2O_3, a reduction in irradiation-induced hardening compared to the dispersoid-free Fe-14Cr alloy has been demonstrated. Electron Beam Backscatter Diffraction (EBSD) images show significant differences in grain size. The dispersion strengthened alloy (Fig. 3, right) is characterised by a very fine grain size which is equivalent to a large number of grain boundaries, and the presence of the dispersoid phase.

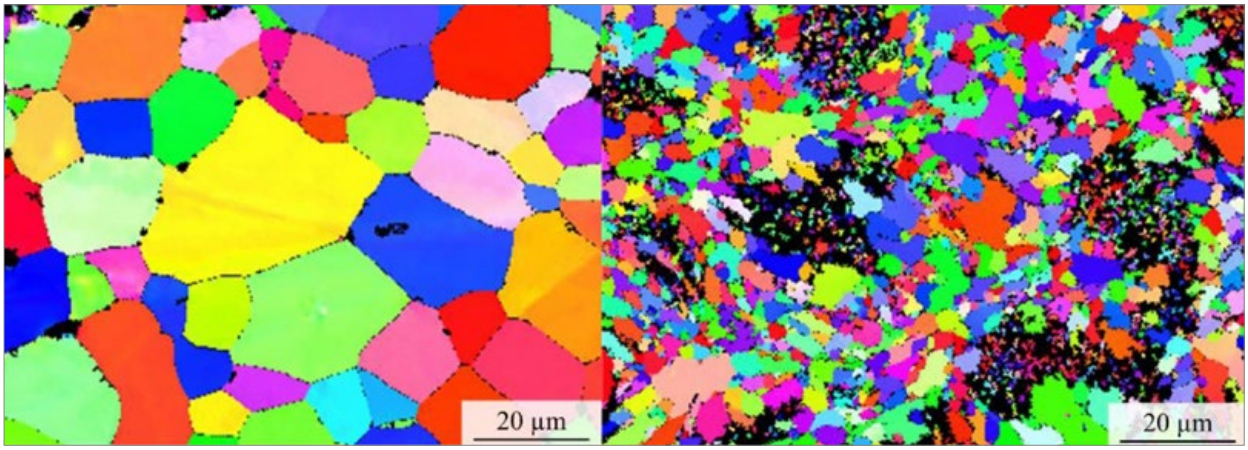

Fig. 3 EBSD images of Fe-14Cr alloy (left) and the same alloy dispersion strengthened with Y_2O_3 (Courtesy IFAM)

Fig. 4 Lever arm (right) and SPS preform made from AlSi7Mg0,6+35 vol-% SiC (Courtesy Fraunhofer IFAM)

Composite materials for electronic systems

The thermal management of power electronic systems requires materials with a high thermal conductivity as cooling elements. Different thermal expansion coefficients of the components may cause thermally-induced stress or distortion. Increased thermal conductivity is desirable for a number of applications, such as in optoelectronics or power electronics in electric mobility, and a number of composites have been developed in recent years. The metallic matrix used is aluminium, copper or silver. For the reinforcement phase, various carbon modifications (graphite, diamond, carbon fibres), but also SiC or Si particles, are selected. The interfaces between the reinforcement phase and the matrix determine the macroscopic properties. The reinforcing constituent can only be fully exploited if the interface is optimised towards high adhesion and minimum thermal interface resistance.

Aluminium is characterised by its low specific weight and excellent corrosion resistance, but it is relatively soft and has limited strength. Particle reinforcement is the solution for aluminium composites with high strength and wear resistance. Weissgärber presented a lever arm made from AlSi7Mg0,6 + 35 vol-% SiC (Fig. 4).

Spark Plasma Sintering (SPS) enables the compaction of aluminium powder mixtures with high proportions of reinforcing particles. The relative density of the semi-finished products produced by SPS is close to 100%, but the surfaces of the aluminium particles are coated with oxide, resulting in low mechanical strength. In addition, there are process-related limitations in the shape complexity of the manufactured parts, which is why another shaping step, known as thixoforging, was performed. A lever arm was prototypically produced from the SPS preform. The residual porosity in the sintered, semi-finished product could be completely eliminated during the thixoforging process and the reinforcing particles are present in a homogeneous distribution in the final component. In addition to a particle reinforcement, short fibres can also be used, so that there are many options for material design in the future.

The future of PM structural parts

The profound changes that accompany the transition from fossil fuels to renewable energies, and their implications for the PM industry, were discussed in a presentation by Michael Krehl and co-author Volker Arnhold, both PM consultants.

"Many of these changes," said Krehl, "will affect the powertrain where 70–80% of the PM components are used today." The automotive powertrain, consisting of engine, gearbox and power transmission, is completely eliminated in the case of Electric Vehicles (EV) in favour of an electric motor. Those gearboxes that remain will be different to gearboxes

> *"Spark Plasma Sintering enables the compaction of aluminium powder mixtures with high proportions of reinforcing particles"*

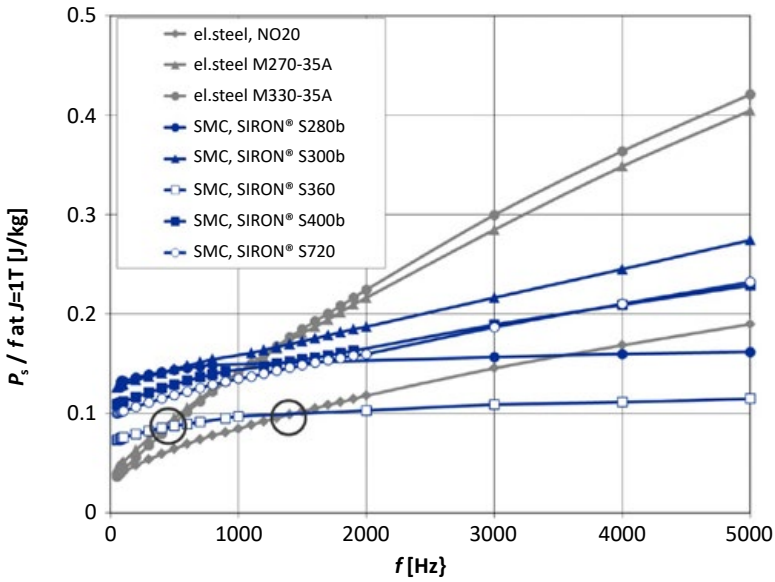

Fig. 5 Magnetic reversal losses of SMC vs electro-sheet (Courtesy Schoppa)

Fig. 6 Prototype SMC components for a transversal flux motor (Courtesy Schoppa)

seen in Internal Combustion Engine (ICE)-driven vehicles with complex multi-speed gearboxes. They will be mostly pure reduction gearboxes, or in some cases two-speed gearboxes.

The timing of this paradigm shift will depend on many factors, such as consumer behaviour, government support, political influence and the solution of remaining technical problems. Thus, a reliable forecast for when the full impact can be expected is hard to make. It is still unclear how much time it will take to build up the necessary infrastructure for electric vehicle charging, and who will pay for it. Not only will there be Battery-Electric Vehicles (BEVs), but also electric vehicles that generate the necessary electricity on board with fuel cells (FCV) using hydrogen (H_2) or synthetic fuels, and even vehicles with conventional engines which are powered by H_2 or synthetic fuels, and many kinds of hybrid vehicles (PHEV, HEV, etc).

"The condemnation of diesel technology is more damaging to the environment than it helps," stated Krehl, "because the decline in diesel fuel puts the attainment of the CO_2 targets fixed in the Paris Agreement into the far distance." Diesel cars consume significantly less fuel than gasoline-powered vehicles and therefore produce less CO_2 per route travelled. Nevertheless, the PM industry will have to adapt to the changing conditions.

In addition to PM applications in the powertrain, there are numerous applications inside and outside the automobile that will not be affected by the paradigm shift of individual mobility, such as parts in vehicle chassis or in the interior, as well as non-automotive applications such as power tools, household appliances, electronic hardware, lawn and garden, recreational vehicles, construction and agricultural machinery and other off-highway vehicles where classical PM will continue to find buyers for many years and participate in their growth or even develop new components.

On the other hand, a share of about 60% of today's sintered part production is directly threatened by developments in the mobility sector, according to Krehl. This is why new developments for applications in electric vehicles are necessary, with a few already on the way.

Soft magnetic components

Krehl sees good opportunities for PM Soft Magnetic Composites (SMC) in electrotechnical applications at higher frequencies. The topic of soft magnetic PM materials was discussed in more depth by Andreas Schoppa in a separate lecture. Schoppa stated that about 18.5 million tons of soft magnetic materials are produced every year. Electrical sheets represent the largest proportion of the magnetic materials market, at 95.5%. All other soft magnetic materials, i.e., Fe-Ni and Fe-Co alloys, amorphous and nanocrystalline materials, soft magnetic ferrites and sintered materials, and the soft magnetic powder composite materials (SMC) are contained in the remaining 4.5%. Although the SMC materials represent only a small proportion of the market, the use of these materials in electric drives can contribute significantly to efficiency improvement, and at the same time lead to an increase in

power density and reduction of manufacturing costs.

Magnetic reversal losses in electrical drives at elevated frequencies are dominated by eddy current losses. The unique PM soft magnetic material SMC is made up of metal powder particles which are electrically isolated by either oxide layers or organic binders. This structure reduces eddy current losses. Fig. 5 shows a comparison of the magnetic reversal losses of electrical sheet and SMC materials. At low frequencies, the electrical steel sheets are superior, but with increasing frequency, the losses of the electrical steel sheets grow stronger than those of the SMC materials, so that, beginning at 500 Hz, the SMC materials have the advantage.

Schoppa identified the maximum benefit of SMC materials in Axial Flux Motors (AFM) and Transversal Flux Motors (TFM). These machines have the highest torque density and at the same time the best efficiency. Weaknesses of these machines, however, are their complex control electronics, lack of 'technical maturity' and a complicated and expensive manufacturing process if the components are manufactured on a conventional basis from electrical sheet; sheets can guide the magnetic flux only in two dimensions, and complicated punching and joining operations are necessary to guide the magnetic flux in the third dimension. These processes generate stresses and deformations that adversely affect the magnetic properties of the materials used. The stamping process also creates a significant amount of scrap. By using PM technology, components can be created that solve these problems. This is illustrated in Fig. 6 for a transversal flux motor.

High-strength PM components

Krehl also noted that manufacturers of PM structural components have been able to increase the fatigue properties of their products in recent years. This was achieved by the post-sintering densification of near-surface areas. It is well known that fatigue fractures typically result from cracking at the surface. The densification of sintered components at functional surfaces provides fatigue properties comparable to those of wrought steels. Surface disintegration by wear on tooth flanks (peeling) is caused by stress peaks just below the surface, and a fully densified surface to a depth of approximately 1 mm also largely eliminates these problems (Fig. 7).

There are several approaches to densifying functional surfaces of sintered compacts, such as rolling or drawing, all of which give approximately the same results. Thus, materials and processes are available which are outstandingly suitable for the production of high-strength components, such as load-bearing gear wheels. The proof that such gears also work in real vehicle transmissions has been provided by a consortium of several parts manufacturers together with a powder manufacturer. After a passenger car series gearbox had been equipped with PM gears, the performance of the PM wheels could be demonstrated not only on the test bench, but also on the road. This will give the PM industry a chance to substitute a further 5 kg of components per vehicle over the long term.

Computer simulation of case hardening

The profound changes that accompany the transition from fossil fuels to renewable energies and their implications for the PM industry were discussed in a presentation by Michael Krehl and co-author Volker Arnhold, both PM consultants.

Computer simulation of technical processes has received increasing interest in recent years. Ali Rajaei of the Technical University Aachen, Germany, looked at problems associated with heat treatment of gears with surface densified teeth. The primary challenge in the process adjustment for surface-compacted PM gears is the graded porosity. The compacted portion of the gear cannot be carburised as desired without excessive carbon build-up at the porous side surfaces of the gear. One solution could be to use other carburising technologies such as Low Pressure Carburising (LPC). The results of LPC

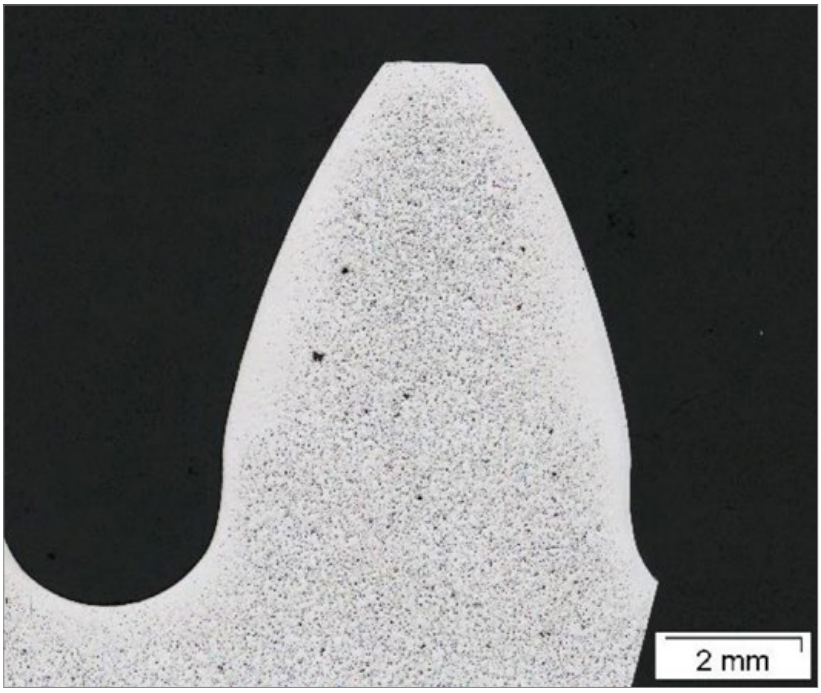

Fig. 7 Cross-section of a surface-densified PM gear (Courtesy Ali Rajaei, Technical University Aachen)

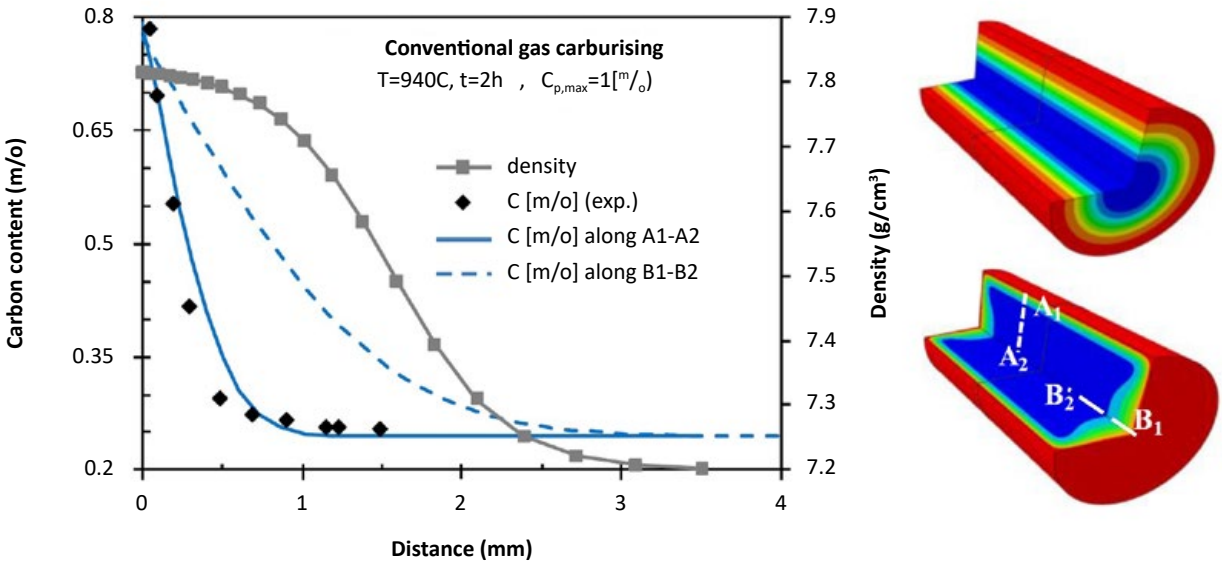

Fig. 8 Gas carburising experiment and computer model (Courtesy Ali Rajaei, Technical University Aachen)

experiments with acetylene at the Technical University Vienna, Austria, showed that the carburisation depth in LPC is much less dependent on porosity than conventional gas carburising. During quenching, temperature gradients and inhomogeneous local phase transformations induce local internal stresses, so that residual stresses remain in the component after hardening. The residual stress state after heat treatment has a significant influence on the fatigue resistance of the gears. A comprehensive study of the effects of porosity, carbon content and hardenability, together with a knowledge of the residual stresses, forms the basis for optimising the fatigue strength of PM gearboxes.

Rajaei developed a numerical model of the processes associated with the case hardening of PM gears. In a first step, carbon distribution is analysed in the carburised gear. The solubility of carbon in austenite and the diffusion coefficient are the required material data for this calculation. Solubility is defined by the iron-carbon diagram as a function of temperature. The effect of the other alloying elements was considered negligible. The diffusion mechanism of the fully dense material is volume diffusion and the open porosity causes an additional diffusion mechanism, i.e., surface diffusion. The model was quite consistent with an experiment in which a cylindrical sample with a solid surface was carburised (Fig. 8).

" The yield strength depends not only on temperature and density, but also on carbon content and microstructure"

The calculated carbon distribution is then transferred to the second step, the thermomechanical analysis of the quenched product. Heat transfer is the main cause of triggering other physical processes during quenching. The temperature change is the driving force of the phase transformations which are associated with volume changes and conversion strains. Temperature gradients due to rapid cooling induce thermal stresses. The rate of heat transfer depends on the quench media and the thermophysical processes occurring at the gas-component interfaces. In most cases, after the LPC, a High Pressure Gas Quench (HPGQ) is used, which has some advantages over conventional gas carburising combined with oil hardening. For example, the cycle times for the LPC-HPGQ are shorter and cleaner, and the results are oil-free components with less distortion. This is accompanied by a reduction in the heat treatment costs.

A possible disadvantage of HPGQ, however, is that the quench rates are often insufficient to achieve a fully martensitic microstructure in the carburised area. Both quenching processes can be modelled by defining the corresponding heat transfer coefficients (HTC) as boundary conditions. The thermal conductivity and the specific heat capacity were defined depending on the temperature. The modulus of elasticity was further described in terms of temperature and density. The yield strength depends not only on temperature and density, but also on carbon content and micro-

structure. Tempering transforms the martensitic structure into a more stable state. This process is associated with changes in hardness, toughness and strength.

Carbon content, microstructure and residual stresses were simulated for two processes: conventional gas carburising in combination with oil hardening and LPC, followed by HPGQ. The results were then qualitatively compared. A quantitative conclusion has not been drawn due to partly incomplete process data, which were previously taken from the literature for the execution of the simulations. The calculated carburisation shows the same carburising depth for both processes in the densified area of the gear cross-section, suggesting that densification may limit the carbon diffusion under gas carburisation. However, the carburising depth in the porous region is higher in conventional gas carburising. During LPC, the inner bore and face surfaces absorb a higher amount of carbon, but the carburising depth is not affected by the porosity.

Fig. 9 shows as an example the simulated homogenised phase composition on the tooth surface and two cut surfaces after the LPC-HPGQ process. The transformation of austenite into bainite and martensite depends on the carbon content and the cooling rate. Due to the lower cooling rates of gas quenching compared to quenching in oil, a higher bainite content is expected here.

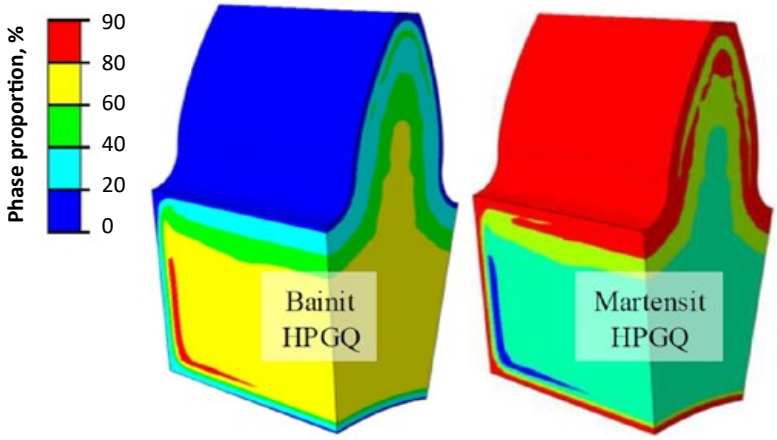

Fig. 9 Calculated phase proportions after LPC-HPGQ heat treatment (Courtesy Rajaei)

New PM steels

Krehl expects that today's PM steels, traditionally based almost exclusively on the alloying elements Cu, Ni and Mo, will be partially replaced by other alloying elements in the future. Formerly, common sintering processes in industrial belt furnaces (Tmax about 1150°C) with carburising, decarburising or neutral atmospheres made the use of Cu, Ni and Mo as alloying elements necessary. The prices of these elements were also relatively constant, apart from intermittent speculative influences. In today's advanced furnaces (Tmax up to 1280°C), under N_2/H_2 atmospheres, the classical alloying elements of conventional steels (i.e., Cr, Mn, Si, V) can be controlled and will be increasingly applied. The costs for these alloying elements are lower, and more critical elements such as Ni or Cu (water protection) can be avoided or reduced from the point of view of occupational safety (according to the REACH regulation). From the viewpoint of a very strong demand in new batteries, Ni is to be viewed critically as an increasingly strategic metal. Significant cost increases are forecast for Ni, Cu and Co.

These excerpts represent only a subjective selection from the rich programme of the Hagen Symposium, which will hopefully coincide with the interests of our readers.

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