We are in unprecedented times. However, these are the times when agility, resilience and innovation of our people define our businesses.

At Rio Tinto Metal Powders we have implemented social distancing measures, promoted good hygiene habits and applied new site access requirements including body temperature measurements. Furthermore, at our Technology Centre in Sorel-Tracy, we produced hand sanitizer to keep our employees and communities’ safe – even supplying paramedics. We also donated hundreds of N95 masks to the local hospital.

These initiatives make Rio Tinto a part of the solution in the fight against COVID-19. If you are proud of your initiatives, please send us details and we will publish them in our next Customer Bulletin. We are all in this together, and it is through teamwork and innovation that we will rise to the challenge. Please feel free to contact your regional sales representative should you have any concerns during the COVID-19 crisis or email us at info.qmp@riotinto.com
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Cover: Multilayer coating on hardmetal. Photo courtesy Herbert Danninger, FAPMI, and Boehlerit GmbH.
I am writing this Editor’s Note at a time when many of us are in stay-at-home mode as a consequence of the COVID–19 pandemic. The co-located WorldPM2020/AMPM2020/Tungsten2020 conferences, due to be held in Montréal in June, have understandably been cancelled, so we will not be getting together to exchange information on the latest advances in powder metallurgy (PM) technology. I hope that this issue of the Journal, in which we have compiled articles that provide an update on PM activities in many parts of the world, will be of interest to our readers. Peter Johnson has also provided his annual Technology Trends article in which he indicates that while the COVID–19 pandemic has seriously impacted the global PM family, the industry’s technical muscle has never been stronger.

This week I participated via WebEx in various subcommittee meetings of ASTM Committee B09 that covers standards related to PM and PM products. We will hold the next meetings of the MPIF and MPPA Standards Committees scheduled for August via videoconference if travel and meeting restrictions are still in place. Having this technology will help with some activities during these troubling times. Nevertheless, I really look forward to being able to meet my friends and colleagues in the PM community face-to-face once again.
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METAL POWDER & MATERIALS DEVELOPMENTS

Hoeganaes Corporation (Hoeganaes.com), Cinnaminson, New Jersey, offers high-performance material solutions, reports Kylan McQuaig, global R&D manager. Established binder-treated premixes have recently shown additional benefits such as improved part-to-part consistency and overall cleanliness, and compaction improvements through ANCORBOND processing. For example, a specialized material with high-apparent density provides much improved filling for thin-walled parts and much faster compacting stroke rates. Excellent part weight control can be maintained (Figure 1).

On another note, cost-effective alloys are out-performing the highest-performance PM materials. Alloying elements such as silicon and vanadium, when used in combination with high-temperature sintering, allow fine pearlitic microstructures that can be readily machined and/or sized.

GKN Hoeganaes is busy developing large-scale, single-powder lot capabilities for low-pressure water-atomized additive manufacturing (AM) materials at its facility in Buzau, Romania. The powders are screened for AM particle-size ranges. Although not spherical, the powders flow and spread for use on most printer platforms. Low-alloy steel 4600 series powders are now feasible for AM applications. For example, AM-printed 4605 provides ultimate tensile strength and hardness ratings comparable to heat-treated PM data in MPIF Standard 35. Another AM powder application is component repair using direct energy deposition (DED).

Kalathur Narasimhan, former vice president of R&D at Hoeganaes and currently vice president of P2P Technologies, Moorestown, New Jersey, has developed an iron and alloy powder that enables a density comparable to warm compaction with no heated tools (Figure 2). He is also investigating applying 3D printing to magnetic materials for motors, inductors, and transformers for electric vehicles.

North American Höganäs, Hollsopple, Pennsylvania (hoganas.com), is focusing on advanced machinability additives (SM3 and SM4) that offer a lowest cost solution for many PM parts, says Roland T. Warzel III, director, technical
services. The company’s machining development center works with customers to provide a link between the material system and machining operations to optimize the entire process. The center has completed projects achieving longer tool life and improving productivity by reducing machine cycle time.

Höganäs will also introduce Lube GS, its newest

Intralube® lubricant designed for higher green strength levels in as-compacted parts. It is zinc free and burns clean. Compared with a traditional amide wax lubricant, Lube GS improves green strength by 70% while maintaining similar ejection characteristics (Figures 3 & 4). The improved green strength increases the robustness of the manufacturing process by reducing the possibility of handling cracks at the compacting press. Green machining is also possible.

Tetsuya Sawayama, general manager, Steel Powder Division, Kobe Steel, Ltd. (Kobelco.com), Kobe, Japan, reports on important trends for the current decade such as new powders and parts for electrification applications. He sees the introduction of new simulation models for powder flow, mixing, and compaction.

New stearate-free lubricants for conventional medium to high-density PM compacting are being launched reports, Thomas Stephenson, powder growth products manager, metallics, Rio Tinto Metal Powders (qmp-powders.com), Sorel-Tracy (Québec), Canada. He stresses that these lubricants offer more stable compaction leading to a reduced weight scatter of parts achieved by a more stable flow rate. High-apparent density, excellent lubrication, and improved and stain-free part surface finishes are other benefits.

Rio Tinto Metal Powders (RTMP) reports increased interest in powders with low nonmetallic inclusion contents for fatigue-critical applications such as powder forging and roll densification.

The company is applying ATOMET 24, an existing product, for high green strength. Irregular particle morphology and increased roughness compared with regular water-atomized steel powders, improve the strength of green compacts.

RTMP is further developing soft magnetic composite (SMC) product mixes aimed at automotive parts to help PM parts makers meet legislative changes for clean emissions. OEMs are developing and experimenting with new engine designs based not only on using one type of magnetic material (SMCs, permanent magnets, or laminates), but on the optimum combination of these materials.

Responding to improved furnace technology, RTMP is working on lean prealloyed powder. These grades allow parts makers to attain high mechanical properties similar to more common highly alloyed sinter-hardening grades, but at significant cost savings. Selecting appropriate levels of alloying elements less detrimental to the compressibility of prealloyed steel can achieve high mechanical properties in sinter-hardened parts derived by combining powder hardenability and high part density.

Improving the machinability of PM steels by adding suitable machining enhancers can significantly reduce production costs. RTMP is working on improving machining additives without adversely affecting physical properties.

According to Roy Christensen, president of Valimet, Inc. (Valimet.com), Stockton, California, aluminum
powders could potentially become the largest growth material for additive manufacturing in the near future as customers explore aluminum’s environmentally friendly and lightweight characteristics. He expects exponential growth of Valimet’s current product line as users develop new techniques and post-processing steps addressing challenges with aluminum alloys for laser-bed applications. Although there has been growth and interest in all alloys, the company is focusing on AlSi10Mg and F357.

Valimet has implemented quality and production parameters to ensure less than 3 µm variations between lot distributions (Figure 5). The company is also developing new processes to provide better powder flow to improve spreadability and speed parts production.

Christensen sees steady growth of traditional aluminum applications in aerospace, defense, automotive, and industrial markets. Thermal spray and propellants will continue to provide stable applications for aluminum powder makers.

**PM EQUIPMENT TRENDS**

After more than nine years of research, Abbott Furnace (abbottfurnace.com), St. Marys, Pennsylvania, announces a new approach (called Vulcan) to remove lubricants from green compacts prior to sintering says Julianne Inzana, marketing coordinator. Abbott has delivered three Vulcan units (Figure 6) during the past year that remove conventional lubricants as well as Interlube E and Interlube HD. Based on weight loss studies, the company claims that the Vulcan process removes 100% of the lubricant.
The defining features of the process include independent heating control, atmosphere composition, and oxidation products. While a lubricant melts and flows from the compact, an amount of solid carbon drops out while the lubricants are heating. Even with an ideal heating profile, the carbon can be seen as soot on a part’s surface. The process introduces moisture into the atmosphere, independent of the furnace atmosphere. Tests on stainless steels show that controlling moisture allows the oxidation of the carbon without oxidizing the product.

Lisa Mercando, market manager, strategic marketing and development, at Air Products and Chemicals, Inc. (airproducts.com), Allentown, Pennsylvania, suggests that stressing the importance of nitrogen-hydrogen for continuous sintering furnaces, annealing, and brazing atmospheres, rarely considers verifying the hydrogen percentage analytically.

The continuous measurement and control of the furnace atmosphere is increasingly necessary to improve quality control, reduce costs, and comply with regulatory requirements and industry standards such as NADCAP and CQI-9. To this end, Air Products offers a compact gas-density sensor that can be installed in minutes in-situ or in sampling lines together with other sensors.

The company’s wireless data communication system combines temperature, dew point, and oxygen signals with gas sensor readings. The gas sensor can also support a dew point and/or oxygen sensor, which together can provide real-time value for the total reducing potential of the atmosphere (pH₂/H₂O).

It also enables operators to optimize hydrogen flows by providing a continuous atmosphere control function to adjust flow rates of process gases automatically. Continuously and accurately measuring hydrogen concentration is essential to receiving high H₂ level alerts at the exit end, which may help prevent risking an explosion or indicating the need to replace curtains.

Bob Orsulak, vice president, operations of Osterwalder, Inc. (osterwalder.com), Northampton, Pennsylvania, offers a full range of CNC-controlled new electric compacting presses.

Osterwalder’s multi-level OPP-2000 electric press (Figure 7) with a fast tool exchange system can reduce energy costs by 80%, Orsulak says. Electric drives feature shorter set-up times by increasing accuracy and repeatability along with better thermal stability. Electric drives also eliminate aging on hydraulic components and adjustment of servo valves. The lifetime of electrical components is much longer than hydraulic components, Orsulak claims. In addition, the OPP press does not need a pit or high working platform for operators.

Quintus Technologies (quintusteam.com), Lewis Center, Ohio, has expanded sales of hot isostatic press (HIP) systems (Figure 8) in North America reports Johan Hjaerne, business unit manager. He cites the main reason for increased sales is the Quintus propriety uniform rapid cooling (URC) system that combines HIPing and heat treating in a single process.

Known as high-pressure heat treatment, this design streamlines steps in material densification and heat treatment. It enables processed parts to cool uniformly, resulting in minimal thermal distortion and non-uniform grain growth. Customers have measured cooling rates up to 900 °F/minute, which offers unusual high-pressure heat treatment cycles.

SACMI USA LTD (sacmiusa), Urbandale, Iowa, a subsidiary of the SACMI Group in Imola, Italy, has designed...
a new series of electric compacting presses to support high-speed manufacturing of smaller parts at reduced energy consumption reports Suraj Desai, North American technical sales manager. SACMI also offers an automatic helical gear device that allows switching angles without replacing components and parts.

TAT Technologies, LLC (tat-tech.com), St. Marys, Pennsylvania, has installed more lubricant burner technology (LBT) units (Figure 9) to upgrade sintering furnaces in removing lubricant/binders from parts to accelerate production rates, says Harb Nayar, president. He claims the units increase throughput by 20% to 50%, depending on which LBT model (I, II, III) is installed.

PM PARTS TECHNOLOGY TRENDS

Jeff Howie, vice president—advanced engineering, Alpha Precision Group (APG) (alphasintered.com), St. Marys, Pennsylvania, reports on investing in a new CNC hydraulic die-set press and a machining cell to enhance production capabilities for one of its main product lines, variable cam phaser parts (Figure 10). He sees significant growth potential by offering specialized machining, finishing, and assembly solutions to this important segment of the automotive market.

High-density parts for the next generation of downsized engines in the automotive, industrial, and lawn & garden markets, is another need APG seeks to service. Current technology is approaching the limitations of conventional PM processing. Accordingly, the company is working alongside powder suppliers to develop multiple technologies to yield higher-density and higher-strength parts. Warm compaction, selective secondary densification, and high-temperature sintering all offer solutions.

GKN Sinter Metals (gknpm.com), Auburn Hills, Michigan, is looking at new opportunities for PM parts in electric vehicles, suggests Alan Taylor, vice president, lightweight technology. Possible applications include drivetrain speed reduction, motor thermal management, and more potential uses for the body and chassis. Taylor points to SMC’s for motors and aluminum metal-matrix-composites in new 2020 product launches.

He reports that some of the world’s largest OEMs have announced new battery electric vehicles bringing disruption to the traditional PM industry. Nevertheless, opportunities could ease the transition with the shift to hybrid vehicles.

Ana Keiko Mizukami, engineering manager of Metalpó Ind. E Com. Ltda (metalpo.com.br), Sao Paulo, Brazil, says her company is focusing on high-density parts with tight tolerances using alloying material for sinter hardening. She also sees the market requiring products with tight tolerances and high density.

MPP (mppinnovation.com), Noblesville, Indiana, continues focusing on proprietary aluminum materials and processing technology that offer a 50% reduction in mass over steel parts, reports Chaman Lall, vice president technology & applications development.

MPP is developing a second high-strength aluminum alloy with superior mechanical properties: UTS of 380 MPa (55,000 psi), yield strength of 310 MPa (45,000 psi), and 4% elongation. Apparent hardness is about 50 HRB while transverse rupture strength values are well above 690 MPa (100,000 psi). Beyond that, MPP has a new aluminum bearing material showing wear test data that outperforms leaded brass and bronze.

Lall further reports that Metal Powder Products and Netshape Technologies have integrated the two companies into a new business entity, MPP. The new MPP has relocated Netshape’s metal injection molding (MIM) plant in Solon, Ohio, to Noblesville. The relocated facility will focus on new stainless steels customized for the medical market, a strategic growth area for MIM.

Diego Castro, global director of powertrain engineering and R&D, PMG Asturias Powder Metal, S.A.U. (pmsginter.com), Mieres, Spain, says PMG is working on low-alloy materials without nickel, and warm compaction and parts for transmissions (manual, dual-clutch, automatic) to reduce CO₂ emissions. Applications for manual and dual-clutch transmission include hubs, sleeves, rings, dog rings, and helical gears. Hybrid technologies will demand components with higher mechanical properties, Castro stresses.

METAL INJECTION MOLDING & ADDITIVE MANUFACTURING TRENDS

Arburg GmbH + Co KG (arburg.com), Lossburg, Germany, manufacturer of the ALLROUNDER powder injection molding machines introduces the “arburgX-
world” program (Figure 11). It comprises all digital products and services and is the name of the customer portal: arburgXworld.com. All machines will feature basic connectivity for networking via standard interfaces with higher-level systems.

DM3D Technology (dm3dtech.com) Auburn Hills, Michigan, is concentrating on making larger AM parts for the space, aerospace and defense industries reports Bhaskar Dutta, president and chief operating officer. Its technology is aimed at smaller quantities, and high-value parts with long lead times. With this in mind, DM3D is designing equipment with a high-throughput capability and a very large work envelope to produce parts up to approximately 450 kg (1,000 lb).

Metal AM trends in the next decade will focus on enhancing throughput, printing large parts, multi-material printing, and repairing and refurbishing expensive parts.

Animesh Bose, FAPMI, vice president, special projects of Desktop Metal (desktopmetal.com), Burlington, Massachusetts, introduces his company’s latest 3D printing machine, the Shop System™ designed for machine shops and metal job shops (Figure 12).

Addressing mid-volume production ranges, the system is 10 times faster than melt-based laser, powder-bed-fusion systems, Bose says. It is a single-pass printer that can process about 70 kg (154 lb) of steel parts daily.

The system can deliver a spot size of 16 micrometres per drop, 1,600 dpi resolution, and can distribute 670 million drops per second. It provides batch production of complex parts without needing tooling.

ExOne (exone.com), North Huntingdon, Pennsylvania, has launched its latest model machine, the X1 160PRO metal 3D printer, the largest metal binder jetting system commercially available, reports Andrew Klein, global director of technology. It features build dimensions of 800 mm x 500 mm x 400 mm (32 in x 20 in x 16 in), or 160 litres (42 gallons) of build space. ExOne’s newest machines have its patented Triple ACT (advanced compaction technology) powder handling and processing system that dispenses, spreads and compacts ultra-fine powders. The company has qualified three stainless steels (316L, 304L, and 17-4PH) for single-alloy 3D printing.

Randall M. German, FAPMI, German Materials Technology, Del Mar, California, (randgerman@gmail.com) reports on gains in sintered density, dimensional uniformity and property optimization of polymorphic alloys. Improved cycles are recommended for several popular ferrous and reactive alloys, notably 17-4PH and Ti or Ti-6Al-4V used in binder additive processes and injection molding. Figure 13 shows the sequence of dominant processes heating 20 micrometre titanium to the sintering temperature where final swelling is a common difficulty. An alternative heating cycle is identified to avoid swelling the trapped gas.

Recognizing opportunities for refractory metals in additive manufacturing, H.C. Starck Solutions, (hcstarcksolutions.com), Cleveland, Ohio, has devoted research on binder-jet printing of tungsten heavy alloys and the directed energy deposition (DED) of molybdenum, according to Mike Stawowy, director of research & development. Refractory metal AM products can advance niche applications that require high performance materials, Stawowy says. Starck’s future plans include shifting from R&D quantities and prototyping to small-scale commercial production for different end markets.

Joseph Tunick Strauss, president of HJE Company,
Inc. (hjeco.com), Queensbury, New York, sees progress ahead for non-fusion metal AM processes such as binder jetting (BJT), material extrusion (MEX), material jetting (MJT), and vat photopolymerization. All of these processes produce a part that must be de-bound and sintered, implying the leveraging of MIM technology already available in MIM facilities. They can supplement MIM for low volumes and for geometries not possible with MIM.

Binder jetting is in commercial production supported by about five equipment builders. Main materials include stainless steels, tool steels, and nickel-based alloys. In addition, the use of MIM-grade powders provides high densities.

Material extrusion (printing MIM feedstock) is supported by three companies, and shows promise. Nevertheless, small parts and small features/high resolution are a challenge due to the minimum build path currently possible.

Material jetting, mainly for ceramics, requires fine powders < 5 micrometres that limits its use with metals. Vat polymerization, proven for stainless steels, builds features and higher resolution and superior surface finish than binder jetting and material extrusion; however, part size is limited.

Although most conventional alloy powders for metal AM are made by the same companies supplying the MIM market, plasma atomization processes (plasma wire) appear to be growing fast for titanium alloy powder.

Tundra Companies (tundracompanies.com), White Bear Lake, Minnesota, has developed a MIM feedstock showing shrink rates below 10% from molding through sintered parts, reports Adam Bartel, head of new product development. This advantage overcomes a significant barrier of making larger MIM parts that have a typical shrinkage rate of 15%–23%, he suggests. Using Tundra’s feedstock meets or exceeds sintered densities specified for MIM alloys.
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POWDER METALLURGY IN CANADA

Roger Lawcock, FAPMI,* Rohith Shivanath,** Yannig Thomas*** and Carl Blais****

UNIVERSITIES

Concordia University is investigating several new ideas related to the use of soft magnetic composites in electrical machines.

Axial Flux Permanent Magnet Wind Generator with a Soft Magnetic Composite Core

The isotropic magnetic property of soft magnetic composites (SMC) and the possibility of shaping in three dimensions, provides opportunities for three-dimensional flux paths in magnetic components, and hence offers new possibilities for machine designers. In this work, an SMC material is utilized in the design of an axial-flux permanent magnet generator for small direct-drive wind-energy conversion systems, Figure 1. In order to compensate for the reduced permeability and higher core losses of the SMC compared with electrical steel, the machine is designed with short magnetic path length and minimized weight. In addition, the axial-flux permanent magnet generator is also designed with SMC teeth, fitted into a laminated electrical steel stator yoke, as the yoke flux flows in the circumferential direction.

Development of 15 kW Axial Flux Permanent Magnet Synchronous Machine (AFPMSM) Using Soft Magnetic Composites (SMC)

The idea behind this project is to use the soft magnet composites produced by Rio Tinto with the cold-spray techniques developed by the National Research Council and the prototyping and design experience of Stackpole International to develop a novel permanent magnet machine for electric vehicles. The SMC

Figure 1. SMC axial-flux permanent magnet wind generator

*Director Product & Process Development, **Director Metallurgy, Stackpole International, Automotive Gear Division, 2430 Royal Windsor Drive, Mississauga, Ontario L5J 1K7, Canada; Email: rlawcock@stackpole.com, ***Research Officer, National Research Council Canada, National Research Institute Canada, 75 de Mortagne, Boucherville, Quebec J4B 6Y4, Canada, ****Professor, Laval University, Dept. of Mining, Metallurgical & Materials Engineering, 1718 B Pavillon Adrien-Pouliot, Quebec, Quebec G1K 7P4, Canada
materials allow special 3D topologies of electrical machines with reduced core losses and optimized windings. This work considers the design of a 15 kW, 10,000-rpm maximum speed machine for an electric axle. Key parts in the stator and rotor use the SMC where complex flux paths are required that are not easily achieved with laminations. The cold spray of the iron powder allows bonding to the machine parts with higher strengths than glue.

Metal additive manufacturing (AM) technology adoption has gained momentum, specifically in light of emerging efforts in deploying new metal alloys, with increased opportunities in product cost reduction and scalable production across sectors. The MSAM laboratory is part of the Mechanical and Mechatronics Engineering Department, in the Faculty of Engineering at the University of Waterloo, Ontario. The MSAM lab is the most comprehensive Canadian academic research and development center for researching the next-generation metal AM processes. Backed by ~$27M in cash and in-kind support, including $8.9M from FedDev Ontario, MSAM addresses the scientific and applied challenges required to bridge the technological gaps necessary to improve part quality, process repeatability and reliability in metal AM. The researchers at MSAM continue to explore novel techniques to develop advanced materials such as AM-grade metal powders, innovative products, modeling and simulation tools, process monitoring and devices, closed-loop control systems, quality assurance algorithms, and holistic in-situ and ex-situ characterization techniques.

In-house facilities include powder-bed-fusion printers (laser and electron beam), laser directed energy deposition systems, binder-jetting systems (commercial and developed in-house), material jetting and material extrusion printers, and advanced material characterization systems such as nano-computed tomography, an X-ray diffraction residual stress analyzer, and powder characterization systems.

Working with Rio Tinto Metal Powders and other metal powder producers and end-users, MSAM is contributing to the development of low-alloy steel powders suitable for state-of-the-art binder jetting and laser-based AM processes. The research is directed towards bridging the gap in the cost of AM materials and processes in order for metal AM to become a viable extension of the powder metallurgy technology. Samples produced with custom-processed water-atomized powders (Figure 2) exhibit near-full-density characteristics (>99.7+/-0.2% relative density) and mechanical properties comparable to the most similar press-and-sinter material specification (FL-4405-175HT). The MSAM group is also hosting the National NSERC Network for Holistic Innovation in Additive Manufacturing (HI-AM) bringing together 22 leading AM experts from 7 partner universities (University of Waterloo, McGill University, Dalhousie University, Université Laval, University of British Columbia, University of Alberta, and University of Toronto), 2 collaborator universities (ETS Montreal and University of Windsor), and 24 industrial/government organizations (NRC, GE Additive, Rio Tinto Metal Powders, Siemens, GKN, etc.). These researchers and their teams share ideas, innovations, and access to advanced research infrastructure and devices essential for holistic AM experiments in fields such as material development, process simulation and control, quality assurance, design for additive manufacturing, etc.

The powder metallurgy laboratory led by professor Carl Blais at Université Laval, performs research on the development of novel powders for PM and AM. These
new powders are mainly low-alloy steels, tool steels as well as ferrous master-alloys. Additionally, several graduate students work on the development of a novel family of additives to improve the machining behaviour of PM steels. In connection with the development of master-alloys, work is carried out on the optimization of the sintering profile in the context of liquid-phase sintering. The laboratory is equipped with a water-atomization system than can atomize batches equivalent to 25 kg of steel (Figure 3). The laboratory is also equipped with a melt spinner and high-energy ball mills. The laboratory regroups several high-temperature (1,700 °C) tube furnaces as well as a 10-cm continuous-belt sintering furnace equipped with a forced-convection cooling unit (Figure 4). The laboratory also has powder characterization equipment such as a rotating drum analyzer, a rheometer, a CMM, TGA/DTA, BET, O/C/S analyzers, and ancillary apparatus.

The Québec Metallurgy Center (QMC) performs R&D for multiple sectors including PM parts manufacturing, thermal spray, and additive manufacturing. Powders can be developed using gas and/or plasma atomization (Figures 5 and 6). QMC also assists in material characterization, process development and prototyping using: DED technologies (Figure 7), hybrid DED/Machining manufacturing technologies; binder jetting; plasma spray, and HVOF. Heat treatments can also be performed using vacuum heat-treatment furnaces or a hot isostatic press (HIP). Characterization of the materials is accomplished within a laboratory equipped for chemical, metallographic, and mechanical analysis. Moreover, part soundness can be evaluated with a fully equipped non-destructive evaluation testing (NDT) facility. QMC holds a Canada NSERC College Industrial Research Chair on the Development of Metal Powders for Advanced Manufacturing Processes and
Applications under the supervision of Dr. Bernard Tougas. The Chair axes of research are: the development of aluminum powders dedicated to additive manufacturing processes, the optimization of high-performance alloys for additive manufacturing of components used in aeronautical applications, the development of aluminum powders for heat-resistant/corrosion resistant coatings, and the development of tool steels and nickel powders for additive manufacturing processes and welding repair.

On April 1, 2019, the Quebec Metallurgy Center (QMC), Trois-Rivières, Québec, announced the creation of the **Canadian Research Center for the Development, Production and Applications of Metal Powders**. This $8.7 million endeavour will permit the development of novel metal powders utilized in various manufacturing processes such as additive manufacturing (3D printing), powder metallurgy, thermal spray, welding, hydrometallurgy, etc. The new research center was initiated by a partnership between QMC and professor Carl Blais director of the Powder Metallurgy Laboratory of Université Laval, Québec City, and professor Gilles L’Espérance FAPMI, director of the Center for Microscopy and Characterization of Materials, (CM)², of École Polytechnique de Montréal. Both universities are closely collaborating with QMC and support its efforts to grow this new R&D center into a world-class research infrastructure for the development, production and utilization of metal powders. The research center is located in a new 800 m² building expansion at QMC and contains a wire-fed plasma atomizer/spheroidizer and a gas atomizer designed to atomize a wide variety of metals including aluminum alloys. This research infrastructure completes the suite of equipment already available at Université Laval for the production of metal powders. Additionally, the new research center also benefits from the characterization equipment of the (CM)².

**École de technologie supérieure (ÉTS)**, Montréal, Canada, is conducting research involving metal and metallic-alloy powders used in AM, metal injection molding (MIM), and powder-bound extrusion (PBE) technologies. These projects are mainly undertaken in collaboration with different powder producers or end-users. The academic and applied research carried out at ÉTS involves various material characterization techniques such as dry-powder rheology, melt rheology, micro-tomography, advanced microscopy, and fatigue testing. The aim is to help advanced manufacturing industry understand better the impact of each process input on the in-service properties of components made from powders.

The metal AM-related research at ÉTS (V. Brailovski) is mainly oriented towards the design, processing, and post-processing of PBF-LB components for the automotive, aerospace, and medical industries. Since one of the main limitations of AM technologies is their difficulty to generate smooth and even surface finish, ÉTS is also committed to an extensive development of surface finishing technologies of AM components, especially those containing difficult-to-access cavities and channels. These technologies include electrochemical polishing, abrasive- and chemical flow machining.

The MIM-related research (V. Demers) is mainly focused on the development of the low-pressure powder injection molding process (LPIM). The use of low-viscosity binder systems such as paraffin wax combined with carnauba wax, beeswax, oleic acid, stearic acid, and ethylene vinyl acetate (i.e., no backbone polymer) provides the opportunity to inject the powder-binder mixture using a pressure generally below 1 MPa. The MIM research group at ÉTS is developing metallic-based feedstocks including superalloys, stainless steels, tita-
nium, and iron-based LPIM mixtures to manufacture intricate parts in the automotive, aerospace, and medical industries.

The PBE-related research (V. Demers and V. Brailovsky) combines the AM and MIM technologies to offer a new manufacturing approach based on 3D printing of metallic feedstocks combining the exceptional shape complexity capability of the AM approach with the high maturity and readiness level of the MIM technology. This technology being in infancy, academic and applied research is required to explore its real capability and transformation potential. To this end, prototype PBE systems (Figure 8) as well as new generation feedstocks are under development.

McGill University has been offering undergraduate and graduate courses on PM and AM, supported by Prof. Mathieu Brochu’s research group and his Powder Processing and Additive Manufacturing of Advanced Materials Laboratory (P2AM2). The laboratory hosts a wide variety of commercial and lab-designed 3D printers, several high-vacuum and inert-gas heat-treatment furnaces, a holistic suite of powder characterization equipment, and part characterization equipment (residual stress analyzer, CMM, etc). The laboratory has 31 students and research associates. Currently, the bulk of the research activities are focused on laser powder-bed-fusion studies to target the fabrication of parts with controlled crystallographic textures, made for alloy systems considered unweldable or with controlled residual stresses. Among the recent achievements is the fabrication of parts with SX-like structures. Prof. Brochu’s group has also developed techniques for processing heat-treatable Al alloys (methodology working for all Al series) and precipitation-strengthened superalloys. These parts are also studied in terms of heat treatment engineering to capitalize on the newly developed microstructure. One recent example deals with the development of a heat treatment cycle for Al alloys that simultaneously capitalizes on second-phase strengthening and precipitation hardening.

The National Research Council of Canada (NRC) has been in operation since 1916 and is the Canadian government premier and largest research and technology organization (Figure 9). NRC works with clients and partners to provide innovation support, strategic research, and scientific and technical services. Since the early 1980’s, the organization has built up considerable expertise and state-of-the-art equipment (laboratory and industrial-scale) in powder metallurgy (Boucherville, Montreal, London, and Ottawa). More than 45 research staff are presently involved in activities covering traditional powder metallurgy forming technology (compaction, compression, hot and cold isostatic pressing, injection molding), metallic and ceramic foams, thermal and cold spray, and additive manufacturing. During the last decades, the research activities have focused on the development of powder characterization techniques, binders and lubricants for various PM processes, the development of soft and hard magnetic materials (in collaboration with electric motor designers), porous metals and metallic foams, new plasma spray and cold spray coating, and additive manufacturing/3-D printing. Various technologies have been successfully transferred to industry.

POWDER PRODUCTION

Canada is home to Rio Tinto Metal Powders, one of the world’s largest iron and steel powder manufacturers (Figure 10). Based in Sorel-Tracy, just about an hour outside of Montréal, Rio Tinto Metal Powders has been
a steady feature in the powder metallurgy landscape since 1968. Originally known as QMP, the company transforms ilmenite ore extracted from its mine in Northern Quebec into iron and steel powders through a proprietary process consisting of smelting the ore into titanium dioxide and molten iron. At the Sorel-Tracy metallurgical complex, several plants were built to transform the ore and manufacture various products, one of which is iron-based metal powders. Rio Tinto Metal Powders is the only producer of such powders sourcing the entirety of its raw materials from ore, ensuring a steady production of pure powders.

Throughout its history, Rio Tinto Metal Powders has strived to maintain active connections to, not only the powder metallurgy industry, but with several stakeholders such as academia and research and development institutes. As such, several partnerships have been established over time. The research and development team at Rio Tinto Metal Powders has partnered with the National Research Council Canada, Université Laval, University of Waterloo, École de Technologie Supérieure, McGill University and University of Toronto, just to name a few. In 2019, the NRC and Rio Tinto Metal Powders even celebrated the 25th anniversary of their ongoing collaboration. Research is being conducted on new alloy steel grades, which, if successful, would offer better mechanical properties than conventional higher-alloyed grades at a reduced cost. A diffusion-alloyed copper alloy, DB10Cu, is now being offered to the market and was developed in collaboration with the technical and development team in Suzhou, China (Figure 11). This type of copper-rich powder is excellent for stabilizing the dimensional change of iron-copper-carbon powder mixes. As powder metallurgy technology relies on the contribution of several elements added to powder mixes, research continues on powder metallurgy additives such as lubricants and machining enhancers. Lubricants free of metal stearates have been introduced, and novel machining enhancers that reduce corrosion risks while improving tool life are receiving continued focus.

While catering to the current needs of the metal powder industry, Rio Tinto Metal Powders still pursues research activities into the products that may shape the industry’s future. Soft magnetic composite (SMC) powders are being developed and tested in various applications where they could potentially replace laminated steels or magnets in electrical motors. In addition, partnering with the leaders in additive manufacturing technology development, Rio Tinto Metal Powders has been working to demonstrate that water-atomized powders can be used in some of the popular additive manufacturing processes.

Vale is one of the world’s largest producers of nickel and has a long history in Canada as a producer of high-quality nickel products. Vale purchased Inco Limited in 2006 and has maintained its operations and base metals headquarters in Canada. Vale is a global leader in carbonyl nickel powder production with the Copper Cliff Nickel Refinery located in Sudbury, Canada, and the Clydach Refinery in Wales, UK. Vale’s high-quality powder is low in iron and sulphur content, uniform, and optimized for various applications including powder metallurgy.
Vale’s T123® nickel powder is composed of discrete, dendritic nickel particles with a tightly controlled particle size and apparent density optimized for the powder metallurgy industry (Figure 12). T123 is an industry-standard nickel powder used worldwide in the production of pressed and sintered parts. T123 is used by powder metallurgy parts manufacturers, either directly by mixing with iron powder, or, through commercially available resin bonded or diffusion-alloyed products.

H. L. Blachford is the only Canadian company that focuses specifically on the R&D and manufacturing of lubricants that are sold both globally and domestically to metal powder producers and powder metallurgy parts manufacturers. Changes in lubricant formulations and manufacturing methods continue to be driven by the requirements for improved performance properties (e.g., green strength, density, ejection properties, die filling, and powder flow) for higher density parts, powder-mix consistency, and quality as well as changes in regulatory requirements, Figure 13.

The use of both EBS (ethylene-bisstearamide) wax and zinc stearate (ZnSt) have stabilized. EBS is still the go-to lubricant for parts in the density range of 6.5–6.8 g/cm³ and provides good green strength for small conventional parts. However, its use is not acceptable for higher density or longer parts. Zinc stearate has advantages over EBS in terms of both improved AD and ejection properties. Nevertheless, its use has reduced by about 50% in the last ten years due to unwanted deposits forming in the furnace as well as regulatory implications related to the use of zinc.

The industry also needs parts with clean surfaces (soot/stain free) after both delubrication and sintering. One common theory is that the inclusion of metallic stearates in a lubricant formula results in staining; this has resulted in a trend, for some, away from lubricants containing stearates (e.g., CAPLUKE K and L). While staining is an issue for some customers, it is very customer and application specific. Furnace conditions and metal powder formulae can also have a major impact on the formation of the stain.

There has been a trend in the industry to move to premixes, rather than parts manufacturers making mixes in-house. As the move to premixes advances, metal powder producers have also looked at in-house development of lubricants or purchase of a lubricant manufacturer. This has resulted in some proprietary premixes for specific applications.

Recent lubricant developments have focused on the need for improved lubricants that can be used at lower concentrations for higher density products. As a lubricant manufacturer, Blachford is actively supporting the development of unique proprietary premixes that exhibit advanced properties. This involves the increased use of advanced techniques during lubricant development; e.g., FT-IR, DSC, TGA, ICP, FT4 Powder Rheometer™, and Granutools instruments.

**ADDITIVE MANUFACTURING**

As a specialist in the production of spherical metal powders designed for additive manufacturing, AP&C, located just north of Montréal, Québec, offers not only quality powders, but first and foremost, it brings to the table over 10 years of experience in all aspects of additive manufacturing metal powder supply. High-throughput, safe and reliable production, handling, and traceability of fine metal powders are only a few of the areas where AP&C has deep knowledge (Figure 14).

To contribute to the ongoing global R&D effort, AP&C has begun an aggressive program in collaboration with GE Additive’s global network as well as clients, government and academic laboratories. Successful R&D results include unique processing that enhances powder dynamic behavior (flowability and “spreadability”).

**Figure 12.** T123 carbonyl nickel powder

**Figure 13.** Metal powder mixtures are prepared in the laboratory using powders such as (a) iron powder, graphite, and copper with a lubricant to manufacture both (b) TRS bars and ejection specimens on the (c) 50 t press. A magnified view of lubricant particles is shown in (d)
Ongoing R&D projects target powder costs. For example, the development and evolution of advanced plasma atomization (APATM) through new technologies will improve the production throughput of high-quality powder with minimum post-processing steps needed (Figure 15). In parallel, the GE Additive ecosystem is testing the use of different lower-cost particle size distributions (PSD). Tests are underway with AM partners to include advantageous types of powders.

To ensure the safe handling of reactive powders and address associated EHS concerns, AP&C has developed the best practices existing in the industry and a full suite of equipment optimized to handle reactive powders efficiently (equipment can be customized for clients and partners). To facilitate traceability and close the loop on the powder life cycle, dedicated software has been developed to track powder throughout the manufacturing route from the ingot to final packaging. Technology to reprocess or regenerate off-sized or end-of-life powders is in the works. Material availability is an ongoing challenge to expand the number of potential AM parts, and therefore, Al-Si10-Mg and F357 (Al-Si7-Mg) were launched in 2019. A roadmap for the introduction of new materials includes Ti-48Al-2Nb-2Cr (Ti-Al) in 2020.

5N Plus Inc. produces advanced high-purity metals and chemical compounds that are used as precursors for base materials in many microelectronics, optoelectronic, renewable energy, pharmaceutical, and industrial applications. The company specializes in purification of metal and chemical compounds. Purities of some metals can exceed 7N5 (99.999995%).

The division of 5N Plus Micro Powders, located in Montréal, Québec, incorporates a unique atomization technology that allows production of fine, spherical metal powders that are used in various industries, including microelectronics assembly and metal additive manufacturing. The technology is perfectly adapted for producing metal and alloy powders with melting points ranging from 60 °C to 1,200 °C with very spherical shapes and low oxygen content (Figure 16). The process provides powders with very tight particle-size dis-
ttributions, which contributes to enhanced performance.

The tin-based and indium-based alloys for solder-paste, conductive adhesive, and other conductive materials are sold to manufacturers worldwide. Highly spherical copper-based powders are produced for additive manufacturing, cold spray, and other niche micro-electronic packaging.

**COMPONENT MANUFACTURING**

**GKN Powder Metallurgy**, which has a facility in St. Thomas, Ontario, has collaborated extensively with Dr. Paul Bishop (Dalhousie University, Halifax, NS) for over 15 years. The core focus of research has been dedicated to the development, processing, and commercialization of innovative aluminum PM alloys and metal-matrix-composites. The collaboration has generated 34 journal papers, 15 full paper conference proceedings, and 6 patents that are presently exploited in the high-volume production of award-winning automotive components. One example is a planetary reaction carrier (Figure 17) utilized within the 9T50 automatic transmission mass-produced by General Motors. Fabricated from an innovative metal-matrix-composite developed by the team, it weighs 50% less than a traditional steel counterpart, removing >650,000 kg of vehicle mass from North American roads each year. As the world’s first lightweight carrier, this ground-breaking component ultimately won a Grand Prize award in the Automotive Transmission category of the MPIF 2018 PM Design Excellence Awards Competition.

A second example is an aluminum heat sink (Figure 18) that was an award-winning product in the MPIF 2016 PM Design Excellence Awards Competition. This component relies on another PM alloy invented by the group that has an exceptional thermal conductivity and a robust response to PM processing. Its launch has highlighted a completely new forum of growth for the global PM community within the rapidly expanding automotive market for electrification and electric vehicles.

**Kuma Brake Pads** are designing and manufacturing high-performance sintered brake pads for wind turbines (Figure 19). Their products are used for the hydraulic brake calliper on the high-speed rotor. Kuma is working closely with wind farms, wind turbine manufacturers, and brake system manufacturers in order to offer high-quality and high-performance products.

**Stackpole International**, part of the Johnson Electric Group with locations in Ontario (Figure 20) and a global manufacturing footprint has focus on supply of innovative PM products to automotive industry customers in support of fuel-efficient and reduced emission powertrain designs in IC and EV applications.

Proprietary PM manufacturing technologies, advanced metallurgical design and testing methods are combined to deliver high-quality components with an exceptional value proposition in high power density and NVH critical applications.

In general, products are high volume and high strength, ferrous alloy materials with complex geometries and high levels of dimensional precision. Advanced PM alloying, sintering, and densification technologies
allow achievement of superior strength characteristics. An extensive variety of components are manufactured.

Engine and transmission oil pump slides and rotors for use in variable displacement fluid power designs (Figure 21) represent perfect examples of high-precision components produced from a range of materials including prealloyed, diffusion-alloyed, and copper-steels to achieve targeted performance requirements.

Stackpole International was the recipient of a Grand Prize award in the Automotive Transmission category in the MPIF 2019 PM Design Excellence Awards Competition for automatic transmission clutch plates (Figure 22). The clutch plates together with a central hub and two roller-bearing races form a transmission sub-assembly. Compaction of the plates involves the use of complex multiple-element punch and die design to form the near-net-shape geometry. The bearing surfaces are surface densified and heat-treated to withstand the high levels of contact stress introduced during transmission function.

Automatic transmission planetary carriers made by Stackpole International were recognized by MPIF with an Award of Distinction in 2017 in the automotive components category (Figure 23). In order to provide a lightweight carrier solution to meet the customer’s design and durability requirements, a sinter-brazing technique is used to join two compacts to form the carrier. Shape complexity is evident, with the combination of thin sections and the net-formed geometrical features. The design is an excellent example of value provided by application of varied PM manufacturing technologies including ferrous alloy selection, sinter-brazing, infiltration, and induction hardening.

**MATERIALS**

**Ceradyne Canada** manufactures composite materials for regulated niche markets (Figure 24). Ceradyne has developed a cladded aluminum/ceramic metal-matrix-composite (MMC) used as a neutron absorber in nuclear applications. Technical highlights include explosive powder management, powder mixing, densification of a powder core through rolling, aluminum metallurgy, and product characterization.

**THERMAL SPRAY**

**Tekna**, with headquarters and R&D center located in Sherbrooke, Québec is the world leader in radio frequency (RF) plasma technology. The company operates manufacturing facilities in Canada and France, as well as sales and distribution offices in China, India, and South Korea. For 30 years, Tekna has specialized in the development, design and fabrication of fully integrated RF plasma systems, also known as inductively coupled plasma (ICP), for a wide variety of applications. From nanoparticles to micrometre-sized powders and advanced coatings, Tekna’s patented core technology enables the production, in industrial quantities, of a broad class of materials. Two proprietary processes were developed in order to optimize powder quality, performance and cost for additive manufacturing (AM) applications: RF plasma spheroidization (RF-PS) and RF plasma atomization (RF-PA)1. Both technologies are used complementarily and enable consistent, class-leading properties, from light metals to refractory materials. The AM powders portfolio comprises aluminum alloys (AlSiMg), titanium alloys (Ti-6Al-4V), nickel-based alloys (718, 625, HX), and specialty refractory metals such as tungsten, molybdenum, and tantalum. With their high degree of sphericity (Figure 25), controlled particle size, high density, and high powder flowability, Tekna’s powders are compatible with the complete range of AM platforms, as well as demanding industrial applications, such as metal injection molding (MIM), thermal spray, and hot isostatic pressing (HIP).
TOOLING

Fordia powered by Epiroc is the world’s leading manufacturer of diamond tools for mineral exploration and is deeply committed to innovation. The company has two manufacturing plants in Canada, one in Montréal and the other in North Bay.

Unlike most goods made by powder metallurgy, diamond-impregnated core bits are not produced by standard sintering, but by infiltration or liquid-phase sintering (Figure 26). This metallurgical process involves casting and brazing features. More precisely, only the copper-based infiltration alloys reach a liquid state, filling all the pores of the skeleton, which is made of hard materials and refractory metal powders mixed with high-grade synthetic diamonds (Figure 27). The correct core bit should drill a particular rock type at a steady penetration rate, with the matrix wearing away at an appropriate rate to expose fresh diamonds, as they are needed. To do so, the R&D team needs to select premium diamonds made by high-pressure, high-temperature (HPHT), and different types of powders made using various processes, such as hydrogen reduction of refractory metal oxides, carbonyl powders, and atomized powders. The diamond tools developed by the metallurgical engineers at Fordia powered by Epiroc are among the most recognized in the world.
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POWDER METALLURGY
IN AUSTRIA
Herbert Danninger, FAPMI*

INTRODUCTION AND HISTORY
As in other countries, “powder metallurgy” (rather “powder forging,” using today’s terminology) started with the introduction of the bloomery furnace; this happened in the early Iron Age, which in Central Europe is also called the “Hallstatt period”, after the small salt-mining town in southern Upper Austria. Modern powder metallurgy started with the founding of a refractory metal plant in Reutte, Tyrol, in 1921 by Paul Schwarzkopf—now Plansee SE—and even earlier, in 1898, by the Austrian chemist Carl Auer von Welsbach who founded Treibacher Chemische Werke in Carinthia; at that time working on rare-earth elements but also manufacturing osmium lamp filaments from 1900 onwards and tungsten filaments from 1905. In the inter-war period, the foundations of further PM plants were laid, such as Miba from Upper Austria, but the big expansion came after WWII when an upturn of industrial production in general resulted in increased demand for PM products, such as automotive components, friction materials, filters etc. A typical feature for the Austrian PM industry as a whole was a strong export orientation, a consequence of the small internal market combined with the availability of a large market—Germany—virtually next door. However, other European countries such as France and Italy proved to be interesting markets, and in recent decades the industry has become truly intercontinental, with production facilities in North and South America, China, and India. The fall of the Iron Curtain proved to be particularly beneficial for Austria. Another “export” of Austria was renowned powder metallurgists such as Franz Skaupy, Henry H. Hausner, and later Hellmut Fischmeister and Winfried J. Huppmann, who got their scientific-technical education in Austria and then pursued successful careers abroad.

POWDER MANUFACTURING
In Austria, there are several companies that produce powders for PM applications. While water-atomized ferrous powders are imported, powders for hardmetals are manufactured by Wolfram Bergbau-und Hütten AG of St.Martin, Styria, a world-leading manufacturer of W and WC powder grades and a supplier to most hardmetal manufacturers (Figure 1(a)). Treibacher Industrie AG from Treibach-Althofen, Carinthia, produces special carbides; the company dates back to Carl Auer von Welsbach. Nonferrous—light alloy—metal powders are made by Mepura from Ranshofen, Upper Austria, and its sister company Nonferrum, Sankt Georgen near Salzburg, both part of Ecka Granules-Kymera, Germany. Another producer of various low-melting point nonferrous powders and granulates is IMR from Velden, Carinthia, with its production plant in nearby Feistritz. The special steel manufacturer voestalpine Böhler

*Professor, Technische Universität Wien, Institut für Chemische Technologien und Analytik, Getreidemarkt 9/164, A-1060 Wien/Vienna, Austria; Email: hdanning@mail.tuwien.ac.at
Edelstahl GmbH & Co. KG from Kapfenberg, Styria, produces powders using two routes: inert-gas atomization of tool steel and high-speed steel powders is done for in-house processing by hot isostatic pressing (HIP) to fabricate ultra-high performance steels (Figure 1(b)). More recently, vaBEG has invested heavily in atomizing equipment for additive manufacturing, offering inert gas atomizing for a wide range of high-alloy steels, superalloys, and Ti-base powders.

Recently INTECO, originally a manufacturer of ingot metallurgy plants, has developed atomizing units for customers in several countries. Another equipment manufacturer, SAB from Deutschlandsberg, Styria, supplies reduction furnaces; especially for production of refractory metals.

PM PRECISION PARTS

Currently there is only one manufacturer of pressed-and-sintered ferrous precision parts in Austria, Miba Sinter Austria GmbH, but it is one of the big global players in this business. Miba Sinter grew out of the bearing company which Franz Mitterbauer, owner of a small mechanical shop, founded after WWII and which is now Miba Gleitlager GmbH. Miba Sinter grew enormously with the expansion of the automotive industry. Miba Sinter is a supplier to all the major car manufacturers in Europe, with subsidiaries in Slovakia (founded shortly after the fall of the iron curtain), USA, Brazil, China, and India. With the future of the internal combustion engine and transmissions somewhat in question, Miba is expanding into areas other than traditional engine and transmission components, in which latter field the company is, however, still a technological leader - see the examples in Figure 2.

With the exception of a few in-house production lines, metal injection molding has not been a particular focus of the Austrian PM industry, but Wittmann Battenfeld of Kottingbrunn, Lower Austria, is a major manufacturer of injection molding machines.

REFRACTORY METALS

Plansee SE, located in Reutte, Tyrol, is the leading manufacturer of refractory metals, predominantly Mo.
and W, for a multitude of applications such as sputter targets, high-temperature technology, lighting, radiation shielding etc. Some examples are given in Figure 3(a). The Schwarzkopf family owns Plansee. The company will celebrate its 100th anniversary in 2021, which coincides with the Plansee Seminar, the most important congress on refractory metals and hard materials, which is organized and coordinated by Plansee SE in Reutte every 4 years.

Every visitor to Plansee is surprised how the company has been able to locate their facilities, both of Plansee and its sister company Ceratizit Reutte, in a very rugged and mountainous area, as visible in Figure 3(b). Plansee SE is part of the Plansee group that also includes Global Tungsten Powders (GTP), 50% of Ceratizit and 21% of Molymet (Chile). Plansee is headquartered in Reutte but runs many subsidiaries in numerous countries such as Germany, the USA, China, Japan, and India.

METAL-BASED FRICTION MATERIALS

Another division of the Miba group is active in the field of metal-based friction materials: Miba Frictec GmbH from Roitham, Upper Austria. Their production range includes metal-bonded friction materials for brakes and clutches in trucks, high-speed trains, mining vehicles, windmills etc. Miba Frictec also has production sites in the Czech Republic, Slovakia, the USA, and China.

TOOL MATERIALS

One of the major manufacturers of powder metallurgy tool and high-speed steels is located in Austria: voestalpine Böhler Edelstahl GmbH & Co. KG (BEG), part of the voestalpine group. Although the large majority of steel grades produced by BEG are ingot-metallurgy grades, PM grades make up the premium grades, with a higher price but excellent performance. The steels are manufactured by gas atomizing of melts using a proprietary technique, encapsulating and hot isostatic pressing (HIP), with subsequent hot working by swaging, rolling etc. The product range includes cold work tool steels with particularly high toughness and wear resistance, high-speed steels that exceed the alloy element content possible through ingot metallurgy, and injection molding grade steels that combine wear and corrosion resistance.

The commercially most important PM product is hardmetals, and two major manufacturers are located in Austria: as mentioned above, the Austrian branch of Ceratizit SA in Reutte, Tyrol (the other branch is located in Mamer, Luxembourg) and Boehlerit GmbH in Kapfenberg, Styria. Ceratizit was formed in 2002 by a merger of Plansee Tizit from Austria and Cerametal from Luxembourg and is producing virtually all sorts of hardmetal tools and tool holders, with a multitude of different hardmetal grades. They are also highly innovative in processing, pioneering for example the environmentally friendly water milling of hardmetals. Boehlerit in Kapfenberg grew out of Böhler but now belongs to the Leitz group of Oberkochen, Germany; they produce a variety of hardmetal tools and grades and are highly active in the field of ceramic coatings on hardmetals - see Figure 4(b). Boehlerit also has production facilities in Germany, Spain, and Turkey.

Tyrolit Schleifmittelwerke Swarovski KG, part of the Swarovski group, is a large manufacturer of abrasive grinding wheels but also of PM diamond tools for concrete cutting, rock drilling, wire sawing etc.

ADDITIVE MANUFACTURING

As in other countries, metal additive manufacturing (AM) is a sector that is very much on the move, with techniques and products developing at a rapid pace. As stated above, voestalpine Böhler Edelstahl are producing atomized powders for AM in Kapfenberg; their laser-based AM facilities are, however, located in Germany (Düsseldorf), North America and Canada, Taiwan, and Singapore. Laser-based techniques are used by Pankl
Racing Systems AG in Kapfenberg, which supplies components for Formula One racing cars; primarily Ti- and Al-based parts. There are, however, also considerable activities in indirect, “binder-based” or “sinter-based” techniques. One of the major players is Lithoz GmbH, a spinoff from TU Wien, which is producing machines for stereo-lithographic production, usually of very small and precise components; the light-curing chemicals required are developed together with TU Wien. Originally Lithoz started with machines for polymer and ceramic parts; recently they have expanded into metals and have founded a daughter company Incus, which handles the metal business. Some metal parts produced by stereo-lithography are shown in Figure 5.

There are further small- and medium-size companies that fabricate machines for indirect metal AM shaping, such as the Fused Filament Fabrication (FFF) process. Both HAGE from Styria and Evo-Tech from Upper Austria supply equipment for FFF; a process significantly more cost-effective than laser-based powder-bed machines. The sinter-based techniques have recently made considerable progress in Austria.

**RESEARCH, DEVELOPMENT AND EDUCATION IN PM**

Technische Universität Wien (Vienna University of Technology) has been the main research and teaching establishment in powder metallurgy for the last decades. Both activities are located at the Faculty of Technical Chemistry, Institute of Chemical Technologies and Analytics (TUW-CTA). In 1964 Richard Kieffer, the former CEO of Plansee, was appointed Full Professor for Chemical Technology of Inorganic Materials there and focused the institute towards PM, which orientation was continued by his successor Benno Lux and subsequently the author of this article, who succeeded Benno Lux as the head of the chair in 2003. The institute is active in all major areas of PM such as sintered ferrous structural and functional materials, hardmetals, cerments and coatings, light alloys and composites. It combines manufacturing of PM materials with elaborate methods for characterization, in particular chemical and structural analysis, as well as ultrasonic fatigue testing.

In the Faculty of Mechanical Engineering, Institute of Materials Science and Technology (IMST), a sizeable group is working on PVD hard coatings, mainly in cooperation with the tooling and sputter target industry. Another group has been the nucleus for founding of the companies Lithoz and Incus (see above), and intense cooperation with both companies continues.

At the University of Mining and Metallurgy Leoben, Styria (“Montanuniversität”, MUL), PM activities are focused on characterization of PM materials, mostly carried out at the Department of Materials Science and the Materials Competence Center Leoben (MCL). In the Technology Transfer Centre of the MUL, PIM is a hot topic. Work is concentrated mainly on advanced binder systems; knowhow having been transferred also to sinter-based metal AM processes such as fused filament fabrication. At the Institute of Chipless Forming, laser-beam-based AM has been established; this work is done in cooperation with industry.

Among non-university research institutions, the Light Metals Competence Center in Ranshofen, a daughter institute of the Austrian Institute of Technology (AIT) works on PM of Al-base materials, in cooperation with the respective companies (Al-base composites and foams). A spinoff research company of AIT located in Seibersdorf, south of Vienna, is “RHP Technology”
which focuses on rapid hot pressing of a wide range of powders. RHP does research as well as small series production and runs a Dr. Fritsch hot press with direct heating of the powder batch through electric current. Another focus is PIM, since the small PIM spinoff formed in 2010 from AIT merged with RHP in 2013.

FOTEC, the RTD company of the Fachhochschule (University of Applied Sciences) Wiener Neustadt, works on powder injection molding—jointly with TUW-CTA—and on additive manufacturing operating several laser machines; also the Upper Austrian University of Applied Sciences is working on AM.

PM teaching is done primarily at TUW-CTA. At the Faculty of Technical Chemistry, the technical chemistry master curriculum offers five special branches. One of these is “high-performance materials,” which is strongly focused on PM, teaching being done not only in classes but also practically in lab courses. Typically, about 15 PhD candidates are working on PM topics at any given time. At Leoben University and Graz University of Technology, optional PM classes are offered within the materials science and mechanical engineering curricula; in these cases, R&D specialists from industry teach the classes.

In general, close cooperation between scientific institutions and companies is a typical feature of PM in Austria. Support also comes from Associations such as the PM group of the Austrian Society for Metallurgy (ASMET) and, mirroring the international orientation of companies and institutes, from membership in the trade association “Fachverband Pulvermetallurgie” and its scientific partner “Gemeinschaftsausschuss Pulvermetallurgie” or in the European Powder Metallurgy Association (EPMA). The latter has also organized PM congresses in Austria such as PM2004, the World Congress held in Vienna 2004, and EuroPM2014 held in Salzburg.

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Figure 5. Metal components produced by stereo-lithography (INCUS GmbH)
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POWDER METALLURGY IN BRAZIL
Thales Lobo Pecanha*

After 40 years of growth, the powder metallurgy (PM) market in Brazil has gradually declined from 26,000 mt/year to 16,000 mt/year, due to the economic crisis in Brazil, which followed the global economic crisis of 2008–2009.

During this period, the local car production also declined from 4.5 million/year to 2.7 million/year; an indication of the strong relationship between sales of PM products and the automotive industry. Our expectation is that the industry will produce 3.2 million cars in 2020, and the recovery to the 4.5 million/year production level will take four or five years more.

The market for PM products is similar to that in other countries; 70% being related to cars and the two-wheeler market, 22% to home appliances, and the remainder to other industries.

There are some studies that indicate that 20% of the PM parts used in Brazil are directly imported as parts or are already inside large automotive components such as gearboxes and home appliance components.

Powder production in Brazil for PM applications represents 65%–70% of the demand and the balance is supplied from the USA, Canada, and Sweden. Small quantities also come from Europe, China, and India.

Brazil has eight medium/large companies dedicated to PM production and two or three in-house facilities; one of them producing MIM products. Specialized and small companies constitute less than 3% of the remaining market. There is one new initiative in the MIM market.

There are several technical institutes, some not related to universities, that are conducting studies in the science of powder technology. Recently there have been developments related to metal additive manufacturing (AM) with laser or plasma, special and high-entropy alloys (HEA) for biomaterial applications, reinforced aluminum, and magnetic materials.

Prior to 2019 there was only one powder injection molding (PIM) producer in Brazil. A second will start production tests in 2020.

AM is being developed, and several technical institutions and companies are studying its industrial and commercial use. There is one producer of additive 3D equipment, and powder production is being considered for this type of application.

Special components have been produced for application in petroleum drilling such as as the cap top shown in Figure 1.

There are six main research institutions in Brazil working in the PM field and around 30 postgraduate students are working on their Masters and PhD courses.

Metalpó, along with four other 100% Brazilian capital enterprises, was established 40–50 years ago. Approximately 20 years ago, international PM groups acquired the two of the larger companies, and another two were incor-

*President, Metalpo Industria e Comercio Ltda., Rua Cel. Jose Rufino Freire, 453, Sao Paulo SP, Brazil; Email: thales@combustol.com.br
Today the four principal producers in Brazil supply 75% of the demand. Metalpó, a PM parts producer, is one of them. Metalpó is also involved in powder production, heat treatment, furnaces, ceramics, and R&D projects in AM and PM electro-mobility products through its sister companies.

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POWDER METALLURGY IN CHINA
Yang Cao* and Kai Xu**

CHINA ECONOMIC DEVELOPMENT AND PM INDUSTRY DEVELOPMENT
Although China’s economic growth has slowed since 2010, its gross domestic product (GDP) has maintained a growth rate of more than 6.6%. In 2018, it exceeded $12.9 trillion, as shown in Table I.

The development of the powder metallurgy (PM) industry in China has mainly benefited from the continuous development of China’s automobile, motorcycle, and home appliance (mainly air conditioner and refrigerator) industries. PM automobile parts, motorcycle parts, and compressor parts for air conditioners and refrigerators have always been the main products of the PM industry in China. There is no doubt that China is now the largest producer of, and market for, automobiles, motorcycles, air conditioners, and refrigerators.

The output of the automobile industry and air conditioner industry has maintained a growth trend in China since 2010. Although China’s automobile production and sales declined in 2018 for the first time since 1991, it still has ranked in first place globally for ten consecutive years. The refrigerator output has basically stabilized at the level of 75–94 million units, while the motorcycle output has decreased year-by-year since 2011, as shown in Figure 1 and Figure 2.

It is noteworthy that the production of PM components for air conditioners, refrigerators, and motorcycles in China has basically been localized, while it is estimated that nearly half of the PM components used in the automotive industry in China are produced by foreign enterprises in China or imported.

IRON & STEEL POWDER SHIPMENTS AND CONSUMPTION
According to the incomplete statistics of PM Business Website (PMBIZ.com.cn), there are more than 110 metal powder producers in mainland China, including a few wholly foreign-owned enterprises of famous global powder suppliers, which meet the needs of PM parts manufacturers in the China market for different grades of metal powders.

The total shipments in China’s iron and steel powder market in 2018 were 595,000 metric tons (mt), and the shipments of iron and steel powders of the

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<tbody>
<tr>
<td>GDP (CNY trillion)</td>
<td>41.2</td>
<td>48.8</td>
<td>53.9</td>
<td>59.3</td>
<td>64.1</td>
<td>68.6</td>
<td>74.0</td>
<td>82.1</td>
<td>90.0</td>
</tr>
<tr>
<td>GDP (US$ trillion)</td>
<td>5.9</td>
<td>7.0</td>
<td>7.7</td>
<td>8.5</td>
<td>9.2</td>
<td>9.8</td>
<td>10.6</td>
<td>11.7</td>
<td>12.9</td>
</tr>
<tr>
<td>Growth Rate</td>
<td>10.64%</td>
<td>9.55%</td>
<td>7.86%</td>
<td>7.77%</td>
<td>7.30%</td>
<td>6.91%</td>
<td>6.74%</td>
<td>6.76%</td>
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Assuming an exchange ratio of 1US$ = 7CNY

*Vice President, NBTM New Materials Group Corp., Deputy Secretary General of Powder Metallurgy Association of China General Machine Components Industry Association (CMPMA), email: caoyang@pm-china.com, **Vice President, NBTM New Materials Group Corp., PhD, PMT II, 1508 Jingjiang Rd., Ningbo, China 315191, email: xuk@pm-china.com
45 members counted by the Powder Metallurgy Branch Association of China Steel Structure Association were 521,000 mt. Since 2006, the iron and steel powder shipments of the members of the association have maintained a sustained growth trend, as shown in Figure 3. About 72.1% of iron and steel powder is used for PM structural components in China. In addition, 7.2% is used for welding materials, 6.3% for metallurgical additives, 5.8% for soft-magnetic materials, and 3.7% for diamond tools.

**THE DEVELOPMENT OF PM STRUCTURAL COMPONENTS**

According to incomplete statistics of the PM Business Website (PMBIZ.com.cn), there are more than 660 PM structural parts manufacturers in Mainland China, among which the sales of the two largest enterprises are about $271 million and nearly $143 million respectively.

According to the statistical data of nearly 50 members of the Powder Metallurgy Association of China General Machine Components Industry Association (CMPMA), the production of PM parts was about 200,000 metric tons, and sales were about $1 billion in 2018. These data do not include the sales of foreign enterprises in China. In addition, there are a large number of PM structural part companies that are not registered with CMPMA. Therefore, the true market scale should be much higher than $1 billion. Production has basically maintained a continuous growing trend since 2006, as shown in Figure 4.

Figure 5 shows the distribution (by weight) of PM structural parts applications according to the 2016 statistics of the Powder Metallurgy Association of China General Machine Components Industry Association. 54.7% PM structural parts are used for automotive, 18.9% used for home appliance (such as compressors in air conditioners and refrigerators), and 9.6% for motorcycles. If the distribution is calculated by sales,
automotive parts account for more than 60%.

Around half of the PM structural parts used in the China automotive industry are made by foreign enterprises in China or imported as assemblies.

Representative PM structural components made in China include sprockets for chain systems, VCT/VVT components, synchronizer hubs for transmissions, and planetary carriers etc., as shown in Figures 6, 7, and 8.

In terms of technology, warm compaction/warm-die compaction, surface densification, high temperature sintering, and sinter hardening have been used in the China PM industry to increase the density and strength of PM components. CNC presses are utilized to make complicated shaped, multiple-level parts. For lightweight materials, sintered aluminum and titanium alloys are being developed. Rubber over-molded sprockets (where a rubber cushion ring is attached to PM sprockets to reduce NVH) is an example of PM technology combined with another technology to enhance the performance PM parts further and expand the application of PM.

Although the China automobile market declined in 2018 and 2019, there is still growth potential for the PM structural parts industry in China. According to Höganäs AB, the estimated weight of PM parts in automotive applications in 2014 was 22 kg in North America, 9–10 kg in Japan & Europe, and 5.5 kg in China. Converting more parts to PM in vehicles made in China could further increase the usage of PM parts and offer more opportunities for PM manufacturers.

**THE DEVELOPMENT OF OTHER PM INDUSTRIES**

**Metal Injection Molding (MIM)**

In recent years, MIM technology has developed rapidly in China. Especially after 2015, the industrial growth trend is significant. It exceeded $830 million in 2018, as shown in Figure 9. About 65.7% of MIM parts are used for mobile phones and 7.2% for automobiles in China, as shown in Table II. This is quite different from the US MIM market, where more than 60% of the MIM market share is for medical applications and firearms.

In 2018 the usage of MIM feedstock in China was about 13,000 mt. Overseas suppliers provided around 6,000 mt, especially for high-end customers. Domestic feedstock suppliers made about 3,000 mt while in-house made feedstock by MIM manufacturers was about 4,000 mt. The most used material in the MIM market in China is SS-17-4PH, followed by SS-316L/304L and carbonyl iron.

China’s MIM industry mainly benefited from the growth of the mobile phone industry in China. Production of the lightning connector (SS-17-4PH) represented the largest quantity of parts made in MIM history.

**TABLE II. MIM PARTS APPLICATIONS IN CHINA**

<table>
<thead>
<tr>
<th>Applications</th>
<th>Mobile Phone</th>
<th>Auto</th>
<th>Wearable Device</th>
<th>Hardware</th>
<th>Computer</th>
<th>Medical</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>Share</td>
<td>65.7%</td>
<td>7.2%</td>
<td>6.9%</td>
<td>6.0%</td>
<td>4.9%</td>
<td>3.9%</td>
<td>5.4%</td>
</tr>
</tbody>
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*Data Source: Powder Metallurgy Branch Association of China Steel Structure Association*
between 2013–2018. In 2014–2017, tray, ring, and button parts (SS-316/SS-17-4PH) for smartphones were produced on a large scale. Multi-function sensor and lens group (PANACEA) used in mobile phone cameras became popular in 2017–2018. In 2018–2019, a MIM micro-gearbox (SS-316/SS-17-4PH) replaced plastic gears in mobile phones, and a hinge for mobile phone flexible folding screens was introduced due to shape complexity and material durability.

MIM’s material designability, combined with shape complexity, gives MIM technology a huge potential in mobile phones, automobile applications, and wearable devices. It is expected that the China MIM market will continuously prosper thanks to the emergence of the 5G era.

**Metal Additive Manufacturing (AM)**

Metal additive manufacturing has grown rapidly in China in recent years. According to the Ministry of Industry & Information Technology, China’s AM industry average annual growth rate was more than 27% between 2016–2018. The AM market growth trend in China is shown in Figure 10. It is estimated that sales were near $2.43 billion in 2019. In November 2017, the Ministry of Industry & Information Technology of China published “The Action Plan for Additive Manufacturing Industry Development (2017–2020)” and intended to reach $3 billion for the China metal AM industry.

The major metal AM materials include titanium alloys, aluminum alloys, stainless steels, tool steels, Co-Cr-Mo alloys, and high-temperature alloys. Applications of metal AM are in the medical, energy, automotive, and aerospace industries. The future of metal AM in China is focused upon rapid growth of large-scale applications in the aerospace and medical fields.

There are still opportunities for breakthroughs in metal AM technology. For example, the binder-jetting (BJT) process, which combines 3D printing and powder metallurgy, shapes the powder feedstock through 3D printing, then debinds and sinters the green parts using conventional MIM post-treatment processes to obtain metal parts.

**Cemented Carbides**

China is a large producer of cemented carbides with about 39% of global output. In recent years, China’s cemented carbide production has grown steadily, with an output of about 38,500 mt in 2018. The growth of cemented carbide production in China in recent years is shown in Figure 11.

**SUMMARY**

China’s PM structural parts industry benefits from the huge volume of China’s automobile, home appliance, and motorcycle industries, maintaining a growth trend. Although the growth of China’s automobile industry has slowed, the world’s largest market for a consecutive 10 years continues to support a need for PM structural parts.

In addition, there are still some quite large-scale PM automotive parts with a localization trend. The impact of electric vehicles on the demand for traditional PM automotive parts is still being watched closely. China still has the most competitive air conditioning, refrigerator, and motorcycle industries in the world, and the demand for PM structural parts will continue. In contrast to other countries or regions, the demand will continue in China for PM parts for home appliances and motorcycles.

China’s MIM industry has developed rapidly in recent years, and the future is expected to prosper thanks to the development of China’s mobile phone industry, wearable devices, and automobile industry. China’s metal AM industry is also growing at a rate of more than 27% per year.

The output of China’s cemented carbides has been in the forefront of the world, and has maintained a sustained growth.

**ACKNOWLEDGEMENT**

Special thanks to Dr. Yau Hung Chiou at You Need Technology Office for MIM information, and Dr. Garrison Zong at 3DP Technology Inc. for additive manufacturing information, both of whom have been actively promoting MIM and AM in China.
INTRODUCTION

The powder metallurgical industry in Germany has a very long history going back to the beginning of the 20th century. Over the years, many of the historically established companies have become well-known global players with production facilities all over the world. The German PM association, “Fachverband Pulvermetallurgie (FPM)”, was founded in 1947 and currently consists of 55 member companies. The list of corporations includes 6 parts manufacturers, 9 powder companies for ferrous and non-ferrous powders, 22 hard metal (cemented carbide) companies, and 17 PM process technology companies, plus a membership of the European Powder Metallurgy Association (EPMA).

After the global recession of the late 2000s, the German PM business was able to show a solid recovery for the following years, reflected in the value of delivered parts. The powder consumption by the German FPM members reached its maximum in 2018 with a usage above 54,000 metric tons (mt) (Figure 1). For 2017 and 2018, the economic growth flattened out and the latest figures indicate a challenging trend for 2019 and 2020.

GLOBAL AND EUROPEAN IMPACTS ON GERMAN PM INDUSTRY

As already shown in previous discussions, German PM has to cope with multiple European and global influences, so a discrete spotlight on only German topics remains challenging. Among others, the influence of the European Registration, Evaluation and Authorization of Chemicals (REACh) regulations and the global trend of increasing electromobility deliver new aspects to the German PM developments.

REACH and Environmental Regulations

The European Regulation REACh was put into force in 2007 and shifts the...
POWDER METALLURGY IN GERMANY

responsibility for collection, evaluation and assessment of materials data from the authorities to industry. This regulation should standardize the various laws and regulations for handling chemicals, ensuring environmental and occupational safety, and should control the flow of materials and the production of the individual substances both within and entering the EU. Individual substances had to be registered with the European Chemicals Agency (ECHA) following the overall principle "No Data—No Market", ensuring the substances are publicly known for everyone in their application and classification. Similar registration requirements are now being implemented worldwide in all trade associations.

Together with initiatives for occupational safety, the influences of REACH heavily facilitate programs to reduce and even substitute substances of very high concern (SVHC) such as nickel. In order to reduce Ni dust in working environments, binder-treated and diffusion-alloyed powders as well as new alloys could be key for the future.

Electromobility

After China and the USA, Germany is the third largest market for electrical and plug-in-hybrid vehicles. In the first quarter of 2019, the demand for such vehicles in Europe increased by nearly 36%. The altered technology compared with classical combustion-engine cars requires a significant shift in the parts portfolio of PM producers. This will have an impact on the parts’ geometry as well as the materials used.

On the materials side, the significantly increased demand for classical PM alloying elements like copper and nickel might intensify the price discussion about these elements and increase the demand for alternative alloys for ferrous PM parts. Materials with chromium, silicon, or vanadium are already commercially available, but often require high-temperature processing to make the optimum use of these oxygen-sensitive alloying elements. Since the availability of high-temperature furnaces with high productivity is still limited, there is still a slow adoption of these materials—although the implementation has already been started in various projects and products.

IRON-BASED POWDER METALLURGY

In recent years, the knowledge in relation to the fatigue design of sintered PM components has increased dramatically. The German-speaking expert circle “Sintered Steels” (Expertenkreis Sinter-Stähle) has derived and applied a few correction factors according to the “FKM guideline” (a standard-like guideline for strength assessment), which improve the prediction of fatigue life significantly. The expert circle “Sintered Steels” (Expertenkreis Sinterstähle) consists of industry and academia members from: VW, Bosch, ZF, Schaeffler, Miba, Schunk, SHW, Sumitomo, GKN, Bleistahl, PMG, BPW, Pometon, Höganäs AB, Rio Tinto, Hoeganaes Corporation, Fraunhofer LBF, RWTH Aachen University, HTW Berlin University, BAM, and FPM. All members agreed in a common way to do the fatigue assessment. It has become standard practice in the German-speaking PM industry to include effects from the density ρ, the loading ratio R, the support effect, the surface/heat treatment, and the material and manufacturing scatter into the fatigue design. This approach will be further improved by its application to different sintered PM components, or derivation of more data sets and the development of more correction factors. Moreover, it is planned to incorporate these findings into the “FKM guideline” to make the understanding of sintered PM steels more widespread. The next potential correction factor concerns internal cracks and defects. In the classical fatigue concepts, materials are assumed as ideal without stronger inhomogeneities. However, customer feedback indicates that this assumption is too optimistic. The assessment of internal cracks and defects (e.g., nonmetallic inclusions, large pores, delaminations, etc.) is challenging. Nevertheless, for the PM industry, it is of critical importance to work on this topic in the future in order to define clear limits. First of all, a common definition (which is acceptable for the PM industry and the end-user) is required of what constitutes a defect. A geometric characterization is then needed to derive a quantity that describes the size and the location of that defect. That is a difficult target, because from the most common 2D micrographs the third dimension is missing. Moreover, a 2D micrograph is not representative of the whole material volume. The critical nature of the defects depends on their size, their location (surface or internal defect), the fracture-opening mode (tensile or shear), the applied stress distribution, and loading history (static or cyclic loading). In general, there are two principles to include the effect of defects into a static or cyclic stress assessment. The classical approach is to model/implement the crack geometry into the FEA mesh. The resulting quantity derived is the stress intensity K, which must be compared with the corresponding material fracture toughness. However, that is a complex and very scientific approach if the stress intensity is a function of time K = K(t) because two scenarios are possible: The crack grows (crack propagation) or the crack propagation rate becomes 0 mm/cycle. In general, a growing fatigue crack will cause damage and fracture after a certain time period. The toughness and the wall thickness of PM components are not so high that this approach will have a strong impact on the service life. The second
approach has a higher practical relevance. If the cyclic stress intensity, $\Delta K$, is smaller than the cyclic threshold stress intensity $K_{th}$, in practice the crack will not grow and the component is safe. This approach was modified and further developed by Japanese research groups.7 Kitagawa and Takahashi have combined the classical fatigue experiment (independent of the crack size $a$) with the stress range, $\Delta \sigma$ resulting from the crack propagation experiment (which is dependent on the crack size $a$). The intersection point of both curves results in the critical defect size, $a_0$. This metric can be used as a compromise for the PM industry and the user of PM parts, since this equation defines the critical defect size, $a_0$, based on two measured values (the fatigue strength at the knee point, $\sigma_A$, and the cyclic threshold stress intensity, $K_{th}$, for a given loading ratio R). The beauty of the Kitagawa-Takahashi approach is that the “virgin” fatigue strength at the knee point, $\sigma_A$, can be corrected with the defect size, a. So, the exact modelling of the crack geometry is not needed. The local fatigue strength at the knee point, $\sigma_A$, will be reduced during the FEA-based fatigue assessment. On the other hand, smaller cracks with $a < a_0$ can be tolerated. In addition, the results from NDT inspections can be interpreted in a different manner. Since every NDT method has its own resolution limit, a defect size $a^*$ of the resolution limit can be applied for very critical components. This damage tolerance design principle is also used in the nuclear and aerospace industries and is essential if the critical defect size, $a_0$, is smaller than the NDT resolution limit, $a^*$. In that case, the reliability of the NDT-inspected component remains uncertain. A similar approach is one from Murakami. However, the predicted drop of the fatigue strength at the knee point, $\sigma_A$, is different for both approaches (Kitagawa-Takahashi vs. Murakami), but the strengths are similar and can be summarized very briefly:

- No explicit modelling of the crack geometry in the FEA model needed
- No focus on the crack-propagation phase but on whether a crack will grow or not
- Local fatigue strength at knee point, $\sigma_A$, depends on defect size and can be reduced
- A critical defect size can be defined ($a_0$ of the Kitagawa-Takahashi approach)
- Reliability of NDT methods can be improved by the damage-tolerance design principle

**ADDITIVE MANUFACTURING**

Additive manufacturing (AM) using metal powders is expected to grow into an established production technology and provide a new market development tool for the whole PM industry. Several market analysts share growth expectations of the AM industry with greater than 20% year-over-year growth for the next five to ten years, especially for metal AM. This is driven through the main advantages of the technology: design freedom (design to function vs. design to manufacturing), lightweight design, mass customization, functional integration, and short lead-time (tool-free production). Germany has an extensive technological background in additive manufacturing, especially in powder-bed fusion using lasers (PBF-LB). Six out of seven major global suppliers of PBF-LB machines have their origins in German-founded companies. This results in a strong R&D infrastructure with globally leading research organizations from Fraunhofer and university-based research groups.

Due to the long-term experience and trust generated in the PBF-LB technology, some industries have already adapted well to the new opportunities the technology is offering. The pioneering applications now being fully established are tooling, medical implants/instruments, dental restorations and prototyping. In other industries, a fully validated production is in development. Aerospace is offering the largest potential with some parts already in production. Within the automotive industry, one of the industries most familiar with powder metallurgy production technologies, additive manufacturing is already established as a prototyping technology. The main advantage is to supply functional models for pre-series testing within two-week lead times. Development cycles can be reduced significantly. Nevertheless, many German as well as international OEM’s are investigating the potential of AM for serial production. BMW recently announced their first metal AM serial production for the BMW i8 Roadster.8 Serial production is still very limited, the greatest hurdle for a successful business case being the cost per part. The main drivers for the high production costs are: high equipment cost with low part throughput, high post processing (machining) cost for functional parts, and high material (powder) cost.

Many fundamental as well as industrial research activities are focused to overcome these limitations to enable a wider range of applications with a lower entrance hurdle for the return on investment. The German government as well as the European Union have a strong focus to support collaborative programs on AM technology development with the overall goal to enable industrialization of AM with new materials, automation, productivity, and industrial internet of things (IIoT) integration. To overcome these limitations and enable wider application, collaboration has been the focus in 2019. One example is the cooperation of GKN, HP, and Volkswagen to develop and industrialize binder-jetting technology (BJT).9 This enables all involved partners to decrease time to market and make...
sure material, hardware, process, and application are well aligned and lead to a technology suitable for mass production.

With the launch of HP’s new Metal Jet system, binder jetting looks like the technology that will help overcome the aforementioned challenges in part cost, to enable mainstream mid- to high-volume manufacturing. Claiming to be up to fifty times more productive than comparable AM methods, the technology represents a significant change in the market. The range of volumes at which AM is more economical than traditional processes will increase. The shaping equipment is only one part of the solution though; understanding how to use the new technology and having a sustainable and efficient process chain including powder material and sintering are also vital parts for success of the technology. A first application launch has been successfully completed with the production of 11,000 Volkswagen ID.3 models (Figure 2).

In conclusion, additive manufacturing seems to be on the brink of establishing a new production technology enabling end-users to increase product value through design to function. Nevertheless, the main hurdles still to overcome are productivity, development of standards through organizations like VDI or DIN/ISO, as well as training the designers, digital integration of machines, and automation.

SOFT MAGNETIC COMPONENTS

A stronger focus on electromobility leading to new e-motor concepts is opening new market potential for PM parts in Germany. In competition with well-established e-motor producers with defined supply chains, it is understood that German (and global) PM manufacturers will need technical differentiators and understanding to increase their market share.

If mechanical power is used as a key parameter for electrical motors, this can be improved by increasing the efficiency of the machine, the electrical input power, the speed, or torque. The optimization of each parameter can be achieved by different physical measures resulting in a variety of possible designs for an electric machine with the same power. Furthermore, the individual physical measures are dependent on each other, so that the design process of an electric motor can be very complex. Design parameters defined by the adjacent systems may include space, electric power supply, performance profile, thermal boundaries, overload capability, lifetime or safety. This illustrates that an overall vertically integrated and systemic approach in the design stage is an essential component for the realization of appropriate electric motors. This might be a challenge for powder metallurgy companies, which have grown over decades into a single part of the horizontally integrated automotive industry. Particularly, in the area of new types of materials—for example, SMC—the successful handling of these new challenges is essential.

The task to create an innovative e-drive concept for a sporty rear-wheel driven Pedelec can be used to illustrate a successful development process. 10 High-driving
dynamics combined with a low-key optic as a core requirement qualified a transversal flux motor as the most promising concept. This complex-shaped motor design can be a technical differentiator using the process capabilities of PM effectively, but it also increases the demands on the electronics and on the cross-component optimization between electronics and engine. All these aspects could be covered in this project leading to significant technological advantages compared with conventional motor concepts (Figure 3). In order to achieve this, PM manufacturers must expand their technical competencies within the very agile technological field of electromobility.

**METAL INJECTION MOLDING (MIM)**

In recent years, MIM technology has developed moderately within Germany by 3%-5%, although competitive pressure from Asia is particularly noticeable. In general, the technology is becoming more and more established as an accepted production process in industry. The process chain can be easily automated and thus becomes less dependent on labor costs. The majority of MIM manufacturers in the EU are following this path. As one example, Figure 4 shows a testing and sorting machine for adjusting pieces of a coupling, which sorts two components into 20 height classes (Δ 50 µm). Approximately 70 million of these components have already been manufactured.

In the automotive sector there are several projects in which MIM components are used in the valve train. This technically interesting product group has particularly high demands on the process capability in the manufacture of the levers and also on the material properties, in particular, the fatigue strength. Here, as well, the degree of automation in the entire process chain is high.

For MIM, the aerospace sector is also becoming increasingly important. For example, MIM technology has already been used successfully in turbine construction. A further expansion of the product range is imminent.11

In general, the German MIM industry is optimistic for the upcoming future to establish technology as the manufacturing process of choice in certain product groups.

**CONCLUSION**

The limited extent of this text only permitted highlighting a few aspects of Germany’s powder metallurgy capabilities. Based on a long tradition, the industry has demonstrated the ability to adapt to new global trends like electromobility and implement new disruptive technologies like additive manufacturing. Increased efficiency in serial production, together with this technological agility, will help to realize a great future even in economically challenging times.

**ACKNOWLEDGEMENTS**

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POWDER METALLURGY IN INDIA

Gopal S. Upadhyaya*

INTRODUCTION AND HISTORICAL ASPECTS

The author has contributed reports about the status of powder metallurgy (PM) in India numerous times during the past forty-five years,¹⁻⁷ the last being in 2014. Throughout this period, there has been growth in the Indian economy, albeit with some roadblocks. The liberalization of the Indian economy at the beginning of the 1990’s attracted many overseas companies to invest in India. Although Indians were well versed in indigenous medicine-making through the powder technology route, the industrial aspect of PM began in the middle of last century, when two engineering graduates from Banaras Hindu University, Varanasi (founded by M.M. Malaviya), J.H. Upadhye (mechanical/electrical engineer) and G.V. Bhat (metallurgical engineer) ventured into the PM industry more-or-less at the same time. The former obtained inspiration from the modern pharmaceutical industry, while the latter was more concerned in making PM parts for home appliances. Mr. Upadhye had toured Europe extensively and had been impressed by German PM technology, particularly at Sintermetalwerke Krebsöge and Dorst Technologies. In 1988 he was awarded Honorary Membership of the PM Association of India (PMAI). Mr. Bhat developed cooperation with Husqvarna in Sweden, where Professor Gerhard Zapf was at the helm, and established a plant in Rajkot, Gujarat.

The history of PM in India can be classified into three periods:

• 1950–1990: This can be called the “Learning and Entrepreneurial Period,” when a number of mostly small companies emerged.

• 1991–2000: With the advent of the liberalization of the Indian economy, this period can be called the “Consolidation Period,” when the existing PM community developed self-confidence and supplied quality sintered parts to various industries in India and Asia, both for automotive and non-automotive applications. Two PM companies, Mahindra Sintered Products, Pune, and Sundaram Fasteners, Hosur, performed admirably. The first was incorporated in May 1960 and was a joint venture with Barfield Ltd (UK). Cemented carbide plants also came into existence in this period, mainly with collaboration from Sweden, Germany, and the UK.

• 2001–Present: This is the “Modernization and International-Collaboration Period,” when a number of companies, both of large and medium size, began to export their high-end products aggressively. Höganas India, Mahindra Sintered Products, Specialty Sintered Products, Sintercom, and Federal Mogul are noteworthy in this context. The driving force for such alliances was the requirement of the BS VI emission standard in automobiles. Sensors became increasingly common and they required a holder. The holder was made effectively by powder metallurgy. The standard also required a reduction in noise, vibration and harshness (NVH). The corporate average fuel economy (CAFE) norm expected to come into effect in

*Consultant, Plot 37, Lane 17, Ravindrapuri Colony, Varanasi 221005, India; Email: gsu@iitk.ac.in
2022, will create more challenges to PM manufacturers, as light-weighting and fuel efficiency will become major requirements. A comment on wholly foreign-managed companies is worth mentioning here. Some are manufacturing and developing based entirely on an international chain of business. Such a spirit of secrecy and competition prevails among them that they often do not participate in industry-wide activities such as technical conferences. American PM manufacturers recently started taking an interest in collaborations in India, particularly in the metal injection molding (MIM) and metal additive manufacturing (AM) sectors. Japanese- and Taiwanese-based companies such as Nippon and Porite have recently taken steps to enter the Indian PM market. Porite India commenced production in Q2 2017.

CONVENTIONAL PM PRODUCTION
In India the conventional “press-and-sinter” technology for metal powders preceded the tonnage production of powders. Electrolytic metal powders, although about three times costlier than atomized powders, were used for small-scale production. It took quite some time for Höganäs, Sweden, after due thought to invest in India for the production of iron powder. They have now diversified their range of powders, except for prealloyed ferrous powders. In 2018, iron-base powder production in India was 36,000 metric tons (mt) compared with 30,000 mt in 2016. During the same period, the production of PM-grade copper powder climbed to 8,900 mt from 6,000 mt. As previous reports have adequately covered the past history of the Indian PM industry, the present article summarizes the status in tabular form (Tables I–IV). Subsequent sections will deal with PM in the automobile industry, including relatively newer advances like MIM and metal AM. The author has recently elaborated on the identification and execution of research projects in powder metallurgy.

PM AND INDIAN AUTOMOTIVE INDUSTRIES
About 80% of all PM sales in India are applications in the automotive sector (two, three, and four wheelers). In the automotive sector, 31% of engine parts and 19% of transmission and steering components are manufactured locally. The present market for sintered automotive parts is three-times what it was in 2010–2011. However, automobile sales in India have currently witnessed their sharpest decline; something that should be a matter of concern for PM part producers. Opportunities in the “clean energy” market are worth considering particularly in such a big country as India that suffers greatly from air-pollution problems in urban areas and drinking water, particularly in rural areas.

The Foreign Direct Investment Program of the Government of India and the introduction of emission standards for automobiles by the Government have provided opportunities for the entry of large foreign companies and collaboration on PM part production. In 2018 growth in the automotive sector was 14%. India’s automobile market is the fourth largest in the world with capacity for significant growth. While the varying level of infrastructure, such as road facilities, is an impediment to domestic growth, the export market for high-quality automobiles is very much in vogue. In other words, India has a spectrum of needs, which sometimes detract a foreign investor. In general, there is a trend for reduction in engine size and the number of cylinders in IC Engines. This reduces weight and also promotes a drop in PM parts. But at the same time, the trend towards increased transmission speeds has provided a challenging opportunity for Indian PM part manufacturers. It is worth noting that automobile industry accounts for half of the manufacturing GDP of India. With a relatively moderate growth in GDP, India has to balance between aspiration and reality. A similar situation exists in the case of electric vehicles. The Government of India is considering a proposal to ban the sale of IC engine three-wheelers by 2023 and less than 150 cc two-wheelers by 2025.

The auto industry body Society of Indian Automobile Manufacturers (SIAM) has also advised the government to follow a well-laid roadmap and practical time frame for the rollout of electric vehicles (EV) in the country. Although the government is thinking to give incentive to EV vehicle buyers they are still too expensive. Advice has been given to emphasize hybrid vehicles initially. According to the chairman of a reputed automobile company, “To force an unrealistic deadline for mass adoption of electric two- and three-wheelers, will not just create consumer discontent, it risks derailing auto-manufacturing in India that support four million jobs.” On the other hand, there is a silver lining too, as EV will encourage production in other sectors like magnetic PM parts, which is in its infancy, particularly as far as permanent magnets are concerned.

As stated above, EV offers opportunities for innovative PM design. For example, soft-magnetic-composite (SMC) cores are used in main-drive motors and motors for oil and cooling pumps. In addition, powerful permanent magnets based on the Nd-Fe-B PM alloy are needed for brushless dc motors. In electric vehicles, we need a dc motor to drive them and an array of batteries is required to provide the necessary current density. Maruti Suzuki, the largest car-making company in India, is very aggressively entering battery production.

Unlike China, which has much cheaper and radioactive-free resources from placer clays, India has the largest resource base of monazite and is already extracting...
uranium and thorium out of monazite before passing it on for extraction and purification of rare-earth metals and their compounds. Indian Rare Earths Ltd is producing rare-earth oxides. Dura Magnets Pvt. Ltd., Satara have set up a full-fledged facility to make Nd-Fe-B magnets directly from the raw material, taking the knowhow from a collaborator in China.

**METAL INJECTION MOLDING (MIM) PRODUCTION**

India is in a proud position to have one of the world’s biggest plants, namely Indo-MIM Pvt. Ltd. in Bangalore. Earlier the company was known as Indo-US MIM Tec Pvt. Ltd., which won numerous MPIF PM Design Excellence Awards for the best MIM Parts. This company was reshaped from AF Technology India Pvt. Ltd. and came into existence in 2001 in the industrial area of Hoskote, Bangalore, where it emphasizes aerospace products. The plant manufactures precision engineered products for customers in more that forty countries in the Americas, Europe, and Asia. The company emphasizes four sectors: metal injection molding, investment casting, ceramic injection molding, and precision machining. In the auto-sector, the company caters for a wide variety of vehicle safety, fuel system, power traction and interior applications. They have developed small-arm MIM applications. Apart from this major achievement, there has not been much significant expansion of the MIM industry. The PMAI is conscious of this fact and organizes intensive workshops. One of the reasons for this temporary halt is the advent of metal AM, in which entrepreneurs are, of late, taking a keen interest. MacMA Engineering Asia Pacific Pvt Ltd, Singapore has

### TABLE I: COMPANIES PRODUCING POWDERS

<table>
<thead>
<tr>
<th>Company</th>
<th>Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>Innomet Powders, Hyderabad</td>
<td>Atomized non-ferrous powders</td>
</tr>
<tr>
<td>Lonza Ltd India, Mumbai</td>
<td>Paraffin wax, synthetic lubricant</td>
</tr>
<tr>
<td>C-MET Hyderabad</td>
<td>High-purity metal powders, e.g. Ta, Hf, etc.</td>
</tr>
<tr>
<td>P.P. Metal &amp; Co., Solapur</td>
<td>Electrolytic and atomized Cu powders</td>
</tr>
<tr>
<td>Satyam Pharmachem Pvt Ltd, Mumbai</td>
<td>MnS machining additives</td>
</tr>
<tr>
<td>SLM Metals Pvt Ltd, Rourkela</td>
<td>Sponge/atomized Fe powder, prealloyed ferrous powder, Cu/bronze powders</td>
</tr>
<tr>
<td>Sri Krishna Abrasives, Delhi</td>
<td>Cobalt powder</td>
</tr>
<tr>
<td>Metal Powder Co. Ltd (MEPCO), Madurai</td>
<td>Cu-based alloy powder, Sn, Pb, Zn, and W powder</td>
</tr>
<tr>
<td>Sarda Metal Powder, Jaipur</td>
<td>Non-ferrous metal powder fibers (since 1981)</td>
</tr>
<tr>
<td>Serena Metal Powder, Bangalore</td>
<td>Metal powders to diamond tools and PM industry (since 2009)</td>
</tr>
<tr>
<td>Sundaram Group Co., Hyderabad</td>
<td>Fe powder for in-house consumption</td>
</tr>
<tr>
<td>Nuclear Fuel Complex, Hyderabad</td>
<td>UO₂, sponge Zr, refractory metal powders in small scale</td>
</tr>
<tr>
<td>Hoganas India Pvt Ltd, Pune</td>
<td>Manufacturers and traders for five different ferrous powder premixes:</td>
</tr>
<tr>
<td></td>
<td>Interlube, Spongemix, Hipaloy, Starmix, and Densemix</td>
</tr>
</tbody>
</table>

### TABLE II: MAJOR CEMENTED CARBIDE AND DIAMOND TOOL MANUFACTURERS IN INDIA

<table>
<thead>
<tr>
<th>Company</th>
<th>Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandvik Asia Ltd, (collaborator Sandvik Coromant, Sweden)</td>
<td>Cemented carbide and HSS tool, rock-cutting tools, solid-carbide tools</td>
</tr>
<tr>
<td>• Pune</td>
<td>Stainless steel extruded tubes</td>
</tr>
<tr>
<td>• Mehsana</td>
<td>Wire and heating technology</td>
</tr>
<tr>
<td>• Hosur</td>
<td>Rock tools</td>
</tr>
<tr>
<td>• Hyderabad</td>
<td>Carbide recycling center</td>
</tr>
<tr>
<td>• Ciplun</td>
<td></td>
</tr>
<tr>
<td>Kennametal India, Bangalore (earlier Widia, Germany)</td>
<td>Cutting tool and wear parts</td>
</tr>
<tr>
<td>Ceralizit India Pvt Ltd (earlier India Hard Metals, Ltd), Kolkata/Ulubria, WB</td>
<td>Cutting tool inserts and tool holders</td>
</tr>
<tr>
<td>Electronica Tough Carbide Ltd, Nasik</td>
<td>Indexable tips, mining bits, WC wear parts, WC mill rolls, hardfacing</td>
</tr>
<tr>
<td></td>
<td>powders, powder recycling</td>
</tr>
<tr>
<td>Rapicut Carbide Ltd, Ankleshwar</td>
<td>Indexable tips, mining bits, milling cutters, WC wear parts, steel-bonded</td>
</tr>
<tr>
<td></td>
<td>carbides, tool steels, spray-formed alloys.</td>
</tr>
<tr>
<td>Stay Sharp Diamond Tool Pvt Ltd, Mumbai</td>
<td>Diamond tools for stone processing</td>
</tr>
</tbody>
</table>
opened a branch in Hyderabad. They offer consultancy in the optimization and tool development in MIM processing. Some new simulation approaches in SIGMA-SOFT virtual molding have offered optimal concepts to meet development requirements.

**METAL ADDITIVE MANUFACTURING (AM)**

Metal AM has been a recent event in India, although it maintains good progress in polymer 3D printing. In the beginning, 3D printing in India was mainly in research institutes. Lately, aerospace industries are showing an interest in the field of metal AM. One of the noteworthy entities is the GE India Technology Centre, which is based in Bangalore. From the techno-economic viewpoint, the binder-jetting process (BJT) appears to be attractive as it suits high-volume component production and in due course should attract conventional PM part manufacturers.

One of the problems for extensive growth in metal AM in India is the high cost of imported metal AM-grade metal powders. The largest user of AM parts is the aerospace sector. Hindustan Aeronautics Ltd, Bangalore, has used AM components in the Turbofan Engine-25. It has also used AM to develop a fuel system for the Sukhoi

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**TABLE III: MAJOR PRESS AND SINTERED PART MANUFACTURERS IN INDIA**

<table>
<thead>
<tr>
<th>Company</th>
<th>Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>GKN Sintered Metals Ltd, Pune (previously Mahindra Sintered Products Ltd till 2002)</td>
<td>Wide range of sintered parts including valve train components</td>
</tr>
<tr>
<td>Sundaram Fasteners Ltd, Metal Form Division, Hosur</td>
<td>As above, valve train components in collaboration with Bleistahl GmbH, Germany</td>
</tr>
<tr>
<td>Federal Mogul, Bhiwadi (formerly, Brico and Goetze, now part of Tenneco)</td>
<td>Valve seat and valve guides; shock-absorbers parts</td>
</tr>
<tr>
<td>Star Sintered Products Ltd, Noida (established in 1991)</td>
<td>Ferrous/non-ferrous non-automotive parts; air-atomization facilities; sintered magnets and metal-graphite parts</td>
</tr>
<tr>
<td>Samvardhan Mothersons Group, Puducherry (original company Sintered metal, S.A., Spain)</td>
<td>Wide range of PM parts</td>
</tr>
<tr>
<td>Nippon Piston Ring (near Bangalore)</td>
<td>Valve seats</td>
</tr>
<tr>
<td>Speciality Sintered Products Ltd, Pune (since 1998)</td>
<td>Part and accessories for motor vehicles and their engines</td>
</tr>
<tr>
<td>Sintercom India Ltd, Pune (till 2007 Maxtech Manufacturing Inc. in collaboration with MIBA Austria)</td>
<td>Automotive PM parts including exhaust systems</td>
</tr>
<tr>
<td>RVB Shorelube Industries Pvt Ltd, Kanpur (from 2017, collaborator ACL Bearing Co., Australia)</td>
<td>Automotive PM parts</td>
</tr>
<tr>
<td>Bimetal Bearings Ltd, Coimbatore</td>
<td>Copper-based bimetal bearings</td>
</tr>
<tr>
<td>Mishra Dhatu Nigam (MIDHANI), Hyderabad</td>
<td>Mo wire and sintered parts</td>
</tr>
<tr>
<td>Glotronwics Pvt Ltd, Mysore</td>
<td>Refractory metal wire/filament</td>
</tr>
<tr>
<td>Modisons, Mumbai (collaboration between 1983–96 with Duduko AG, Germany)</td>
<td>All types of noble metal contact materials in different forms; Ag powder</td>
</tr>
<tr>
<td>Heavy Alloy Penetrator Plant (HAPP), Tiruchirapally (since 1988)</td>
<td>Tungsten based heavy alloys of varying lengths and sizes</td>
</tr>
<tr>
<td>Singhal Sintered Pvt Ltd, Kosi Kalan</td>
<td>Automobile/refrigerator PM parts</td>
</tr>
<tr>
<td>Nikam Sintered Products Pvt Ltd, Kolhapur</td>
<td>Non-ferrous sintered parts since 1996; ferrous sintered parts since 2011</td>
</tr>
</tbody>
</table>

**TABLE IV: SOME PM EQUIPMENT MANUFACTURERS**

<table>
<thead>
<tr>
<th>Name</th>
<th>Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bharat Hydraulics, Amritsar</td>
<td>Presses</td>
</tr>
<tr>
<td>Fluidtherm Technology Pvt Ltd., Chennai</td>
<td>Sintering conveyor belt furnaces, walking beam furnaces, heat/steam treatment plant, handling systems.</td>
</tr>
<tr>
<td>Magnatherm Alloys Pvt Ltd., Gumidipoumdri</td>
<td>Furnace trays/equipment, refractories, muffles</td>
</tr>
<tr>
<td>MVS Engineering Ltd., New Delhi</td>
<td>Sintering atmosphere</td>
</tr>
<tr>
<td>Prexair India Pvt Ltd., Chennai</td>
<td>Sintering atmosphere</td>
</tr>
<tr>
<td>R.K. Engineering Works Ltd., Delhi</td>
<td>Heat/steam-treatment plants, oil-impregnation plant</td>
</tr>
<tr>
<td>Newmet Pvt Ltd., Mumbai</td>
<td>Handling systems / presses</td>
</tr>
<tr>
<td>Malhotra Engineers, Pune</td>
<td>Sintering furnaces</td>
</tr>
<tr>
<td>Krushal Agro Engineers, Kolhapur</td>
<td>Design and manufacturing of die-sets (since 1989)</td>
</tr>
</tbody>
</table>
MKI aircraft. The Indian Space Research Organization is not behind in adopting metal AM components. Automobile industries are also attempting to introduce some metal AM parts in assembly, but the high cost is an inhibiting factor. There are an estimated fifty metal AM systems installed in the country, the full details have been given by Gopinath. A large number of metal AM part producers are service providers. Around 5 mt of metal AM-grade metal powder was imported in the last financial year. HP Inc. India has signed a Memorandum of Understanding with the State of Andhra Pradesh to build a center of excellence for 3D printing in the state.

John F. Welch Technology Centre of General Electric, USA, is active in Bangalore in the area of AM and trying to receive orders from HAL (Hindustan Aeronautics Ltd), the major aircraft maker in India. They offer design data to enable efficient material selection, product design, and materials science services.

Metal AM is able to select either of two routes. One uses the special grade powders obtained from outside agencies. The other is an integrated approach, where all steps from powder production to final AM part production are carried out in one location. The latter looks more attractive for reactive metal AM, where the size of the plant can be of varying extent. The SMS Group of Companies in Germany has done good work in this aspect. Indian agencies like Atomic Energy and the Space Research Organisation can take advantage of this for producing niche AM parts.

Indo-US MIM Pvt Ltd has announced a strategic partnership with Desktop Metal USA, the facilities of which shall be installed at its San Antonio, Texas facility. This shall shift the paradigm from prototyping to include full-scale metal AM manufacturing.

Vyapti Technica Solutions Ltd, Bangalore has started office-friendly metal 3D printing. The method they use is Binder Metal Deposition; where layer-by-layer a green part is shaped by extruding rods made from a metal powder/wax- and polymer-binder mix.

RESEARCH AND DEVELOPMENT

Industrial

Indian PM industries of both large and mid-sizes have recognized the importance of R&D for growth. This is particularly true amongst those companies that have foreign joint ventures; the driving force being an eye on enhanced exports. Equipment for real-time product performances has been promoted to withstand competition. Cemented carbide industries, particularly, Sandvik Asia, have established five main R&D units within India with about 300 engineers and scientists, making up approximately 15% of global R&D capability. Maruti Suzuki is planning a major investment in expanding its R&D center in Rohatak in Haryana State.

Academic

The basic research in PM is carried out mainly in educational institutes and government-based research organizations, but is very limited in industry. Among educational institutes, the Indian Institute of Technology (IIT) Kanpur is the foremost, particularly on sintering aspects. Its research growth has been uniform and consistent. The laboratory is directed by Professor Anish Upadhyaya and at the last international event organized at Pune in February 2019, under the aegis of the Asian Powder Metallurgy Association (APMA), most of the papers presented were from members of this group. This was the first time that the PMAI hosted the conference.

Some of the areas of activity include sintering of stainless steels, microwave sintered tungsten alloys, activated sintering, micro-texture evolution in sintered alloy systems, stereology of sintered microstructures, eutectic additives in 2014Al sintered alloys etc. Other IITs are also engaged in PM aspects, particularly IIT Hyderabad, IIT Roorkee, and IIT Madras. IIT Bombay has reported some interesting results on ceramic processing. Among state government colleges, engineering college, Pune is also active. Other mid-size colleges have a genuine problem of a dearth of well-trained teachers and research guides; apart from the proper selection of project topics. One of the reasons for this is that practically all engineering colleges in India have mechanical engineering departments and not metallurgy departments, whose staff teach courses in PM to undergraduate engineering students. Unfortunately, the mechanical engineers are not trained in metallurgy and hence a real materials education is missing. Perhaps PM companies should propose some suitable research projects with shared responsibilities.

Atomic Energy Centers in India are doing good work, but rather slowly despite their large budgets. The problem is primarily due to the lack of trouble-free functioning of sophisticated equipment. The Defense Metallurgical Research Laboratory has done some interesting work on inert-gas atomization (100 kg per batch) for complex superalloys and steels, and warm isostatic pressing, where the pressure medium remains liquid but the pressing is performed at temperatures in the range 80–300 °C. In the areas of rare-earth permanent magnets, PZT ceramics have reported research. The technology of producing SiC whiskers from rice husks has been developed, but not yet scaled up.

The International Advanced Research Centre for Powder Metallurgy and New Materials (ARCI), a department of science and technology center managed by the Central Government at Hyderabad has initiated some work to produce indigenously on a pilot scale, the Ni-based superalloys Inconel 625 and Inconel 718 using gas atomization, followed by AM part manufacturing.
System Design

Design has a general as well as a special connotation. Tooling design is an area where India was lagging, but of late, a computational approach has made the job easier. The personnel in design and materials departments need to interact more often. When part sizes in assemblies are getting smaller and more complex, this challenge is more acute. Government R&D Centers have to forego any ego and embrace cooperative, and well-planned collaboration from any sector that benefits them.

PM TRAINING

The PMAI holds annual short courses in PM in different cities. As it is mostly for beginners in the industry, more sequentially graded courses covering different specialized aspects of PM operations are called for. They should not hesitate to invite overseas experts. For management level staff from industry, specially tailored courses are required. This will help them make unbiased decisions in procuring sophisticated equipment. The author is aware of some cases, where unsatisfactory equipment led to closure of some plants. Nevertheless, there is a silver lining. Sandvik Asia Ltd, Pune, has started a training academy in Nagpur, mainly catering for mining organizations and the efficient use of mining tools.

REFERENCES


POSTSCRIPT

Since this article was written, many upheavals have been witnessed at a global level due to the COVID 19 pandemic. The pandemic has presented many challenges, and each country faces a unique situation. The biggest problem is the lack of an adequate supply of PPE and ventilators. The AM companies in India have come forward to help with this, although on a humble scale. In a multi-religion country like India, with a high population density, and where there are some religious dictates against social distancing, the problem is a formidable one. It is true that in the past India has witnessed other epidemics like SARS. However, the current unexpected crisis has had an impact on GDP growth. Even with strict social distancing, the modern technological tools need to be pooled, and herein lies the challenge of Governance more than Government. One thing is certain, the present crisis has put globalisation in a reverse gear, which is understandable. That bilateral cooperation shall be more visible is a logical fall out. It is worth noting the enhanced Indo-US cooperation in this direction.
POWDER METALLURGY IN JAPAN
Yoshinobu Takeda*

PRESS AND SINTER
This is the most important area for the powder metallurgy (PM) industry in Japan. A number of outstanding developments were awarded by the Japan Powder Metallurgy Association (JPMA) and reported in the Journal of the Japan Society of Powder and Powder Metallurgy (JSPM). PM components need to have more complicated configuration, more functions, and higher strength/densities with higher traceability, and most importantly cost less. The following examples show the reality of what has been accomplished by the Japanese PM industry in the past five years.

The large ravigneaux planetary carrier (Figure 1) developed by Toyota Motor Corporation was, at first, two PM components simultaneously sinter-brazed with a stamped steel sleeve and welded to a stamped steel hub. The real innovative development is compaction with a newly developed, large electric servo press, equipped with a quick tool-change system, which enabled a 160 second tooling change. This was coupled with a proprietary powder-filling system that required no press adjustments after changing the compaction tools.\(^1\)

Sumitomo Electric Industries developed a cycloid gear set for an electric VVT system: camshaft gear, planetary gear, and sprocket gear. They constructed a new “Internet of Things” (IoT) plant for mass production.\(^2\) Each component is marked with a 2D code right after compaction, and a production record that includes the date and time of production, process conditions (press operation diagram, bottom dead center, sintering temperature chart, etc.) stored as a large data file. It ensures the traceability of the components. The plant is almost fully automated to realize one-piece-flow manufacturing and synchronized production as illustrated in Figure 2. It has a capacity of 500,000 pieces per month, including heat treatment and finish machining.

A new die-wall lubrication method to achieve density over 7.5 g/cm\(^3\) with-
out heating was developed by Hitachi Chemical for the mass production of engine sprockets.\textsuperscript{3} As shown in Figure 3, a liquid lubricant is fed from the bottom side through the channel.

In order to get either higher precision and/or a more complicated configuration, machining is often used and various technologies to reduce machining cost have been developed. Both powder suppliers and a component manufacturer developed machining enhancers. Kobe Steel developed KS-100X, 500X\textsuperscript{4} and 600X, and JFE Steel developed JFM\textsuperscript{3,4} and JFMX.\textsuperscript{5} JFM\textsuperscript{3} is made exclusively for the improvement of drilling, while the others are for both turning and drilling. The basic principle of these enhancers is to protect the tools by creating a coating, to induce stress concentration, have finer cutting tips, and minimize the fluctuation of the cutting load by filling the porosity. Sumitomo developed a machining enhancer by exploiting computational science to find the optimum chemical composition of the compound oxide that works as a lubricant at the tool chip interface, and reduces the temperature during turning. Figure 4 shows the effect of this machining enhancer, at different cutting speeds with different tool materials.\textsuperscript{6}

Another way of achieving a cost reduction is through green machining. It had previously been used only on a limited basis in Japan, primarily because of a difficulty to satisfy customers’ quality concerns. A major breakthrough was made by Sumitomo with the development of a newly designed drill and a cutting tool for dual-groove turning, optimization of machining conditions, and a 2D code-marking quality assurance system.\textsuperscript{7} Figure 5 shows the VVT rotor made using green machining for vertical, horizontal, and inclined 9 to 10 holes,
and 2 horizontal grooves.

Conventional gas-furnace hardening or induction hardening has been used widely, but new demands forced the introduction of a new technology. For the purpose of selective quenching, particularly on a curved, limited small section, a laser quenching method was implemented. Toyota and Fine Sinter used the process for selective hardening the ball grooves of the JPMA 2019 grand prix awarded 4WD cam clutch system shown in Figure 6. The same technology has also been implemented by Sumitomo for several engine and transmission components.

New materials for engine valve seat inserts, valve guides, and a turbo charger system have been developed. Fine Sinter and Toyota developed a new material that meets the tougher demand of highly efficient gasoline engines. The material consists of approximately 50 micrometre round, hard particles, and a matrix dispersion-strengthened with fine, hard particles - (Figure 7). Fine Sinter improved their multilayered compaction method and reduced the mass of expensive valve seat

![Figure 3. A new die-wall lubrication method](image)

![Figure 4. The effect of a machining enhancer developed by Sumitomo at different cutting speeds with different tool materials](image)
This resulted in better thermal conductivity that reduced the surface temperature by 20 °C, achieved 20% longer grinding-tool life, and a 20% reduction of material cost (Figure 8).

Hitachi developed an austenitic stainless steel strengthened with fine carbide for a turbocharger, which replaced a heat-resistant bearing made from a cast high-Cr steel. 11

Oil impregnated bearings have been improved to meet various new demands and/or applications. Porite, Diamet, NTN Advanced Materials, and Hitachi developed new materials, coupled with extremely high dimensional tolerance; such as a 1 micrometre allowance for a 2.5-mm bore diameter, and bearings with fine dimples on the bore have been developed by Porite (Figure 9). 12

NTN and Fukuda Metal Foils and Powders developed the world’s first commercialization of an Al-bronze bearing for a turbocharger. Al-bronze has excellent corrosion and heat resistance with bearing performance, but it is difficult to sinter due to the presence of Al oxide. 13

Soft magnetic composites (SMC’s) became popular in the automotive industry due to electrification and the
smart grid system. In addition to reactor cores for HEV/EV and industrial use, a high-energy ignition core-set has been developed and commercialized by DENSO and Sumitomo for a gasoline engine (Figure 10).

Epson Atmix has produced amorphous magnetic powders for making microelectronics devices. Their proprietary S.W.A.P. atomizing process enabled a cooling rate over $10^{6}$ K/s, (Figure 11).

METAL INJECTION MOLDING (MIM)

The MIM market shipments in Japan increased from $94.5$ million in 2014 to $106$ million in 2018. By exploiting ultrafine ($D_{50} = 3$ or $4$ micrometre) powder made by Epson Atmix using high-pressure water atomization, extremely small parts with smooth surfaces have been commercially produced by several companies (Figure 12).

Teibo developed injection molding with soluble inserts, which made it possible to mold hollow shapes. This expands the shape capability of the MIM process. Heat-resistant superalloy Inconel 713C made with the MIM process had an issue of creep resistance due to its fine grain size. Kawasaki Heavy Industry and Atect Corporation reported significant improvement of creep resistance by promoting grain growth coarser than $200$ micrometres (Figure 13).

ADDITIVE MANUFACTURING (AM)

TRAFAM (Technology Research Association for Future
Additive Manufacturing) was established in 2014 and had a 5-year project to develop advanced metal AM machines, materials and software with industry and academia. Metal Additive Manufacturing Support System Co., Ltd. (MAMSS) was established to provide the results of the project for members of MAMSS. Hybrid type AM technology, a combination of laser powder-bed-fusion (PBF), or directed energy deposition (DED) and high speed machining, has been developed and commercialized, particularly for making metal molds for plastic injection molding etc.\textsuperscript{21,22,23} Hitachi, Ltd., and Hitachi Metals, Ltd., succeeded in making a component from high-entropy alloy (HiPEACE) using metal AM.\textsuperscript{24}

**HARD METALS**

Direct milling of cemented carbide dies and molds is a new trend to reduce cost and delivery time for various industries including PM. Sumitomo has developed new ball-nose end-mills made of a binder-less nano-poly- crystaline diamond that shows superior wear resistance, chipping resistance, and edge sharpness.\textsuperscript{25} (Figure 14)

**ALTERNATIVE SINTERING METHOD SPS**

Field Assisted Sintering Technique (FAST) and spark plasma sintering (SPS) have generally been considered to be processes limited to a laboratory environment. However, several industrial applications have been announced by the world-leading companies NJS Co. Ltd. and KK Sinter Land.\textsuperscript{26} The world’s largest semi-tunnel type automated SPS production system has three
It indicated that micro-void coalescence on shear planes formed close to the enlarged open pores, or between closed pores, could play an important role in crack initiation.

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POWDER METALLURGY IN SCANDINAVIA

Ulf Engström* and Linus Svensson**

INTRODUCTION

The Scandinavian powder metallurgy (PM) industry has a strong position internationally, and globalization is a key issue because the home markets are quite limited as Denmark, Finland, and Sweden have together only about 20 million inhabitants. The international presence is evident from the fact that exports are as high as 95%, some of the larger PM companies have international owners, and several companies have large global production facilities and service centers. About 50% of all employees work outside the Nordic countries. The largest PM companies support R&D globally; for example doctoral studies at technical universities and research institutes.

Some key figures (2019) for the Nordic PM companies are:
• Invoiced sales: ~ US$13 billion
• Employees: ~ 36,000
• R&D expenditures: 4%–5% of sales

METAL POWDERS

Höganäs AB is the world’s leading producer of iron and metal powders with 18 production units in Europe, the Americas, and Asia. The annual production volume is 500,000 metric tons (mt) of metal powder with a turnover of around US$1.1 billion (2018). The company operates in 75 countries and has a base of some 3,000 customers worldwide. The portfolio consists of more than 1,500 products, including metal powders for sintered components, soft magnetic applications, surface coating, brazing, additive manufacturing, welding, water treatment, and much more. The headquarters and global development center is located in Höganäs, Sweden. Development is also performed at technical centers in the three operational continents the Americas; Asia Pacific (APAC); and Europe, the Middle East, and Africa (EMEA).

The PoP Centre established in Höganäs provides a platform for cross-functional development work of different companies and competencies to work in all parts of the value chain, from a desktop idea to a finished product. Materials expertise is available to help select the right powder solution, design support to create innovative PM solutions, and process know-how to ensure optimum production efficiency and quality. One area of development is high-performance gears for various transmissions. Figure 1 shows different prototype PM gears for a manual 6-speed transmission.

The PoP Centre also contains equipment for metal injection molding (MIM), surface coating (including a laser unit), and brazing-application methods. Equipment is also available for the mechanical testing of rolling-contact fatigue performance, tooth-root fatigue, and various types of wear testing.

The activities in the field of magnetic materials focus on the soft-magnetic properties of new, soft-magnetic-composite (SMC) powders and their process-

*Business Development Manager, **Sales manager, Nordic Countries, Höganäs AB, Bruksgatan 35, Höganäs 263 83, Sweden; Email: ulf.engstrom@hoganas.com
ing for component manufacturing. Applications are primarily components for electrical motors, Figure 2, generators, and inductors.

In 2012 Höganäs AB founded Digital Metal AB with the objective of broadening applications for powder technology. More information about Digital Metal follows under the headline Additive Manufacturing later in this article.

In 2018 Höganäs acquired the PM tooling company Alvier PM-Technology of Switzerland. Alvier develops and produces high-quality, innovative and complex tooling solutions for powder metallurgy components. It is regarded as the world’s leading independent provider of PM and soft-magnetic-composite tooling solutions. Its solutions focus on the entire value chain, from engineering and manufacturing, to installation and customer service and training. They are also known for development of helical gear tools and adaptor systems.

The same year Höganäs also acquired Surface Technology & Ceramic Powders division, STC, from H.C. Starck. The production units in Goslar and Laufenburg, Germany, produce metal and ceramic powders, mainly for the surface coating and additive manufacturing industries.

Erasteel Kloster AB, Söderfors, Sweden, significantly increased its production capacity for inert-gas atomized powder in 2011 and introduced a new product range named Pearl® powders. These are produced by inert-gas atomization and include a wide range of compositions such as stainless-duplex and super-duplex steels, tool steels, and other alloys upon request. The powders are available in large batch sizes (up to 10 mt) and are dedicated to the manufacturing of large, near-net-shape components by HIP. Erasteel offer tailored particle-size distribution and high cleanliness as well as low oxygen content for improved material properties.

The powders are used in various industry sectors such as oil and gas, power generation, tooling, and automotive. In 2019, the Söderfors site set up a sieving line dedicated to additive manufacturing.

Carpenter Powder Products AB, Sweden, owned by Carpenter Technology, Inc., U.S., is one of the leading global producers of inert-gas atomized powders with production facilities in both North America and Europe. The production capacity in Sweden is about 10,000 mt annually and the company is one of the largest suppliers in the world of ferrous-based gas-atomized powders. The gas-atomized powder is used in various applications, such as thermal spray, high-temperature brazing, plasma-transferred-arc welding, MIM metal additive manufacturing (AM), and hot isostatic pressing. The production program comprises primarily high-alloy steels (high speed steels, tool steels, stainless steels), and nickel- and cobalt-based alloys. A substantial quantity of the powder that is produced (primarily tool steels, HSS, and duplex and super duplex steels) is consolidated by HIPing into near-net-shape (NNS) products, billets, bars, and hollows. CPP also markets its own PM HSS and tool-steel semi-fabricated products, consolidated by HIP, under the registered trademark Micro-Melt®.

Tikomet Oy, part of Global Tungsten & Powders Corp., located in Jyväskylä, Finland (Figure 3), specializes in the production of tungsten carbide cobalt powders by the zinc-reclaim process. The company has expanded its powder production capacity to over 2,000 mt/year, becoming a global market leader in this area.

Tikomet offers services to external customers interested in buying zinc-reclaimed powders for the production of cemented carbide tools or having their cemented carbide tool scrap converted into powder. Tikomet’s growth has been motivated by the strong interest of the industry in the recycling of used cemented carbide tools, which is both economically attractive and environmentally friendly. In addition, there is a desire to reduce the dependence on China for tungsten raw materials. Traditionally, the use of powders produced by the zinc-reclaim process has been focused on applications such as indexable-insert grades and tire studs. As a result of technical innovations by Tikomet, both the purity and particle-size-distribution of the powders...
produced by the zinc-reclaim process have improved considerably. Therefore, new applications have clearly surpassed traditional ones.

**PM PARTS PRODUCTION**

Callo Sintermetall AB is a family-owned company in the south of Sweden producing structural components, PM bearings, sintered filters, and soft-magnetic-composite (SMC) material for electromagnetic applications. Callo has recently expanded the production of bushings and structural parts for forest and garden, and also some automotive applications. Presses and sintering furnaces are, to a large extent, produced in-house. The company reports that the sintering atmosphere is very well controlled, which makes it possible to manufacture parts made from low-alloy chromium steel with close dimensional tolerances and precise carbon control. The sintering system is also used for sinter hardening of chromium-alloyed steels.

FJ Industries A/S, Ferritslev, Denmark, is a PM parts manufacturer with an additional product range that includes investment cast and machined components for the automotive industry and general industry. The company has production facilities in Denmark, China, and Sweden. Their focus is conventional sintering of steel and stainless steel structural parts. Other materials like bronze, soft magnetic components, and wear-resistant materials are also used. The company produces more than 30 million PM components each year. Multi-platen presses are used for production of complex parts with tight tolerances to obtain high material performance. Warm compaction, sinter hardening, and high-temperature sintering processes are available.

Sintex A/S is a Danish producer applying PM technology for stainless steel, MIM, magnet manufacturing, and high-velocity oxygen fuel (HVOF) thermal spraying. Sintex started in 1997 with six employees and a turnover of $47 million. They work, to a large extent, as a technology partner for powder-based solutions and several solutions are patented jointly with customers. The technologies of Sintex are applied within the electronics industry, but are also used for automotive applications, pumps, motors, pharmaceuticals, energy, and food products. Recent material developments and new production equipment have been in the area of stainless steel PM components and MIM.

Soft-magnetic-composites (SMC) are one of the powder technologies offered by Sintex, which provides unique geometrical possibilities compared with laminated iron as it can be shaped in all three dimensions. This makes stators for electrical motors one of the interesting applications for SMC. With the right design, one can potentially make a cheaper, smaller, and more efficient motor by reducing the amount of copper and thereby also the copper losses. Figure 4 illustrates an example of an assembly of an SMC component with copper windings.

Dansk Sintermetal A/S, established in Denmark 1959, works closely with industrial companies in order to develop cost efficient and innovative solutions. A wide capability of presses and furnaces enables the production of parts ranging from 0.3 g up to 3 kg per piece. Dansk Sintermetal works with a number of different alloy systems ranging from soft magnetic materials through stainless steel and high-performance steel, to copper-based alloys such as bronze and German silver. The company has 65 employees and offers design/construction services, pressing and sintering, with in-house tool manufacturing capabilities.

SKF Mekan AB in Katrineholm Sweden, a part of the SKF group produces bearing housings and accessories for bearing mounts in cast iron, and PM guide rings for spherical roller bearings. SKF Mekan consumes 370 mt of steel powder from Höganäs yearly to produce 4 million guide rings. PM guide rings for spherical roller bearings are made in various sizes, from 40-mm diameter with a weight of 8 g, to 288-mm diameter and 700 g. Figure 5 (left) shows examples of guide rings of different sizes and (right) a schematic illustration of the use of a guide ring in a bearing.

Metec Technologies has continued the development performed by Scandinavian Powdertech AB. Tests with double pressing/double sintering have shown that very high final densities can be reached for a number of steels and alloys without using high-velocity compaction. Metec was renamed Bofors Bruk AB and was sold in 2019, including patents and know-how, to the French/Italian Calvi group. They have installed production machines from Bofors Bruk AB at their French premises. One license for the SCANPAC process has been sold to the French company Metal Additive Technologies who are starting up installed equipment for.
commercial production. Calvi is a world leader in extruded profiles in steel and alloys and sees the SCAN-PAC process as a complement to their own products as well as having a potential for selling licenses. The high-velocity compaction technique from Hydropulsor AB has been sold to a German company that supplies three types of machine.

Plastoco Oy Ab, Porvoo, Finland, a manufacturer of technical plastic parts, has been producing metal components using MIM technology since 2012. Plastoco has a staff of 30 professionals. The family-owned business has forty years of experience in plastic injection molding, primarily for the electrical and electronic industries, as well as in mold design. This long experience of injection molding and mold manufacturing has provided a firm base to move into MIM production. The company is mainly processing MIM-17-4PH and MIM-316L stainless steels, but MIM-4605 low-alloy steel and nickel-free stainless steel parts are being introduced. A specialty material of Plastoco is porous 316L stainless steel with 40%–50% porosity and a 20–50 µm pore size. The company operates two MIM machines, 35 mt and 50 mt. Equipment is available for both catalytic and thermal debinding, and sintering up to 1,450 °C in vacuum, hydrogen, or neutral atmospheres. Order sizes can vary from 1,000 to 200,000 parts. Plastoco also uses BASF Ultrafuse 316L filament for printing metal components. Figure 6 shows a steel grid part made from MIM-316L for a sensor filter application.

**MAGNETS**

Sura Magnets AB, Söderköping, Sweden is one of the leading manufacturers and suppliers of permanent magnets in Europe with a turnover of about $12 million. The company primarily produces injection molded polymer-bonded magnets, 70% of which are exported to over 40 countries. In recent years, the company has made large investments in new technology and automated production methods for high-volume production for the automotive industry. The production is highly focused on two components; fully automated injection molding of NdFeB and ferrite magnets. Primary applications are sensors in the mechanical industry and especially in the fields of mechatronic and med-tech.

Sura Magnets AB are currently making further large investments to be in the forefront of molding technology by going to micro-molding, where cycle times are cut down to fractions of the present ones. The integrated magnet processing will have 100% calibration and measurement. Micro-molding is also highly suitable for micro parts, Figure 8. In the state-of-the-art laboratory, advanced measurements, FEM-optimizations, and R&D developments are offered to find optimal and cost-effective designs together with their customers.

**FULLY DENSE STEEL COMPONENTS AND SEMI-FINISHED PRODUCTS**

Bodycote Hot Isostatic Pressing AB in Sweden is the market leader in fabrication of components using HIP technology. The fabricated products are used globally in various market segments. The trade name for the technology is Powdermet®. The company is a part of Bodycote plc., with headquarters in Macclesfield, UK.

The Powdermet® technology gives engineering freedom in design and removes several production steps compared with conventional methods, such as machining and welding. These advantages often provide improvement both in project cost and schedules. From a material quality perspective, the solution gives a homogeneous microstructure that is superior to standard forging or casting. Powdermet® is used for a wide range of materials. Figure 7 shows an as-HIPed manifold header used in oil & gas subsea production systems made with Bodycote Powdermet® technology.

Uddeholm AB, Hagfors, Sweden, is an international leading producer of PM tool steels and high-speed steels for tooling applications. All PM products are manufactured at the Böhler Uddeholm Powder Technology plant in Austria, which is a joint venture between Uddeholm AB and Böhler Edelstahl. The production is based on inert-gas atomization and HIPing followed by hot forming using their proprietary SuperClean process. The Uddeholm line of PM grades includes the Vanadis...
grades for cold forming, stamping and blanking, thread rolling, etc., and the Elmax grade for molding abrasive plastic compounds, primarily for the electronics industry. Uddeholm AB’s latest invention is the nitrogen-alloyed steel grades known as Vancron and Vanax. Vancron is a unique type of PM steel alloyed with high nitrogen content. It has a low-friction coefficient and excellent resistance to galling and adhesive wear. Vanax is a nitrided PM stainless steel with a unique combination of wear and corrosion resistance.

Metso Materials Technology was sold to Tevo Oy in 2015 along with Metso Lokomo Steels foundry. Since then Tevo Lokomo has continued the sales of PM HIP components to former customers of Metso. The company produces both monolithic and bi-metallic components from various high alloy and tool steel materials. Metal-matrix-composite materials are also used to produce tailored wear parts for energy and oil & gas industries. The facilities of Lokomo steel foundry are utilized in manufacturing of the components (ie., heat treatment and machining workshops). Tevo Lokomo also has its own material testing laboratory.

Damasteel AB, Söderfors, Sweden, has a unique production of Damascus steel in flat or round bars for design-oriented handicraft companies, artists, and industries around the world. The production is based on HIP of different tool-steel powders and ingenious ways to obtain the different patterns. This Damascus steel art is used in many aesthetically designed products: firearms, jewelry, ornaments, cutlery, chef’s knives, and golf clubs. An example of a decorative Damasteel® product is the knife shown in Figure 9.

Kanthal AB, Hallstahammar, Sweden, is part of the Sandvik Group. Kanthal-branded materials and products are used in systems generating, controlling, and protecting against, or measuring, heat. The product line includes many items that are commonly used in the PM industry, such as electrical heating elements, thermocouples, thermal insulation, furnace muffles, and load supports.

Kanthal APM is a PM-based ferritic alloy with excellent form stability and oxidation resistance, enabling design of electrical resistance heating elements operating at up to 1,425 °C. Many industrial furnaces use radiant tubes made of this material.

Kanthal APMT is another PM based heat-resistant alloy with higher strength at high temperatures. Applications are furnace muffles, retorts, furnace rollers, hangers, and load supports operating up to 1,300 °C.

HARD MATERIALS (CEMENTED CARBIDES)

Sandvik Machining Solutions is a market-leading manufacturer of tools and tooling systems for advanced industrial metal cutting, optimizing customers’ machining operations. It is a part of Sandvik Group, a high-tech and global engineering group with approximately 42,000 employees and sales of approximately $10 billion in more than 160 countries (2018). The company was founded in Sweden in 1862.

Kanthal APMT is another PM based heat-resistant alloy with higher strength at high temperatures. Applications are furnace muffles, retorts, furnace rollers, hangers, and load supports operating up to 1,300 °C. Kanthal offers 3D printed parts made of Kanthal AM100. Typical applications are heat-resistant components with complex design, difficult or time-consuming to produce from conventional product forms.

Research and development work within cemented carbide materials is mainly concentrated in Coromant’s Research and Technology Centers in Stockholm and Sandviken. Several smaller R&D centers exist around the world.

Epiroc was created 2018 as a part of the Atlas Copco Group, to focus on mining and infrastructure customers. Atlas Copco, founded in Sweden in 1873, has been very successful, and has grown quite large. Epiroc was...
therefore split off, and the shares distributed to the shareholders of Atlas Copco and listed on the stock exchange.

Epiroc is a leading productivity partner for the mining and infrastructure industries. Using cutting-edge technology, the company develops and produces innovative equipment, consumables, and service for use in surface- and under-ground mining, infrastructure, civil works, well drilling, and geotechnical applications. Epiroc provides equipment and a complete range of related consumables and service to customers in more than 150 countries. Drilling tools are an important part of the consumables. Most drilling tools have cemented carbide or diamond buttons at their tips, doing very tough work. These buttons are mostly made by powder metallurgical methods.

**ISOSTATIC PRESSES**

Quintus Technologies specializes in designing, manufacturing, installing, and supporting high-pressure systems for sheet metal forming and the densification of advanced materials and critical industrial components. Headquartered in Västerås, Sweden, and represented in 45 countries worldwide, the company is a world leader in high-pressure technology. It has delivered more than 1,900 systems to aerospace, automotive, energy, and medical implant industries across the globe.

As a global leader in hot isostatic technology, Quintus® has been supplying high-pressure equipment since the middle of the 20th century, including cold isostatic presses (CIP), hot isostatic presses (HIP), diamond presses, and sheet-metal forming presses. The introduction of unique uniform heating, holding, and rapid cooling quenching processes for HIP has led to the advent of high-pressure heat treatment (HPHT), where full heat treatment cycles can be carried out under pressure with extremely uniform temperature. Unique technology facilitates uniform rapid quenching, URQ® of parts whilst under pressure in the HIP, allowing development of processes previously not possible. Quenching rates in excess of 3,000 °C/min are possible in the Quintus URQ® furnaces. High-speed, uniform rapid cooling, UR®, can cool additively manufactured or cast parts at rates up to 600 °C/min, depending on machine size.

**METAL ADDITIVE MANUFACTURING**

Sandvik Additive Manufacturing, part of the Sandvik Group, is a leading developer and manufacturer of gas-atomized metal powder for near-net-shape technologies, such as metal AM, MIM, and HIP. The company has more than 40 years of experience in gas atomization of metal powders. Their production footprint consists of ten gas-atomization towers; eight in the UK and two in Sweden.

Sandvik offers a wide alloy program and can customize materials according to customer specifications. The Osprey® metal powder range includes low-alloy steels, tool steels, stainless, and duplex steels, high-temperature materials, nickel-based superalloys, cobalt, titanium, copper, aluminum, low expansion, and soft-magnetic alloys. Flexible manufacturing facilities make it possible to manufacture customized batches from 20 kg up to 3,000 kg, with the ability to support the total product-life-cycle from prototyping through to series production.

Sandvik has made sizeable investments into a wide range of AM process technologies for metal components since 2013. In July 2019, Sandvik acquired a significant stake in BEAMIT, a leading European AM service provider, which has further strengthened Sandvik Additive Manufacturing’s offering and capabilities.

Digital Metal is the world’s first company to commercialize high-precision 3D metal printers for the production of small components in large volumes. Digital Metal’s proprietary binder-jetting (BJT) technology enables the production of complex objects with superior surface finish, which is not possible with competing technologies. In addition to offering metal printers Digital Metal also offers manufacturing services for metal components. With more than 500,000 printed components and +30 geometries in serial production, ranging up to 40,000 pcs, it is a well-proven system. Among the customers are many of the world’s leading technology companies such as Honeywell, Koenigsegg, CETIM, and Volvo. The company is part of the Höganäs Group, the world’s largest producer of metal powders.

Höganäs has been involved in AM since 2010 and acquired the company fcubic in November 2012. The company was renamed to Digital Metal and uses technology that is based upon a precision ink jet on a powder bed. Printing takes place at room temperature, followed by a separate sintering step to provide the final strength and properties. The result is a combination of high tolerances, excellent resolution, and good surface finish. Since the start of offering printing services, the printer has undergone several upgrades. The Digital Metal printer is upgradable, and all printers on the market have been retrofitted with the upgrades to perform at the same level as the printers built today.

The build box has grown from 126 x 80 x 50 mm³ to 203 x 180 x 69 mm³ and a further increase in build volume is planned. The build-box volume can be utilized efficiently as no supports are needed during printing. Therefore the components can be packed densely and printed in several layers. All this enables serial production in large quantities, with consistent quality in a cost-efficient way. The method is especially suited for small components with complicated shape, or special functions, Figure 11.

Arcam EBM situated in Mölnlycke, Sweden, was founded in 1997 and is now part of GE Additive. Its
technology, electron-beam melting (EBM), is suitable for a wide range of metallic materials. The most common are titanium alloys for medical implants, and crack-prone titanium and nickel alloys for aerospace components. The company provides solutions for cost-efficient production and offers EBM machines, auxiliary equipment, software, services and training.

RESEARCH

Powder metallurgy research is carried out at a number of universities or research institutes covering most processes, products, and applications in the metal powder field. To a large extent, the research mirrors the industries in the Nordic countries, with activities in sintered steels, hard metals, and fully-dense steels. Recently, metal AM has become an important new field for research and development. Many universities and institutes have acquired equipment for metal AM to perform research regarding simulation, materials, and processing. A number of research consortiums have been initiated, with partners covering the whole value chain. There is a strong emphasis to create cooperation between academia and industry to generate new, applicable AM solutions.

Swerim is a leading industrial research institute within mining engineering, process metallurgy, materials, manufacturing engineering and applications. Swerim has 190 professionals in two locations in Sweden (Luleå and Stockholm) and has an extensive international network and customers throughout the world. Research covers the whole value chain of the powder metallurgy route, from powder manufacturing on a pilot scale to the production of consolidated metallic components. Support is offered to identify, tailor, manufacture and/or analyze metal powders and ceramic powders to suit specific requirements. For 3D printing, support is offered throughout the entire production process, from idea to finished product. The Linux cluster offers high-computation capacity with short simulation times. An additional strength is the capability to provide experimental verification at ones own premises.

PM and metal AM research are significant parts of activities in the Department of Industrial and Materials Science at Chalmers University of Technology. Overall focus is on correlation between processing, microstructure and material properties, aimed at tailored product performance. Of particular interest is the chemical characterization of metal powder surfaces and tailoring them for improved product performance. Equipment available for advanced surface chemical analysis includes X-ray photoelectron spectroscopy, XPS, and Auger spectroscopy.

Development of powder and materials for metal AM is a growing activity involving hosting of the national competence center CAM2 and a number of national and European projects. Novel approaches to reach full density PM steels are addressed. A sintering route has been developed that has permitted HIP processing of low-alloy PM steel without the need for encapsulation - Figure 12. Factors influencing the compaction behavior of metal powder have been studied, such as using electron backscatter diffraction (EBSD) to study the interior grain structure of metal particles. Approaches to tailor PM steel sintering by the addition of nano-powder are being studied within a large framework program.

VTT Technical Research Centre of Finland, offers R&D and pilot production services covering the whole chain from powder to product, with state-of-art equipment and world-class know-how on powder production and characterization for gas atomization, plasma spheroidizing, and spray drying. Other focus areas are components and coatings made by additive manufacturing, MIM, HIP, thermal spray, and heat treatments. Evaluation of component performance can be performed using a wide variety of lab and field tests. VTT also provides expertise to support R&D and pilot production needs with integrated computational materials engineering solutions and services for PM, with special focus on metal AM for computation driven design of novel alloy compositions, powder, and AM manufacturing processes.

One specialty at Luleå University of Technology, Sweden, is modeling and simulation using nonlinear finite element analysis (FEA). The method is developed and used for material and friction modeling. Through laboratory tests, models for die compaction and HIP can be verified. The focus is on materials for sintered, hard metals, and titanium components.

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POWDER METALLURGY IN SPAIN

Cesar Molins, Jr., FAPMI*

The industrial and scientific communities in Spain officially created an active local chapter of the European Powder Metallurgy Association (EPMA) called CEP-EPMA in 2014. The objective was to organize long-existing symposia and technical meetings better and to foster cooperation between Spanish industry, research institutions, and academia. In addition, they would represent the interests of PM, both to Spain’s government and become a coordinated voice within EPMA.

Fifteen industrial companies that directly employ over 2,000 people, and supply in excess of 35,000 metric tons (mt) of PM parts are members of CEP-EPMA, while 10 of the best known Universities and Research Centers comprise the scientific side of the Chapter.

CEP-EPMA sponsors a biannual Spanish and Latin-American Powder Technology conference, which is organized in a rotating role by the universities and technology centers. This is in addition to annual assemblies at which the general evolution of the industry, market, and technology are presented. The technological analysis and possible industrial impact of additive manufacturing and the development of PM applications in the increasing presence of electrification in the automobile industry are examples of the recent cooperation activities within CEP-EPMA.

(Contacts: Jordi Macarulla jordi.macarulla@hotmail.com or René Zaragüeta rene.zaragueta@enginyers.net)

TECHNOLOGY CENTERS INVOLVED IN PM TECHNOLOGY IN SPAIN

Fundación TECNALIA Research & Innovation (TECNALIA) (www.tecnalia.com) is a research organization resulting from the merging of eight Spanish research organizations. It is the leading private research and technology body in Spain, and the fifth largest in Europe. It has more than 1,500 employees and is present in 20 countries, having over 15 technical and pilot plant sites. TECNALIA is organized into seven Business Divisions including Sustainable Construction, Energy & Environment, Industry & Transport, Health, etc. TECNALIA has led numerous EU-funded multinational research projects.

The Powder Metallurgy and Ceramics group belongs to the Industry & Transport Division and has a long experience in working with particulate materials; both ceramics and metals. The group comprises 17 scientists, seven of whom have PhD’s.

Some of the main research areas and singular facilities are described below:
• Hot pressing (hot press and vacuum hot press) of high-performance ceramics & ceramic composite components (carbides, nitrides, and borides).
• Additive manufacturing (AM): sinter-based additive manufacturing pro-

*General Director, AMES S.A., Ctra. Laurea Miro, 388, Poligono Industrial El Pla, 08980 Sant Feliu de Llobregat, Barcelona, Spain; Email: cm@ames.es

GLOBAL UPDATES

Spain continues to be a major player in Europe’s powder metallurgy (PM) technology and industry. A number of widely recognized technology centers and university departments are involved in teaching and researching many aspects of PM technology. They cater to an active PM manufacturing industry, mostly based on press-and-sinter technology, but also with a presence of powder forging, metal injection molding (MIM), and even special powder production for metal additive manufacturing (metal AM).
cess of metals, ceramics and their mixtures by binder jetting (BJT), metal and ceramic direct energy deposition (DED), and robocasting processes. Also working on the warm metal-spray process with low and high melting point alloys.

- **PIM:** injection and micro-injection of ceramic and metal powders of Ni-based intermetallics, stainless steels, low carbon steels, titanium alloys for biomedical applications, porcelains, ferrites, and Al₂O₃ based ceramics (Figure 1).
- Conventional powder metallurgy: uniaxial pressing, sintering and thermal treatments of stainless steels, low carbon steels, Ti alloys, Ni alloys, and Al alloys.
- Non-conventional sintering technologies: energy efficient and flexible sintering processes to obtain products with specific microstructures, such as microwave sintering, spark plasma sintering and electrical resistance sintering (ultrafast sintering process developed by TECNALIA) for MMC’s and cermets.
- Thermal spray technologies: atmospheric plasma spray (APS), high velocity oxy-fuel (HVOF), and specific deposition processes developed by TECNALIA: high-frequency pulse detonation (HFPD), high-velocity combustion: oxy-fuel ionization (OFI), and HVOF/HVAF.
- Advanced joining processes: joining of materials (including dissimilar materials: metal-metal, metal-ceramic and ceramic-ceramic) by brazing and diffusion bonding processes.

The **IMDEA Materials Institute**, one of the seven Madrid Institutes for Advanced Studies (IMDEA), is a public research center founded in 2007 by Madrid’s regional government. The goal of the Institute is to conduct research at the forefront of material science and engineering, attracting talent from all around the globe, and collaborating with companies worldwide in an effort to transfer fundamental and applied knowledge into valuable technology.

The Institute is organized into sixteen research groups one of them being “Solid-State Processing.” Over 150 people perform research at the Institute, including more than 45 post-doctoral scientists and 60 pre-doctoral students. State-of-the-art experimental and computational facilities enable the groups to perform research at the forefront of material science and engineering.

One of the strengths of the Institute is their high capability in multi-scale characterization of materials and processes (3D characterization of materials [X-ray tomography and diffraction, SEM, TEM], 4D characterization [In-situ characterization of deformation and processes across multiple length scales (750 °C)], and integrated computational materials engineering, including virtual materials design, processing and testing. In addition, simulation techniques are available at different scales (electronic, atomistic, mesoscopic, and continuum) and they have the capability for thermodynamic calculation to design new alloys (CALPHAD, DICTRA). The designed alloy can then be prototyped through casting by induction and arc melting before going to powder manufacturing.

The powder metallurgy lab at IMDEA Materials, comprises all the steps to produce advanced PM materials: intermetallics, special steels, superalloys (cobalt and nickel base), magnesium-base composites for bio-applications, high-entropy alloys, etc. Mechanical alloying and gas atomizing can be used to produce powders that can be consolidated by field-assisted hot pressing to obtain full density materials (in a Gleeble 3800 machine (Figure 2)). The selective laser melting process is also applied.

**Centre de Estudios e Investigaciones Técnicas de Gipuzkoa (CEIT):** Research in powder metallurgy at CEIT is led by the Advanced Manufacturing in Powder and Laser Group (FAPL). This group comprises 25 doctors, 10 PhD students, 6 technicians, and 8 project engineers. FAPL activity combines basic and applied

![Figure 1. Some examples of alumina parts obtained by micro-injection molding (Courtesy of: Iñigo Agote inigo.agote@tecnalia.com)](image-url)
POWDER METALLURGY IN SPAIN

research with more than 40 ongoing industrial projects, ten of them within the H2020 European program, and an average of 4 PhD theses are presented each year. The FAPL Group has 35 years of experience in powder technologies. Its mission is to serve industry through efficient and economical solutions in both new products and processes. The FAPL Group is able to cover the entire value chain in processes like press-and-sinter, near-net-shape HIP, and additive manufacturing. Key research areas are: gas and water atomization, sintering, hot pressing, HIP, AM, solid-gas interaction, solid-laser interaction, surface functionalization with ultra-fast laser, powder design, atomization, design for AM, and post processing (finishing operations). Some of the main equipment available includes a gas atomizer for up to 250 kg per batch, a hybrid-atomizer able to atomize with gas or water (up to 3 kg per batch)—Figure 3, a HIP unit, a hot press, furnaces up to 3,000 °C, two scanning electron microscopes (SEM), three field-emission-gun SEM’s (FEG-SEM’s), one focused ion beam SEM (FIB), and a transmission electron microscope (TEM).

Apart from processing facilities, FAPL group has the latest “know-how” on physico-chemical characterizations of PM products, including chemical, microstructural, mechanical, electrical, and magnetic NDT methods. In-house modeling tools are also available for analyzing atomization processes, optimizing dimensional control (sintering, HIP, canister design, thermal gradients inside furnaces under different atmospheres, CVD reactors, etc.) and predicting stress fields of PM-AM components and systems including macro and micro residual stress measurement. Materials under study include lean PM steels, hard metals, cermets, diamond tools, lightweight materials, Ni- and Co-based superalloys, soft and hard magnetic materials, special steels, tungsten-based alloys, and high-technology ceramics.

The ICV (Institute for Ceramic and Glass) is a part of the Spanish National Research Center (CSIC). Its “Tailoring Through Colloidal Processing Group” uses its knowledge of very-fine-grain ceramics to apply their technologies to design and produce materials with novel compositions and microstructures by using metallic and ceramic powders suspended in a liquid, mainly water. Research is focused on a wide variety of metals (Fe, Mg, Ti, Ni, W) and ceramics (TiCN, WC) to produce complex alloys, cermets, and hard materials with microscopic and nanosized particles.

The group comprises two permanent staff members, two postdocs, and two PhD students. In spite of its small size, the group is very active in industrial cooperative projects.

High solids-loading suspensions are achieved with the developed technologies. The influence of processing additives on the dispersion and rheological behavior of the slurries is studied in order to optimize the processing techniques and make granules for compacting and sintering, and complex microarchitectures such as coatings or multilayers.

The processing techniques from slurries, common in the ceramic sector, are used on metallic compounds. The colloidal approach is also used in additive manufacturing techniques, optimizing the feedstock for material extrusion and on inks for Inkjet 3D Printing. They have created the spin-off Coled4Pring to commercialize feedstock processed by colloidal routes.

(Contacts: Begoña Ferrari bferrari@icv.csic.es or Javier Sánchez ajsanchez@icv.csic.es)
ers from prestigious international institutions from China, USA, Chile, and Mexico. The main research focus of the group is the development of materials by powder techniques, mostly metals, but also ceramics and ceramic-metal composites.

This core line is currently developed through the following areas:

- **Design of new alloys by thermodynamic and kinetic simulation (ThermoCalc and DICTRA).**
- **Synthesis of nanoparticles and powder production: nanostructured metallic oxides with functional properties by advanced synthesis methods (spray-pyrolysis, hydrothermal synthesis); steels, bronzes, and high-entropy alloy powders by gas atomization; metal-ceramic composites or oxide dispersion strengthened (ODS) steels by mechanical milling.**
- **Study of sintering mechanisms in metals and ceramic-metal composites: titanium alloys, especially low-cost alloys and beta-alloys for biomedical applications, high strength aluminum alloys (Al-Li), Co-based superalloys, high-entropy alloys; MAX phases, biodegradable Mg alloys, hard materials, especially with alternative compositions.**
- **Processing by compacting and sintering and powder injection molding (PIM): The group has a complete laboratory with presses, sintering furnaces and equipment for feedstock development and injection. Current work in PIM is on porous MAX phases.**
- **Surface treatments and coatings. Development of multifunctional and smart coatings for improving corrosion and wear resistance or improving bioactivity, studying special characteristics of sintered substrates. Sol-gel techniques and thermo-reactive diffusion are used to this end.**
- **Additive manufacturing (AM): Projects related to AM including direct and indirect techniques, although its expertise in PIM fosters the indirect ones as a priority. Current work is on superalloys; Al alloys, in particular production of wires by powder extrusion for WAAM; selective laser melting (SLM); polymer-Mg wires for FDM and feedstocks for 3D printing by extrusion of pellets.**

The GTP works on characterization studies, such as corrosion studies by electrochemical techniques; high-temperature wettability studies for liquid-solid interaction, tribology and coatings.

The GTP has numerous industry cooperation projects and is recognized as a Centre of Excellence in Hard Materials Research by the EPMA.

(Contacts: Prof. Elena Gordo egordo@ing.uc3m.es or Prof Monica Campos campos@ing.uc3m.es)

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**University of Castilla-La Mancha (UCLM) in Ciudad Real.** The UCLM PIM Research Laboratory was created in 2010, led by Dr. Gemma Herranz, who manages the DYPAM research group. It has a pilot plant equipped with cutting-edge technology for the advanced processing of metallic and ceramic materials and it is a training center for students.

DYPAM initially specialized on powder injection molding of metals and ceramics, with the possibility of performing the whole process at a laboratory scale. The wide interest in additive manufacturing motivated the expansion of the group to include a research line in fused filament fabrication technology (FFF), Figure 4.

Nine researchers and technicians work now in the Group, which will host the next EPMA PM Summer School, to be held in Ciudad Real in July, 2020. Continued competitive research projects and industrial contracts helped finance the expansions and research machinery of this Institute.

The research lines currently in progress are:

- **Feedstock and filament development (thermal and catalytic) for PIM and FFF.**
- **Hybrid-feedstock development for PIM prototyping field.**
- **Applications in automotive, aerospace, biomedicine, and energy sectors comprising aesthetical components, high temperature and thermal shock resistant parts, magnetoelastic and metal/ceramic matrix composites.**

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**Center for Research in Structural Integrity, Micromechanics and Reliability of Materials (CIEFMA)—Universitat Politècnica de Catalunya (UPC):** CIEFMA is a research group of the Polytechnical University of Catalonia aiming to conduct basic science and applied industrial research within the field of Structural Integrity, Micromechanics and Reliability of Engineering Materials. It comprises 17 members. The main research
activities involving powder metallurgy (PM) are: surface integrity effects on the mechanical and contact behavior of hard (bulk and film) materials; fatigue and failure mechanisms of advanced PM materials at both room and high temperature; microstructural design of metallic alloys processed by powder metallurgy; property tailoring through small-scale testing and micromechanical design of additive manufactured materials and coating/substrate couples; and implementation of additive manufacturing routes for the development of innovative metallic, ceramic and composite systems. CIEFMA is a Centre of Excellence for the European Hard Materials Group (EHMG) of the EPMA. A significant number of the research activities have been conducted in collaboration with other national and international research groups as well as worldwide leading industries in the field. More than ten PhD theses have been developed in the last five years in fields related to powder metallurgy and ceramics; with another eight currently in progress.

Experimental facilities of the CIEFMA-UPC research group include unique mechanical and microstructural characterization equipment, including micro- and nanomechanical testing units. This Central Research Center has a FIB/SEM (focused ion beam) (Zeiss Neon 40) equipped with backscattered detectors, STEM detector, EDS, micromanipulators for TEM lamella fabrication and in-situ manipulation, able to mill micro-samples, and sequential milling for 3D reconstruction.

(Contact: Prof. Luis Llanes luis.miguel.llanes@upc.es)

The Materials Technology Institute of the Polytechnical University of Valencia, Powder Metal Materials Research Group works on development of Ti alloys and Ti-matrix composites for aeronautical and biomedical applications. Applied technologies include high-energy mechanical alloying, spark plasma sintering in cooperation with TECHNALIA, and electrical resistance compacting and simultaneous sintering in cooperation with AMES. It specializes in the characterization of laser-melted surfaces, in anodizing surface treatments, and the production of TiO₂ nanotubes.

Together with the medical school of Valencia University and La Fe Polytechnical Hospital it studies the cytotoxicity of the developed alloys and the formation of surface biofilms, plus the corrosion behavior and ion liberation for biomedical applications.

Numerous alloys have been developed with high refractory metals contents such as Mo, Nb, or Ta. Ti-Mo and Ti-Nb alloys with biocompatible metals such as Zr, Ta, or Sr and bactericide elements such as Cu or Ag have also been developed. They are currently working on severe plastic deformation techniques in collaboration with IMASH (Russia): ECAP (equal channel angular process) technology and HPT (high-pressure torsion) processing.

(Contact: Prof. Vicente Amigó vamigo@mcm.upv.es)

CPCM Research group in Characterization and processing in Materials science, Faculty of Chemistry-University of Barcelona: The experience of the group in powder metallurgy started in the 1990s with the incorporation of Professor Pere Molera. Initially, the main topics researched were related to the whole press-and-sinter processing route with emphasis on compacting, sintering, and powder materials. More recently, mechanical alloying of new functionalized alloys has become the central part of the research.

(Contact: Prof. Nuria Llorca nullorca@ub.edu)

Thermal Spray Centre (CPT), Materials Science and Physical Chemistry, faculty of Chemistry, University of Barcelona: The CPT has over 25 years of experience in the field of surface engineering. Its team consists of 20 researchers and the best available thermal spray technologies including arc, flame and plasma spray, high velocity oxygen fuel (HVOP) coating, and four different cold gas spray units.

CPT’s relevant accomplishments are: 1,000 research contracts with industrial partners, 65 doctoral theses generated, 35 patents, and more than 400 publications in international journals.

The three main areas of activity of the CPT are the development of novel surface engineering and coating solutions, the development of new powders, and the use of cold spray for additive manufacturing by itself or in combination with other AM techniques.

(Contact: Prof. Irene Garcia-Can. irenegarcia@ub.edu)

University of Girona, Materials and Thermodynamics group of the Polytechnical School of Engineering, UG: This group is focused on the production, characterization and development of nanocrystalline or amorphous alloys, mainly as powders by mechanical alloying/milling or in bulk shape. Main areas of research include: Fe-base soft-magnetic alloys for frequency applications or as sensors, magnetic alloys with shape memory for the development of magnetic refrigeration systems, lanthanides for hydrogen storage systems, or zero-valent metal alloys for wastewater treatment. The specialization in characterization is linked to thermal and structural analysis.

(Contact: Prof. Joan Josep Sunyol joanjosep.sunyol@udg.es)

The school of Mines and Energy (Polytechnical University of Madrid) Laboratory of Metallographic Research (LIM) main research areas are conventional sintered steels, friction materials, and aluminum foams.
The lab is equipped with optical microscopes, attrition milling, CIP, LPIM, and metal hot extrusion, as well as tribology and mechanical characterization.

(Contact: Prof. Luis Garcia Cambronero luis.gcbromero@upm.es)

**INDUSTRIAL PRESENCE**

**Press-and-Sinter Parts Makers**

AMES is the largest PM parts producer in Spain, ranking 4th in Europe. It has four parts producing plants, three in Catalonia, near Barcelona and one in Aragon, also north-eastern Spain, producing together in excess of 500 million and over 11,000 mt of PM parts and bushings annually. The AMES Barcelona plant specializes in soft-magnetic applications, being one of the world leaders in this specialty, plus sophisticated materials. It is capable of high-temperature and pure-hydrogen sintering. The Barcelona site houses the Tech Center and central R&D lab of the group with over 25 people who perform research on high-resistance steels, master-alloys, lubricants, titanium alloys, solid-oxide fuel cells, and additive manufacturing, in collaboration with a number of universities and technology centers both in Spain and internationally. The Barcelona site has also AMES CMA, a plant to manufacture machinery and automation, where it designs and builds presses, furnaces, robotics, computerized vision systems and general automation for the entire group. AMES Medical, a new division, also located in the Barcelona site will soon start production of titanium prostheses for human and animal applications.

AMES Montblanc is the largest production site in the Group. It houses the large presses of the group, reaching 800 mt compacting force. In addition to the traditional press-and-sinter operations, it is equipped with continuous steam treatment, press-hardening, induct-hardening, and sophisticated machining lines, including green machining. AMES Tamarite specializes in small parts and short manufacturing process, achieving remarkable productivities. AMES Solsona is the production plant for bushings, and is among the world’s technological leaders, having developed new, patented technologies for self-lubricated bushings for very low friction coefficient. The Solsona site also houses the Filter division, where traditional bronze and stainless steel filters are manufactured in a clean-room environment, including CIP technology and a newly developing membrane filter technology in collaboration with the Dutch X-Pore Company. Solsona houses a specialized research lab for the bushings and filters.

The PMG Group has two state-of-the-art manufacturing plants and R&D centers in Spain, both in the northern regions of Asturias and Basque country, and an auxiliary plant in Tarragona, in the northeast of Spain. PMG Asturias specializes in the design and cost-effective production of components and systems for manual and dual-clutch transmissions. It produces more than 20 million parts and systems per year. New generations of hybrid powertrain have boosted the demand for sophisticated synchronizer systems. PMG Asturias developed innovative solutions that led the company to be a market leader in PM synchronizing hubs and sliding sleeves.

PMG Polmetasa is a state-of-the-art manufacturer of shock absorber components with more than 60 years of experience in this specialty, being a world market leader. Capacity is installed to manufacture more than 180 million components in fully automated lines. Product engineering and its R&D center, develop and validate customized solutions to increase performance of the shock absorbers in close collaboration with the customers. The PMG Constanti site transforms PTFE materials into Teflon discs for shock absorber pistons, delivering solutions to increase performance durability, and reduce friction in a shock absorber.

Motherson Sintermetal is the oldest PM parts manufacturer in Spain, established in 1946 in Ripollet (Barcelona). Since 2013, Motherson Sintermetal Products SA (MSPS) has been a division of the Motherson Group. The Motherson Group is one of the world’s largest and fastest growing full-system solution providers to the automotive industry, with over 135,000 employees in 41 countries worldwide.

Since its creation, Sintermetal has had a strong presence in the shock absorber market, redirecting its production to powertrain and transmission applications in recent years. It uses the latest generation machines, with forces up to 500 mt. The plant has computerized vision systems for dimensional and cosmetic verification. On the technology side, Sintermetal has green machining capabilities, and the possibility to produce liquid-tight parts.

Stadler, located in the Basque country, north-central Spain, is another of the long-standing Spanish suppliers of the automobile sector. With 70 people in its team, it specializes in pulleys and oil pumps, making 10 million parts/year with a total weight of approximately 1,300 mt.

MEK, formerly AISI, located in Burgos, also north-central Spain, has presses of up to 120 mt, including the latest technology, a multi-platen electrical drive. Its highly efficient team of 25 people manufactures a total of 850 mt of parts per year. Its main products are water-pump hubs and car body components.

MFS Trápaga formerly Metasint Fersint, is located in Trápaga, Basque Country. It specializes in shock absorber and power-steering parts. With a team of about 120 people, it manufactures in excess of
3,000 mt of parts per year.

**Sinterpress** is a small family company, with presses up to 50 mt force, specializing in niche, low-volume markets. They are located in Barberà del Vallès, near Barcelona.

**POWDER FORGING INDUSTRY**

**Metaldyne Sintered Components España**, located in Valencia, central eastern Spain, is the only powder-forging manufacturer in Spain. Established in 1998, it is located in the vicinity of Ford Motor Company’s plant and specializes in powder-forged connecting rods, which it sells to numerous countries in Europe and Asia. It has a proprietary powder forging process, which was proven to outperform the wrought forged counterparts. Its team consists of 80–90 people and they have sales in the range of $22 million per year.

**MIM INDUSTRIES**

**Mimecri, S.A.,** founded in 1991 in Santander, North-central Spain, is a member of the Ecrimesa Group. Originally and still a manufacturer of investment castings, it is Spain’s largest manufacturer of MIM parts. It was the first company in Europe to develop the MIM process in a continuous furnace, using the BASF feedstock and Cremer’s furnace technology, with catalytic de-binding. It currently has three continuous production lines and two batch ones, manufacturing over 1.2 million parts per month with a total weight of about 170 mt per year. Its parts traditionally range 1–50 g, with some exceptional cases above 100 g – Figure 5. The majority of parts produced are carbon steel, but they also produce parts in MIM-316, MIM-17-4 PH, Fe-Si 3%, etc. With a total team of 60 people, sales exceeded $14.5 million in 2019. They have a very diversified customer base, including parts for automotive, defense, locks, power tools, etc. and generate over 80 new projects yearly. The group offers complete auxiliary operations such as machining, heat treatments, or assemblies.

**MIM TECH ALFA, S. L.,** created in 2004 for the manufacturing of metal parts by MIM technology, is part of ALFA Group, an industrial corporation founded in 1920 with a great tradition in the Basque industry, specializing in metal manufacturing technologies.

Since 2016, MIM TECH ALFA has owned a 2,100 m² plant dedicated to the MIM process, from tool design and fabrication, to final operations and inspection of the parts. The facilities include injection machines, debinding and sintering furnaces, and quality control equipment including non-destructive and mechanical testing. The company produces large series of small and accurate complex parts for different industrial sectors, like the automotive industry, microelectronics, defense, hand and electrical tools, etc. The company supplies finished and assembled parts, including machining processes, surface treatments, etc. MIM TECH ALFA exports over 85% of its production.

**MIM TECH ALFA** has an intense R&D activity in collaboration with universities, research centers and other companies, having been involved in recent years in projects about automated inspection systems, microinjection, ceramic injection molding, or the development of parts for aerospace actuation systems. Now it is working on sinter-based additive manufacturing technologies, collaborative robotics, magnetic materials, etc.

**POWDER MANUFACTURING INDUSTRY**

**AD Irun,** located close to the French border in San Sebastian, is a subsidiary of the French company Aubert & Duval, part of Eramet. It was a spinoff of CEIT in San Sebastian and it is dedicated to the production of superalloy powders for additive manufacturing. It produced approximately 40 mt of highly engineered powders for a yearly turnover close to $3.6 million in 2019. Supplying major aerospace and land gas turbine OEMs, in 2019 the plant developed new innovative powders, including new ABD 900 with its partner Oxmet from the UK. With strong R&D support from A&D in France, they expect to increase production by 15% to 20% in 2020.

**AMES** has an in-house production of bronze powder that it uses for the manufacture of part of its bushings. It makes approximately 1,000 mt per year of powder, strictly for internal use. This production is the continuation of AMES’ needs from the Spanish autarchy times of the 1950s, but it results in Ames being one of the significant producers of bronze powder in Europe.
### MEETINGS AND CONFERENCES

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The Powder Metallurgy Technologist (PMT) Certification Program was created by APMI International to recognize individuals who possess defined bodies of knowledge encompassing the broad field of powder metallurgy.

**The next PMT certification examinations will be offered October 6, 7 and 8, 2020.**

For more information, complete rules, and application forms, visit: [apmiinternational.org](http://apmiinternational.org)
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