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RESEARCH PAPER

POWDER METALLURGY IN AEROSPACE – FUNDAMENTALS OF PM PROCESSES AND EXAMPLES OF APPLICATIONS

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ABSTRACT

Powder Metallurgy (PM) is one of the technologies that are going to play an important role in manufacturing in all sectors in the future, including aerospace, as it can combine the ease of alloying with net shape capabilities, freedom of design and high performance. Over the years, several different processes have established, each with distinctive features, using dedicated metal powders, and delivering materials that rival the properties of conventionally produced ones. The portfolio of available compositions, properties and part shapes is constantly increasing and penetration in many sectors, including automotive and aerospace, is also deeper year by year. Especially Additive Manufacturing, the latest big development in powder metallurgy, is attractive because of the unprecedented possibilities of weight optimization to obtain at the same time a lower mass and outstanding performance. In this review, a number of examples of applications in aerospace taken from the available literature are shown.

Keywords: powder metallurgy; additive manufacturing; hot isostatic pressing; metal injection moulding; press&sinter; aerospace; case studies

INTRODUCTION

Powder Metallurgy (PM) [1, 2] is a wide range of technologies that allows for the fabrication of solid metal parts starting from elemental or prealloyed powders of almost any kind of metal, and it relates and combines with similar technologies and methods for the fabrication of even more complex materials including ceramics. The main reason for the success of PM in many fields is in fact the ease of alloying, as this can ultimately be obtained even just by mixing of appropriate powders. Sintering, i.e. heat treatment under suitable atmospheres (and sometimes added external pressure) but below the melting range of the bulk material, is also used in most of the PM processes to obtain a solid body, with a shrinkage from the initial formed shape or not, although some remarkable exceptions have been developed over the years where conventional sintering is not the densification step.
Among PM processes we can list:

- The common, and most widely used, Press&Sinter (P&S) route, consisting of compressing the powders in rigid dies, ejecting the parts using the movements of the punches, and sintering them into solid components after removal of the lubricants contained in the parts to aid compaction.
- Metal Injection Moulding or Molding (MIM), where the powders are mixed with an organic "binder" to confer the ability of being injection moulded, like in the case of plastics, into moulds: the complex shaped components are then treated to remove the binder and sintered to the final (almost full) density.
- Hot Isostatic Pressing (HIP), where the powders are poured into a sealed metal container with a suitable shape (simple but sometimes already with some geometrical details) and then pressed isostatically at high temperature to compact them to almost full density (to be distinguished from Cold Isostatic Pressing that is only a way to compact powders at room temperature, prior to sintering).
- Metal Additive Manufacturing (AM), that is a family of methods all starting from metal powders, where the parts are built by 3D printing addition of layer after layer. This can happen in:
    - Beam Based AM: a beam of focused energy (laser, or electron beams, normally) is guided by a CAD-driven 3D actuator to "draw" sections of the part in a bed of powders, melting them so that a solid section is prepared. After that, the base on which the part is gradually built is lowered by a typical layer thickness of a few tens of microns and a new layer of powders is deposited on top, so that a new layer can be drawn and welded and the part can grow layer by layer. This process is not requiring sintering as the part coming out of the printer is already a solid metal part.
    - Sinter Based AM: similar technique to the beam based, but without powder melting, as the powders are just "glued" by inkjet printing so that the printing is quicker than in the beam based. On the other hand, printed parts need to be treated to remove the binder and then sintered in a furnace like for MIM parts. In a variant, Fused Filament Fabrication, a powder/binder mixture feedstock shaped into thin wires is extruded and deposited in sections to build the parts, that need as well debinding and sintering afterwards.
    - Direct Deposition, where a flow of heated (with a laser, plasma, etc.) powders or a wire is impacted on the surface of the part to add another

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  section. This technique does not require subsequent sintering and can be seen as a variant of the Beam Based methods.
- Other densification techniques, like Fast Sintering, Spark Plasma Sintering, Field Assisted Sintering, etc., which combine high temperature obtained quickly by flowing a strong electrical current through the powders with the mechanical pressing of the softened body via punches. These techniques are normally exploiting much quicker densification processes that are not activated in common sintering and are less used in industrial production.

Sometimes the process includes a combination of techniques, like for instance when HIP is used on already dense parts to achieve full density, like in MIM + HIP or AM + HIP processes.

PM also includes of course all the technologies for the production of metal powders, the widest share of which is represented by the various atomization processes from the metal melt, that can be tuned to obtain powders with different particle size and particle size distribution, and particle shape. Different PM processes will normally use different powders, larger of finer, rounder or more irregular and so on.

In this paper we will discuss in some details the various PM technologies, and finally show several applications of these to aerospace parts.

The authors belong the European Powder Metallurgy Association, that gathers most European companies and research groups devoted to PM.

MAIN POWDER METALLURGY PROCESSES

Production of metal powders

Metal powders are the common denominator of all powder metallurgical processes. They are produced in many ways and variants and are available nowadays in a very wide range of chemical compositions, size, size distribution, and shapes. The possibility of further mixing among different powder compositions and grades opens the field to a virtually infinite number of starting points for the fabrication of complex and performant materials.

Apart from composition, the further processing and the properties achieved in the PM final solid part are influenced by the characteristics of the powder [3], like:

- particle size and size distribution
- particle shape
- particle bulk structure and surface condition
- that are strongly dependent on the powder production process.

We will give here just a short description of the main production routes, namely:

- Atomization
- Chemical routes
- Mechanical routes

Atomization

Atomization [4] is the source of most of the powders used in common powder metallurgy processes, like Press&Sinter, MIM, HIP and AM. It is the choice when the metal composition can reasonably be produced from the melt, thus for instance iron based compositions, that are by far the bulk of the global consumption, are normally produced this way, and also for the production of copper, tool steels, alloy steels, brass, bronze and the low melting point metals, such as aluminium, tin, lead, zinc and cadmium.

It consists in melting the alloy in a suitable crucible, with the usual metallurgical procedures to control the composition and the impurities, and then letting the melt flow through a nozzle at the bottom of the crucible so that a thin stream of molten metal is created. Very close to the nozzle orifice, this stream is impacted by a strong high-pressure jet of gas or liquid (normally water) and "atomized" into small droplets that while further falling in the container below cool and solidify into metal particles that are collected at the bottom of the container and sieved or classified to separate them in different size classes.

There is normally a clear difference between powders atomized in water and powders atomized in inert or protective gas: because of the different mechanical and thermal properties of the atomizing media, gas atomized particles of the larger sizes are very round in shape, almost spherical or anyway rounded, whereas water atomized powders appear irregular in shape. Also, atomizing in water brings to a higher O content in the final composition, that must be reduced afterwards or anyway taken into account. The readily oxidizable metals (e.g. chromium-bearing alloys) are thus being atomized on an increasing scale by means of inert gas, especially argon.

Depending on nozzle geometry, gas or water pressure, and other parameters, the particle size distribution obtained with these processes can be changed, so that the yield in a certain size fraction can be optimized. Atomized powders will have different particle size distributions, often with a peak at a characteristic size, and tails at lower and larger sizes. Sizes may vary from submicron and micron size to 150 µm or more. The so-called close-coupled nozzle design is usually more suitable to produce finer powders, in the range below 50 µm, thus MIM and AM powders, whereas larger powders can be obtained with the simpler free fall design.

In more recent developments, rotating cups, plates or cones (or just a rotating bar of the source alloy which is heated at one end) on which the metal melt is centrifugally forced to produce radially travelling droplets that solidify in a very controlled atmosphere, allow the production of very clean (but larger) powders of highly reactive metals (centrifugal atomization).

An interesting procedure to fabricate alloyed powders consists in atomizing a master alloy, for instance even just Fe or Fe-Cr, mixing it with finer alloying powders (like Mo, etc.) and heat treating the mixture so that the smaller particles stick to the larger base powders by contact and diffusion. Each final particle contains roughly the final composition, even if alloying will have to be completed during the sintering, later. This gives the possibility of having a softer matrix, with very good compressibility during compaction, whereas a fully alloyed powder could be difficult to process by simple pressing.

Fig. 1 Gas atomizer for fine metal powders (courtesy Atomizing Systems Ltd)

Chemical routes

Even before atomization was developed, solid state reduction was for a long time the most widely used method to produce iron powder from crushed ore mixed with carbon and passed through a continuous furnace. This brings to a cake of sponge iron which is then further crushed, purified from impurities, and sieved. The purity of the powder, soft irregular sponge-like particles that readily compressible, is dependent on that of the raw materials. Refractory metals are normally made by hydrogen reduction of oxides, and the same process can be used for copper.

Electrolysis can be used for many metals to deposit them in a spongy or powdery state, and then by washing, drying, reducing, annealing and crushing the relevant powders are obtained. Copper is the main metal to be produced in this way, but chromium and manganese powders are also produced, and in the past even iron, but environmental regulations are making production less and less popular.

Thermal decomposition of a chemical compound is used in some cases, like in the Carbonyl Process, that was originally developed to refining Ni. Crude metal was made to react with carbon monoxide under pressure to form the carbonyl which is gaseous at the reaction temperature and which decomposes on raising the temperature and lowering the pressure. The same process is used for iron, and carbonyl iron powder finds small scale application where its very high purity, and its small grain size (1-5 µm), is useful.

Thermal decomposition is used for platinum powder (from platinum ammonium chloride) and Ni (by hydrogen reduction of a solution of a nickel salt under pressure).

Chemical precipitation of metal from a solution of a soluble salt is used in other cases, e.g. Ag, and Co. Powders of the latter are also produced by reduction of cobalt carbonate powder, produced by chemical precipitation with CO_2, starting from cobalt amino-sulphate solution.

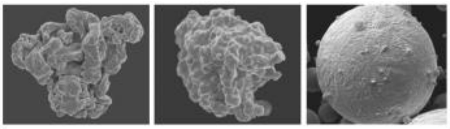

Fig. 2 Left to right: Sponge iron powder NC 100.24 (courtesy Höganäs AB); atomized iron powder ASC 100.29 (courtesy Höganäs AB); spherical ex-carbonyl iron powder

Mechanical routes

Mechanical comminution is normally used for brittle materials such as inter-metallic compounds, ferro-alloys (ferro-chromium, ferro-silicon, etc.). These are mechanically comminuted in ball mills sometimes with very high impact energies, a process (particle-to-particle welding, embrittlement by mechanical strain, fracture, etc.) that can also be used for mechanical alloying of heterogenous powders, even for mixtures that would not normally form alloys. Powder shapes and sizes can very but the shape is normally very irregular, usually platelet-like, while the size can even reach the submicron range, so behavior in the subsequent process is strongly influenced. Other special processes, like the Coldstream Process (used to reduce the size of coarsely atomized powder) can be included in this category.

Press&Sinter

The Press&Sinter process [5] is so established that it is commonly referred to as "powder metallurgy" or "conventional powder metallurgy" [5] as it has been the dominating process since its adoption, although PM is truly the name of the set of processes using metal powders, and not just of this particular route.

The process is shown schematically in Fig. 3. The powders are mixed homogenously together with a lubricant, poured to fill a die and compacted under pressure (or no pressure to obtain porous bodies as e.g. bronze filters), after which the compact is sintered and can later be subjected to further post-treatments.

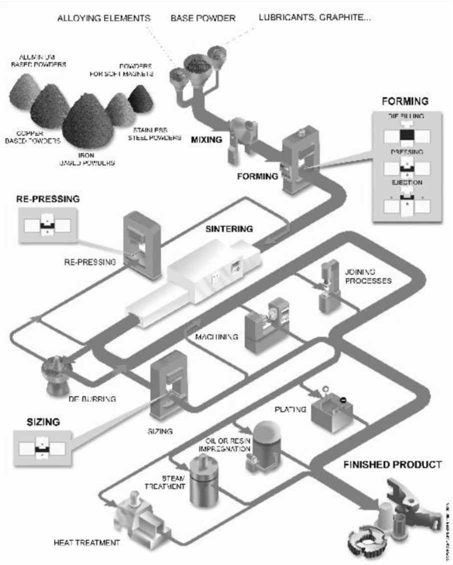

Fig. 3 Scheme of the Press&Sinter process

Mixing

Mixing provide a homogeneous mixture comprising the powders and the lubricant (usually stearic acid, stearin, metallic stearates, especially zinc stearate, and increasingly, other "waxy" organic compounds). The choice of the lubricant and its amount must take into account the need

- to be easily removed during or better before sintering without unwanted residues or reactions,
- not to reduce the maximum attainable density during pressing by occupying excessive volume in the mixture,
- to have a flowable mixture that will evenly fill the compaction die.

Compaction

The mixed powders are pressed to shape in a rigid steel or carbide die under pressures of 150-900 MPa. The tools to impart the desired geometry are mounted in hydraulic or electrical presses, with several independent highly precise punch and die movements. Depending on geometry, the tools may have relatively thin or relatively bulky punches and features, thus the maximum safely attainable pressure to avoid tool damages can be lower (e.g. only 600 MPa) or higher (even more than 1000 MPa), choosing a compromise between part density and tool wear. After pressing, the compacts maintain their shape because of cold-welding of the powder grains within the mass and are sufficiently strong to withstand ejection from the die and subsequent handling before sintering.

The final shape and mechanical properties are essentially determined by the level and uniformity of the as-pressed density. Powders under pressure do not behave as liquids, the pressure is not uniformly transmitted, and very little lateral flow takes place within the die. The attainment of satisfactory densities therefore depends to a large degree on press tool design and the actual

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pressing procedure. To produce parts safely, the tool must be designed [7] with several factors in mind:

- Length-to-Width-Ratio: because of the compression behavior of the granular material, the pressure locally applied and therefore the density decrease over the length of the compact: this can be strongly reduced by lubrication and double-sided compaction, but a lower density region at the middle section of the part is unavoidable, so length-to-width ratios in excess of 3:1 are not recommended.
- Reverse tapers and lateral holes cannot be normally produced by pressing because of the impossibility of ejection (they are normally machined afterwards), although elaborate, sometimes flexible die assemblies have been designed, patented and industrially used that overcome this limitation.
- Bevels require feather-edged tools, which are fragile and easily fractured; so, if design permits, the beveled edge of the component should end in a small flat.
- Abrupt changes in sections should be avoided since they introduce stress raisers, which may lead to crack formation especially during ejection.

Roughly, the size of the part that can be made is a direct function of the capacity of the press available, but the complexity of the part and number of punch motions also play a role. The simpler the part, the easier it is to press at high speed, up to roughly 1 part per second, but 10 parts per minute is a typical compaction rate for parts of comparatively simple geometry.

Special variants include: warm compaction, where the material and/or the die itself are heated to a point where the yield stress of the powder is significantly lower, attaining thus higher compact (and final) densities with lower amount of lubrication; hot pressing, where the temperature is so high (a special high temperature press is needed) that densification happens during pressing (also used for non-metallic parts); and high velocity compaction, where a more impulsive pressing is imparting compaction in milliseconds.

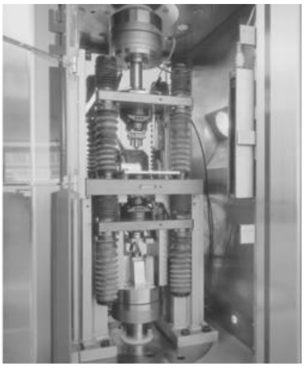

Fig. 4 Powder compacting press (courtesy Fette GmbH)

Another possibility for compacting finer powders is to cold press them isostatically (Cold Isostatic Pressing, CIP [9]) using rubber moulds (“wet” or “dry” bag variants) immersed fully or partially into a fluid (water/oil emulsions or similar) that is brought to high pressure and held under pressure for a few minutes, typically at 200 MPa (2000 bar, for powders mixed with binders) and up to 700 MPa (for pure metal powders). The compacts can then be treated for sintering, although they are previously machined to a more complex shape (the shape complexity attainable with the CIP is somewhat basic, although some features, like internal cylindrical cavities, for instance, can be achieved by using rigid steel inserts in the mould). Dry bag systems are preferred when productivity is a critical factor, whereas wet bag systems are normally used for larger parts with lower production volumes.

Sintering

During sintering the compact acquires the strength needed to fulfil the intended use. In general, sintering is a thermal treatment of a powder or compact at a temperature below the melting point of the main constituent, for the purpose of increasing its strength by bonding the particles together [15]. At a such temperature, atomic diffusion takes place with various mechanisms and the welded areas formed during compaction grow until eventually the primary particles may be lost completely. Recrystallisation and grain growth usually happen, pores in the part tend to become rounded and the total porosity, as a percentage of the whole volume, tends to decrease.

Due to the high reactivity of the powders, sintering is carried out under a protective atmosphere (H_2, N_2/H_2 mixtures, dissociated ammonia, exo- or endogas produced from hydrocarbons, depending on the material to be sintered, to achieve the right control over oxides, carbides and other unwanted phases), at maximum temperatures between 60 and 90% of the melting-point of the particular metal or alloys (this might mean, for powder mixtures, that the sintering temperature may be above the melting-point of the lower-melting constituent, e.g. copper/tin alloys, iron/copper structural parts, tungsten carbide/cobalt cemented carbides, hence the term “liquid phase sintering”, but the amount of liquid phase must be low in order to avoid impairing the shape of the part). During the first part of the cycle, at lower temperatures, the lubricant, if present, is removed thermally. Heating rate, time, temperature and atmosphere control is required for reproducible results. Generally, electrically heated continuous belt furnaces are preferred, with typical sintering temperatures up to 1150°C, but higher temperatures (up to 1350°C) can be achieved with the walking beam design.

In recent years new types of sintering furnaces allow low alloy steel parts to be sintered with neutral carbon potential (without decarburization or carburization) and then to be hardened in a rapid cooling zone (sinter hardening).

For special applications batch vacuum or hydrogen furnaces are used, normally when higher temperatures are needed.

Sintering can be enhanced under certain conditions, like for liquid phase sintering. In activated sintering, a special “activator” (normally finer powders or an alloying component), may be used to promote diffusion at the early stages, sometimes by reacting with the thin oxides on particle surfaces. In sintering of iron alloys, a ferrite phase stabilizer can be added so that the much higher self-diffusion of iron in ferrite compared to austenite can be exploited.

Sintering leads to progressively increased strength by diffusion-driven welding of the primary particles. Generally, the part tends to increase in density as well, with an overall shrinkage; but in some systems even a growth may happen, because of gases that develop inside the part during the process or, in reactive sintering mixtures where alloying takes place during sintering (e.g. Cu diffusing into Fe), because the new phase formed by the alloying has a higher volume. Under controlled plant conditions, reproducible size change can be maintained, and this must be foreseen in the design and manufacture of tools, but it is increasingly practiced balancing the composition and sintering regime so that no dimensional change takes place. As dimensional change is influenced also by compact density (the lower, the greater the tendency to shrink), this is one of the reasons why uniformity of density of the compact is of such importance. If there is significant variation from one part to another the differential dimensional change in the various sections can lead to warpage.

Final sintered parts normally achieve a density ranging from slightly below 90% and about 95% of the theoretical density, with typical values for most popular compositions and parts just above 90%.

Fig. 5 Continuous belt sintering furnace (courtesy Mahler GmbH)

Further treatments and variants

Many treatments can be carried out on sintered parts to improve them for several aspects.

In repressing, an improvement of the already good tolerances is achieved (sizing and coining), with often an associated density increase. When followed by a second sintering, this is normally referred to “double pressing -double sintering”.

As an extreme, if a simple blank is produced by sintering it can be forged, i.e. hot repressed in a closed die [8]. This is very popular especially for automotive high strength applications and is named powder forging.

Fig. 6 Powder forged connecting rods (courtesy Metaldyne Sintered Components)

Even HIP (see below) can be used on pressed parts, but this is normal for special materials like cemented carbides, not for steel or metal parts in general.

A further surface densification can be achieved by Surface Cold Rolling, that is common for gear teeth, and resembles a “localized” repressing.

As porosity is a typical feature of pressed&sintered parts, as it might represent 5-12% of the body of the part (and ranging from completely interconnected to not interconnected depending on part density), there are treatments that use or try to compensate the presence of porosity.

Infiltration is a method of improving the strength of inherently porous sintered parts filling the surface connected pores with a liquid metal having a lower melting point (e.g.: ferrous parts using copper as infiltrant). This can be used also to make composite electrical contact materials such as tungsten/copper and molybdenum/silver.

In impregnation the pores are filled with an organic as opposed to a metallic material: oil-impregnated bearing materials are the best example, but also thermo-setting or other plastic materials are used, to increase mechanical properties or seal of the pores (for pressure-tightness or to prevent the entry of potentially corrosive electrolyte during a subsequent plating operation), or to improve part machining.

Heat treatment is very common for steels, that often are used just as sintered or sized, but many times are supplied in the hardened and tempered condition (frequently sinter hardened, see above). If steel density does not exceed 7.2 g/cm^3, interconnected porosity imposes the use of processes where heating is done in a gas atmosphere, followed by oil-quenching. Similarly, PM parts can be carburized and carbonitrided, but again gaseous media are indicated, and porosity will bring the effect inside the first layers of the part so the 'case' is generally deeper and less sharply defined than with fully dense steels.

Steam treatment is a process peculiar to PM steel parts: exposing them at a temperature around 500°C to high pressure steam, a layer of magnetite (iron oxide) forms on all accessible surfaces and:

- corrosion resistance is increased by the filling of some of the porosity;
- the reduction in porosity of the surface layer leads also to improved compressive strength;
- the oxide layer significantly increases the surface hardness and the wear resistance.

At a lower temperature (200-250°C) in air a thin magnetite layer that gives some increase in corrosion resistance, but it is much less effective than steam treatment, is formed (“blueing”).

As mentioned earlier, with a previous impregnation in case of interconnected porosity, parts can be plated, e.g. with copper, nickel, cadmium, zinc, or chromium plating. are all used.

Parts are also often machined, for several reasons: usually because of limitations to the geometry that can be pressed in rigid dies, for example for transverse holes. Although porosity alters the machining characteristics and in general tool wear is greater than with the same composition in the fully dense form, with carbide tools and relatively low cutting speeds this is quite possible.

Deburring, and tumbling, sometimes in a liquid medium with an abrasive powder, is normally employed to remove machining burrs.

Parts can be joined by welding or brazing, although special care may again be needed to accomplish for open surface porosity.

Materials and typical applications

P&S is commonly used to produce a wide variety of materials and parts.

It is also used to produce non-metallic materials and composites like metal matrix composites, cemented carbides [10], diamond cutting tools [11], and ceramics, that are not discussed here.

Structural Parts:

The bulk of structural P&S parts, that means parts with a mechanical function, is based on iron, but significant quantities of copper, brass, nickel silver, aluminium and bronze parts are made.

Ferrous structural parts are the core of the P&S offer, and are usually chosen by customers for cost reduction, yet performing the function, over the cast or machined counterparts. The net shape capability of the powder route avoids costly machining and, in the end, proves to be a winner, despite the reduced properties deriving from the residual porosity.

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In order to be cheap, compositions are based on iron, with additions for strength starting from simple C and Cu; to achieve better properties, Ni and Mo have been added (frequently by diffusion alloying), and more recently also Cr, Mn and Si have been gradually introduced to obtain better hardening.

As properties are strongly depending from density, techniques for density improvement, many of which have been listed above, have been introduced: a special mention must be made for powder forging, that has the great advantage of reaching almost theoretical density. Simultaneously, an effort to expand the limits in geometrical features is continuously undertaken by the major producers and some very clever solutions for, e.g. transversal details are nowadays used in industrial practice for many parts.

These advances both in geometrical complexity and performance level have led to a great expansion in the types of P&S ferrous structural part applications.

The automotive sector is the dominant customer industry for P&S structural parts: worldwide, 75-80% of these go to the automotive sector. Engine (timing pulleys, sprockets and hubs, valve train parts like valve seat inserts, valve guides, valve timing control and coupling devices, balancer gears, main bearing caps, engine management sensor rings, oil and water pump gears) and transmission (synchronizer system parts, clutch hubs, gear shift components, planetary gears and carriers, turbine hubs, clutch and pocket plates) components are particularly important, accounting for at least 70% of total automotive usage (other parts include shock absorber components like piston rod guides, piston valves and end valves, Anti-lock Braking System (ABS) sensor rings, exhaust flanges and oxygen sensor bosses out of P&S stainless steel, gears and bearings in small electric motors, door lock parts)

P&S ferrous structural parts are also popular in a number of important non-automotive markets, like DIY hand power tools, domestic appliances, business machines, leisure and garden, industrial motors and controls, and general hardware like lock parts, latches, etc.).

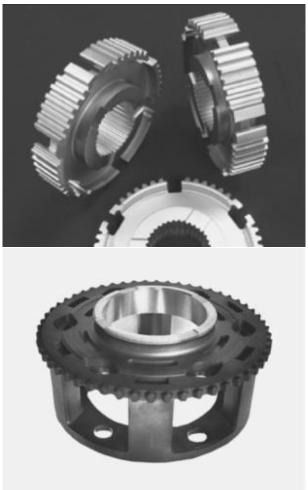

Fig. 7 Left: Synchronizer hubs for automotive (courtesy PMG Füssen); right: planetary carrier for automotive transmission (courtesy AMES SA)

Non-ferrous structural parts: The production of structural parts in non-ferrous materials is on a much smaller scale but significant quantities of copper, brass, nickel silver, and bronze parts are made, and the production of aluminium from powder is now developing, driven largely by the automotive sector’s desire for weight reduction. Camshaft bearing caps have emerged as a leading application for P&S aluminium parts. Aluminium can of course be considered for some aerospace applications for weight reduction.

Bearings and filters

The advantage of porosity is used to produce bearings. As explained, the pores can be filled with lubricating oil, so that the bearing requires no further lubrication during the whole life of the machine in which it is used. The pores form an interconnected system of controlled size and volume, so that oil is supplied to the entire bearing surface and the rate of oil supply automatically increases with temperature and, therefore, with increasing speeds of rotation, to achieve optimum working conditions. Election material is bronze, or sometimes iron, iron copper, or iron mixed with bronze is used.

Alternatively, copper/lead or copper/tin/lead (leaded bronze) non-porous bearings can be also produced.

Controlled porosity is also employed in the manufacture of metal filters and diaphragms out of bronze (e.g. 89/11 Cu/Sn), copper, nickel, stainless steel and 'Monel', and are widely used for the filtration of fuel oils, chemical solutions and emulsions, separating liquids of varying surface tension (like water from fuels in jet engines), or sound damping on air compressors and the like.

Friction Materials

Sintered metal friction components, consisting essentially of a continuous metal matrix, into which varying amounts of non-metallic friction generators, such as silica and emery, but also copper, tin, iron, lead, graphite, carborundum, alumina and asbestos substitutes are bonded, are particularly useful for heavy-duty applications, e.g. aircraft brakes, high speed train brakes, race cars brakes, heavy machinery clutch and brake linings etc. The resistance to wear is superior to resin-bonded materials, and therefore, permits the use of components of thinner section. Compared with solid phosphor bronze or aluminium bronze friction elements, the sintered material offers many advantages, the most important is probably the much wider range of friction characteristics, which can be obtained from variations in the dispersion of non-metallic particles, that is a feature distinctive of powder metallurgy

Magnetic and Electric Components

A range of soft magnetic materials can be processed by P&S [12], like iron, silicon-iron and iron with about 5% of phosphorus, overcoming difficulties due to the limited ductility of the alloyed compositions. These are widely used in the manufacture of pole pieces and armatures for DC application.

For AC applications, minimized eddy current losses can be obtained via the Soft Magnetic Composite (SMC) materials. In these materials, the individual powder particles are insulated from one another by a resin addition, which is cured in a baking process after compaction, so that the thickness of the flux path becomes equivalent to the powder particle size, i.e. very small. Sintering in the accepted sense is not required, the parts are just pressed, cured and stress relieved. Cores for self-inductance coils in high-frequency communication equipment are a typical application.

Sintered high-permeability laminated components in nickel-iron and permalloy-type materials are also used for transformer applications.

Soft ferrites or magnetic oxides have the widest application in the manufacture of cores for radio and television.

But especially the hard magnets are nowadays mostly processed by P&S: hard ferrites (maybe over 90% of the current market by volume), AlNiCo, CuNiFe and CuNiCo, but also Sm-Co, and later Nd-Fe-B magnets are all successful examples.

Composite structures attainable only by powder metallurgy methods have been used extensively in the manufacture of electrical contacts and current collector brushes, combining the desirable conducting properties and low contact resistance of silver or copper with the strength, heat-resistance, and resistance to arc erosion of tungsten, molybdenum, nickel, etc., or with the lubricating qualities of graphite.

Metal Injection Moulding

A technology developed in the 1980’s and that started gaining industrial significance in the 1900’s is Metal Injection Moulding [13, 16]. Stemming from the sister technology developed for ceramics, it combines the ease of shape fabrication of injection moulding with the typical powder metallurgical advantages of alloying and net shapes, with the bonus that the use of very fine powders brings to very high, sometimes, almost theoretical, sintered densities. In its basic form (See the scheme in Fig. 8) it includes the fabrication of the so-called feedstock, a mixture of metal powders and organic binders, the injection moulding into the desired shape, the removal of the organic binders, and the sintering at high temperature to almost full density. Due to its characteristics, it suits especially small parts with high demands in terms of properties, and large series.

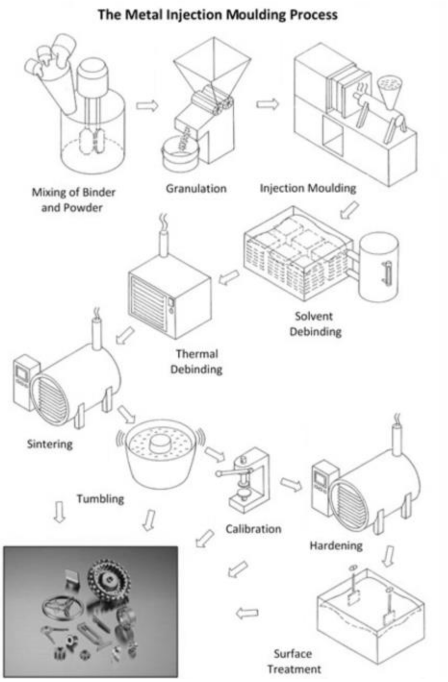

Fig. 8 Scheme of the Metal Injection Moulding process

Feedstock compounding

The powders for MIM are somewhat specific as they must possess properties that are quite different from the ones necessary for P&S and other part fabrication routes. The powders are not mechanically deformed during the process, so they can be as alloyed as desired, on the other hand they have to be highly flowable, able to mix well with the organic binders, and finally with high sinterability to achieve the high density. Thus, the ideal MIM powder is normally very fine (even <20 µm) but with a wide particle size distribution, and spherical. Nevertheless, applications to other less ideal powders are possible and the tuning of the mixing can compensate for that.

The organic binders are normally thermoplastic polymers and waxes, with other additions to ease wettability to the powder and decrease or control mixture viscosity and other features.

In the mixing, a volume ranging from about 50% to about 70% of powders are added to a complementary part of organic binders (usually a mixture of different components) and mixed in the melting range of the binders, by extrusion or shear rolling or kneading, until the desired homogeneity is achieved. This high fraction of binders determines one of the important factors in the MIM process, i.e. the shrinkage during sintering (compare with Press&Sinter, where the lubricant has a volumetric fraction of some %). The cooled and granulated feedstock can be subsequently moulded.

Feedstock technology is the characterizing point in the process, and affects the rest of the steps, injection moulding (via its rheology), debinding (via the route for removal) and sintering (via the residual debinding and the shrinkage). Nowadays a significant fraction of the feedstock is made by specialized companies, although some producers prepare their mixes in-house.

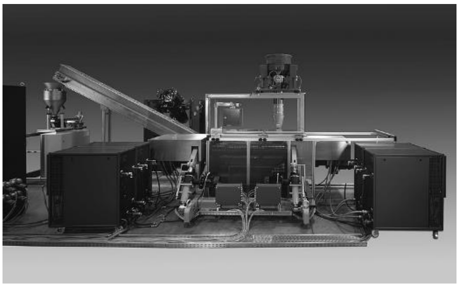

Fig. 9 Shear roll mixer for metal injection moulding (Courtesy Bellaform GmbH)

Injection moulding

Injection Moulding in MIM is somewhat similar to the injection moulding of plastics, as the equipment (injection moulding presses and accessories) are the same (with small but important modifications) and tool designs can be similar (but normally with more wear resistant tool steels to accomplish for the higher wear). The injection moulding of the metal feedstock itself, however, is more complex, as rheology is affected by the different properties of the mixture. Furthermore, all defects introduced in this phase are likely to be amplified by the subsequent steps, so although the process is truly offering a wide freedom of shape, mould design and part design must be addressed properly, to avoid or reduce distortion, flow lines, junction lines, powder and binder separation and errors in final dimensions, taking into account the specific properties of the feedstock used (flowability, green strength limitations, etc.). Design guidelines are available with general recommendations about thickness, sizes, tolerances, position of injection gates, etc., and respecting them is preferable, although some challenging parts have been produced successfully. An “ideal” design will deliver the best properties at the lowest cost and effort.

The mould must be oversized by a factor (mould or shrinkage factor) to compensate the shrinkage during sintering and sometimes slightly unbalanced oversizing factors in different areas should be considered to compensate for later deformation in sintering. Many cavities can be placed in the same mould (normally copies of the same part to avoid unbalanced injection) and that enhances productivity.

For a typical thermoplastic feedstock, the process starts with the loading of the press by rotating the screw inside the heated barrel and bringing the molten feedstock to the front of the screw; then the screw is brought forward with a precisely controlled movement to push the feedstock (maximum pressures are around 1000 bar typically) though the mould channels until they reach the cavities and fill them. During a pressurization phase the injected material cools and solidifies in the cavities, then the screw rotates again to load more material for the next injection, and the mould is opened and the parts pushed out of the cavities via ejection pins. Parts are checked and normally placed onto trays for the debinding. The solidified channels (sometimes minimized using heated sections in the mould) and all scrap parts are separated but can normally be recycled in later mouldings by remixing, improving process efficiency.

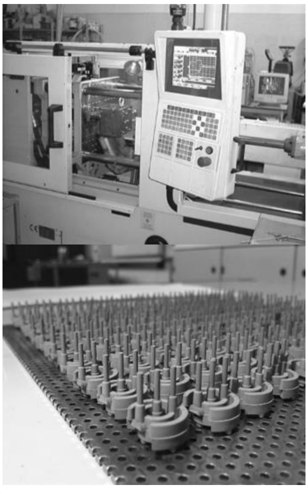

Fig. 10 Left: injection moulding press; right: moulded MIM parts placed on trays

Debinding

Debinding is the binder removal process, and is very dependent on the feedstock selected, that dictates the debinding strategy. The modern approach to binder removal includes normally 2 steps: the first is carried out separately but the second is normally executed inside the sintering furnace. The first step is normally one of these:

- a solvent debinding, where a solvent (even water for some binders) is used to remove the soluble ingredients of the binder by immersing the parts at low temperature in it;
- a thermal debinding, where the parts are exposed to temperatures where the polymer binder evaporates and extracted by gas flow or vacuum in the debinding furnace;
- a catalytic debinding, exploiting the decomposition of POM feedstock using gaseous nitric acid or oxalic acid (very popular)

All these processes can be carried out in batch or continuous debinding equipment.

After the debinding the parts contain a small residue of the original binders, tend to be fragile and sometimes difficult to handle but maintain roughly the same dimensions as green parts. Careful debinding is needed to avoid warping, blistering, cracking, and subsequent problems in sintered parts (for instance, due to insufficient binder removal in some areas of the parts).

The secondary debinding is normally a thermal step and as anticipated is carried out during sintering.

Fig. 11 Left: catalytic debinding furnace (courtesy Nabertherm GmbH); right: solvent debinding units (courtesy Lömi GmbH)

Sintering

The high temperature sintering process brings the parts to their final size. Depending on the initial binder volume content the linear shrinkage is between 12 and 20% (mostly 15-18%). As sintering is a thermal diffusion process based on thermodynamics, it is the surface energy per volume of the fine MIM particles, much higher than that of coarse particles, that strongly promotes the diffusion of atoms, pushing the final density much higher than the sintering process of Press&Sinter, usually above 96% of the theoretical density of the alloy applied.

Sintering is performed in high temperature (just below the melting temperature) batch or continuous furnaces applying process gas (hydrogen, nitrogen, argon) or vacuum. The time-temperature-atmosphere scheme of the process is critical, a slower ramp and hold for secondary thermal debinding is sometimes needed and then the sintering temperature can be reached safely: MIM steel components are sintered between 1200°C and 1400°C depending on their specific chemical composition, but each material can have different optimal sintering schedules.

Special care must be placed in the choice of the ceramic materials for the trays and support of the parts (MIM parts have complex geometries and generally might need shaped supports to avoid gravitational slumping during sintering), as the high shrinkage can cause sticking and warping if the friction is not ideal, especially for heavier parts.

Fig. 12 Top: batch debinding and sintering furnace for MIM (courtesy Elnik Systems); bottom left: continuous debinding and sintering furnace for MIM (courtesy Cremer Thermoprozessanlagen GmbH); bottom right: MIM parts placed on special sintering supports to avoid distortions

Further treatments and variants

Metal injection moulded parts achieve a sufficiently high density after sintering, normally well above 96% of theoretical, to allow for most standard post-treatments, including deburring, surface finishing (even at very low R_a values, almost mirrorlike), coating and plating, and of course heat treatment, machining and mechanical deformation (sizing, coining, bending and straightening) when the alloy has sufficient ductility in the sintered state. Being normally net or near net shape parts, thermal treatments require suitable atmospheres as the part surfaces should not be damaged by oxidation or other surface contaminations.

MIM is actually a family of different processes, one for each binder variant, as binder properties influence mixing, mould design, injection moulding, debinding and partly sintering.

Extrusion is starting to be used to produce profiles, by using MIM feedstocks and applying the rest of the process on the extruded and solidified products. This experience is partly used in the Fused Filament Fabrication additive manufacturing route (see below).

For some alloys, even using fine powders, sintering is made difficult by the very tight sintering window in temperature (due to the small difference between solidus and liquidus), hardly attainable with industrial furnaces, so the common practice is to sinter the parts at a lower “safe” temperature to a lower final density but make use of Hot Isostatic Pressing (see below) to achieve full densification. The same procedure can be applied on already dense components for highly critical applications (in aerospace for instance) where no residual porosity or other internal defect is tolerated.

By using special presses and moulds, two-component MIM is possible, to combine in the same part for instance a magnetic and a non-magnetic steel, or a hard and a soft steel, or even metal and ceramic materials. Although this is not standard practice and a careful choice of feedstocks and processing conditions must be made to comply with all demanding requirements for the co-sintering of different materials, the first industrial applications are becoming reality.

The MIM process lends itself to produce micron-sized feature in very small parts, in a process variant named microMIM.

Materials and typical applications

Almost all metals that can be processed to obtain suitable MIM powders (usually spherical and fine) have been successfully processed by MIM, with some exceptions like aluminium and magnesium, whose oxide surface film and low sintering temperatures make industrial production difficult. A short list would include low alloy steels, stainless steels, tool steels and high speed steels, nickel based superalloys, cobalt alloys, copper alloys, titanium, intermetallics, magnetic alloys, refractory metals and hardmetals (cemented carbides), but the portfolio is constantly expanding. Even if the fine powders have a definitely higher cost than wrought steel and even compared to the powders used for P&S, the net shape capabilities of MIM can be leveraged to best effect for high value alloys as process scraps that are associated with machining are minimized.

In terms of volume, almost 50% of the global production is related to stainless steels, with 316L and 17-4 PH as main contributors (consumer electronics has been a large customer in the recent decades, especially in Asia where most of the production of mobile phone frames and electronics is undertaken), followed by low alloy steels and other steels. Titanium and superalloys are steadily increasing also because of the growth of applications in engines and turbines, some of which in aerospace applications.

Some examples of MIM aerospace parts will be shown in a following chapter. Other typical sectors for MIM are medical (orthodontics, special tools), consumer parts (watch cases and components, eyewear parts, the mentioned mobile phone and electronic parts), firearms (mechanical parts in smaller weapons), automotive (many small parts in sensors and actuators, and esthetic parts), electrical and hand tool parts, textile machinery parts, general industrial machinery parts, etc.

Hot Isostatic Pressing

Hot Isostatic Pressing (HIP) is a process to densify powders or sintered parts (or even cast parts) in a furnace at high pressure (100-200 MPa) and at temperatures from 900 to 1250°C, for example for steels and superalloys [17, 18]. The gas pressure acts uniformly in all directions to provide isotropic compression and 100% densification. It provides many benefits and has become a viable and high-performance alternative to conventional processes such as forging, casting and machining in many applications. Its positioning is very complementary to other PM processes such as MIM, P&S, or the new AM technologies. It is even used in combination with these PM processes for further part densification and the production of semi-finished bars or slabs.

A wide range of component types can be manufactured thanks to HIP. Its capabilities include large and massive near net shape metal components such as oil & gas parts weighing up to 30 tons, or net shape impellers up to one meter in diameter. Equally it can be used to make small PM High Speed Steel cutting tools, such as taps or drills made from PM HIP semi-finished products, which can weigh less than 100 grams, or even very tiny parts such as dental brackets. As a result, HIP has developed over the years to become a high-performance, high-quality and cost-effective process to produce many metal (or ceramic) components.

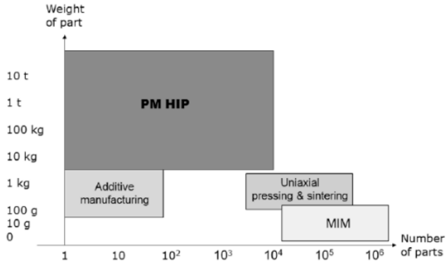

Fig. 13 Positioning of PM HIP technology vs. other PM technologies (source O. Grinder, Euro PM2009 Congress & Exhibition)

The production of a PM HIP component is leaner and shorter than usual conventional metallurgy processes, and the cost of HIP relative to energy and materials costs has decreased by 65% over the last two decades.

Main process steps are:

1. Container design and manufacturing
2. Container filling with powder and sealing
3. Hot Isostatic Pressing
4. Container removal
5. Post processing operations

Container Design and Manufacturing

Container manufacturing involves the following steps:

- Container sheet cutting and forming/shaping
- Assembly of steel sheets and optionally pipes and metallic inserts by TIG welding
- Leak testing, by evacuating the container and introducing helium or argon under pressure. If a leak is detected and located, repair is undertaken.

The integrity of welds is critical, otherwise when the vessel is pressurized, argon will enter the container and become entrapped in the powder mass. The argon will remain in the material and argon-filled pores will strongly deteriorate the mechanical properties.

Container filling with powder and sealing

Fig. 14 Example of container construction with filling/evacuation tubes (courtesy Rolls Royce)

Once assured that the container is leak-free, the powder is introduced via a fill-tube. In order to achieve maximum and uniform packing of the powder, which is necessary to ensure a predictable and consistent shrinkage, a vibration table is used, so that the powder better fills narrow spaces and remote areas. In special cases such as critical aerospace applications, the filling operation is done under inert gas or vacuum to minimize contamination of the powder.

The next step is outgassing to remove adsorbed gases and water vapor. After outgassing, the fill tube is welded under vacuum to seal the container. As explained, the absence of leaks is critical.

The Hot Isostatic Pressing Process

During the hot isostatic pressing process, the temperature, argon (in special applications, other gases or gas mixtures are used) gas pressure and holding time will vary depending on the material types. After filling and closing, the HIP vessel is evacuated to eliminate the air. Then, while heating up, Argon gas pressure is increased in the vessel. After reaching a set pressure by a compressor, the further increase in pressure is done through gas thermal expansion by heating. The gas pressure is equal inside and outside the insulation. But the gas density is higher outside the insulation than inside because of the lower temperature. In the holding time, gas pressure and temperature are constant. Chosen temperatures are below approx. $0.8 \cdot T_{solidus}$, to avoid having a liquid phase.

After this, a rapid cooling takes place, with decreasing pressure and temperature. Modern HIP systems can feature Uniform Rapid Cooling (URC) which circulates lower temperature gas to cool the part at a controlled rate of up to 100°C/min. The HIP quenching technique cuts cycle time dramatically by shortening the cooling stage by as much as 80%. It also provides the benefit of combining heat treatment with HIP in a single step. The URC restricts grain growth and thermal distortion of the parts and avoids surface contamination by using high purity argon gas. A HIP treatment cycle usually lasts from 8 hours up to 24 hours.

A HIP unit consists mainly of a pressure vessel, a heating system and an Argon gas system. Various HIP constructions are available:

- with or without a frame (for pressures above 100 MPa and HIP diameters above 900mm, frame construction is chosen for safety reasons)
- with or without top screw thread locking systems
- with different heating systems

Molybdenum furnaces are used for temperatures up to 1350°C and carbon graphite/tungsten furnaces up to 2200°C. Inside the pressure vessel, insulation (ceramic fibers and Molybdenum sheets) is used to protect the steel pressure vessel against the heat and to hold the high temperature inside the insulation. The bottom, cover and pressure vessel are water cooled to protect the sealing ring and the vessel against the heat. In large HIP units, diameters can reach 2200 mm and height of more than 4000 mm, with a capacity of up to 30 tons.

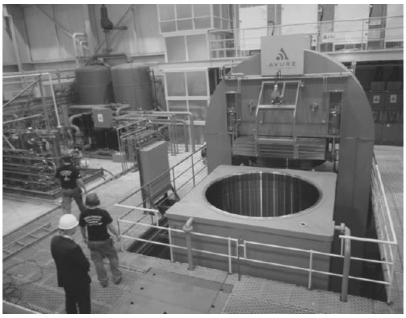

Fig. 15 Large-scale HIP unit (courtesy MTC/Avure)

After HIP, the container can be removed (when the container is not to be re-used) by machining, acid pickling or slipping off. After container removal, various additional operations can take place, including heat treatment, machining, finish grinding and surface treatment. Depending on the size and value of the parts being made various types of quality testing will be undertaken. Two of the most common are ultrasonic testing and dye penetrant inspection. CAT scanning is also used in critical high value applications.

Materials and typical applications

In addition to standard or customized compositions of steels, HIP is used for nickel-base and cobalt-base alloys, but also for titanium, copper, lead, tin, magnesium and aluminium alloys. As during hot isostatic pressing the elements do not have time to segregate like in cast parts, because the temperature is below the melting point, new alloy compositions can be successfully produced, like tool steels for higher wear or temperature resistance, stainless steels for high corrosion resistance in difficult environments, and even composite materials, e.g. wear resistant metal and ceramic composites.
Typical application sectors are aerospace, automotive, energy (even very large parts like valves, manifolds, rotors and impellers), tooling and wear resistant parts for manufacturing equipment, etc.

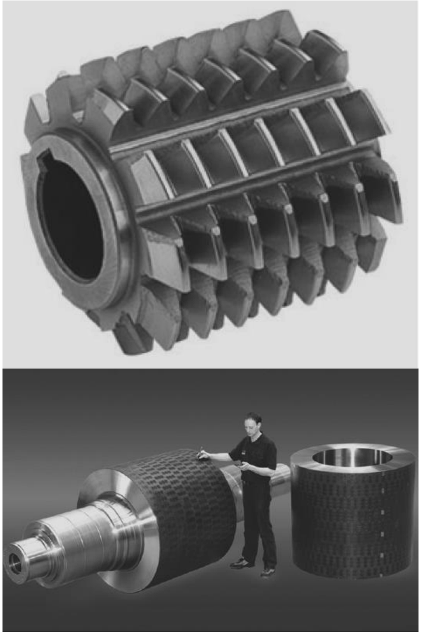

Fig. 16 Top: HIPped high speed steel automotive gear cutter (courtesy Erasteel); bottom: tool steel clad grinding roll for cement processing impeller (courtesy Köppen)

Metal Additive Manufacturing

Additive manufacturing, according to the ASTM standard F2792-10, is the "process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining” [19]. Additive manufacturing technologies for metals are numerous, hence the development of a wide variety of terms and acronyms, as can be seen in the graph below. But today Additive Manufacturing (AM) is the most common term in industry markets while 3D printing is more used in the consumer market. An overview of metal additive manufacturing processes is given in Fig. 17.

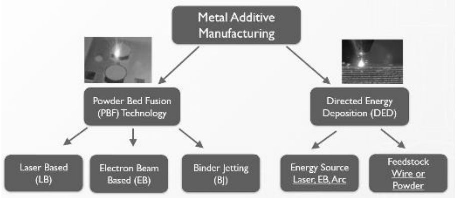

Fig. 17 Mapping of main metal powder additive manufacturing technologies

The use of AM with metal powders is a new and growing industry sector with many of its leading companies based in Europe. It became a suitable process to produce complex metal net shape parts, and not only prototypes, as before. Additive manufacturing now enables both a design and industrial revolution, in various industrial sectors such as aerospace, energy, automotive, medical, tooling and consumer goods.

AM for complexity

Metal additive manufacturing technologies offer many key benefits. The design ideas referring to maximum performance, or minimum weight that cannot be realized by conventional manufacturing techniques such as casting, and machining, are usually possible by AM. In general, the process is recommended for the production of complex parts in small series.
Benefits of AM technology can be summarized as:

- Increased design freedom versus conventional casting and machining.
- Light weight structures made possible either by the use of lattice design or by designing parts where material is only where it needs to be, without other constraints. This procedure is normally referred to as “topology optimization”.
- New functions such as complex internal channels, or several parts built in one.
- Net shape process meaning less raw material consumption, up to 25 times less versus machining, important in the case of expensive or difficult to machine alloys. The net shape capability helps creating complex parts in one step only thus reducing the number of assembly operations such as welding, brazing.
- No tools needed, unlike other conventional metallurgy processes which require molds and metal forming or removal tools.
- Short production cycle time for complexity: complex parts can be produced layer by layer in a few hours in additive machines. The total cycle time including post processing usually amounts to a few days or weeks and it is usually much shorter than conventional metallurgy processes which often require production cycles of several months.

Beam based Technologies

In beam-based powder bed systems (LBM or EBM), a powder layer is first applied on a building platform. Then a laser or electron beam selectively melts the upper layer of powder. After melting, the platform is lowered and the cycle is repeated until the part is fully built, embedded in the powder bed. During laser beam melting, the laser beam, with diameter of the order of 100 μm, will locally melt the upper powder layer on the powder bed. The laser will be partially absorbed by metal powder particles, creating a melt pool which solidifies rapidly. Laser power typically varies from 200 W up to 1000 W.

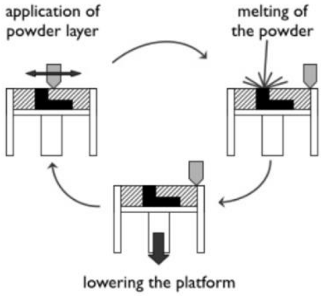

Fig. 18 The powder bed manufacturing cycle (courtesy Fraunhofer)

In the laser beam melting process, a powder layer is first applied on a building platform with a recoater (blade or roller) and a laser beam selectively melts the layer of powder. Then the platform is lowered by 20 up to 100 μm and a new powder layer is applied. The laser beam melting operation is repeated. After a few thousand cycles (depending on height of the part), the built part is removed from the powder bed.

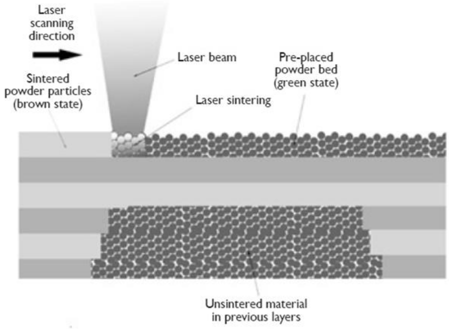

Fig. 19 Cross sectional view of the Laser Beam fusion process in powder bed

The Electron Beam Melting (EBM) process is based on a high-power electron beam that generates the energy needed for high melting capacity and high productivity. The electron beam is managed by electromagnetic coils providing extremely fast and accurate beam control. The EBM process takes place in vacuum (with a base pressure of 1×10^{-5} mbar or better) and at high temperature, resulting in stress relieved components. In fact, during the build the entire powder bed is heated at an optimal ambient temperature, specific for the material used. As a result, the parts produced with the EBM process are almost free from residual stresses and have a microstructure free from martensitic structures.

Binder based 3D printing

The Binder based 3D printing process is an indirect process in two steps. After applying a powder layer on the build platform, the powder is agglomerated thanks to a binder fed through the printer nozzle. Like in the beam based techniques, the operation is repeated by gradually lowering the platform and adding new layers of powder until parts are produced, which shall be then removed carefully from the powder bed, as they are in a 'green' stage. The metal part solidification takes place in a second step, during a debinding and sintering operation, sometimes followed by an infiltration step.

Fig. 20 Lightweight stainless screws made by binder based 3D printing (courtesy Höganäs AB - Digital Metal®)

The Binder based 3D printing technology is more productive than laser beam melting and requires no support structure. Besides it provides a good surface quality by using one of several post processing techniques:

- Peening/Blasting/Tumbling for average of R_a 3.0 μm
- Superfinishing for an average of R_a 1.0 μm down to < 1.0 μm

But the range of available materials is limited, and mechanical properties achieved can be lower than with laser and electron beam melting.

A variant not based on the same approach is the so called Fused Filament Fabrication (FFF): here, a thermoplastic feedstock containing a relatively high amount of metal powders is made into a thin wire, that is then fed into an extruder, that melts the binder and, being controlled in 3D, deposits the molten feedstock layer by layer to build the part gradually. In this case, the powder bed is missing; after printing, the part needs again to be subjected to debinding and sintering, to obtain a sintered part with a rather high shrinkage as in MIM sintering (even with higher shrinkage because the feedstock wires usually contain a lower amount of metal powders compared to common MIM feedstocks.

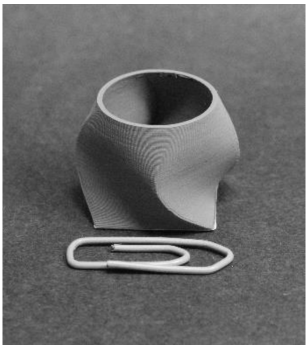

Fig. 21 316L stainless steel demonstrator part made by FFF (Courtesy Fraunhofer IFAM)

Direct Energy Deposition

With the direct energy deposition process, a nozzle mounted on a multi axis arm deposits melted material onto the specified surface, where it solidifies. This technology offers a higher productivity than selective laser melting and the ability to produce larger parts, but the freedom in design is much more limited: for instance, lattice structures and internal channels are not possible.

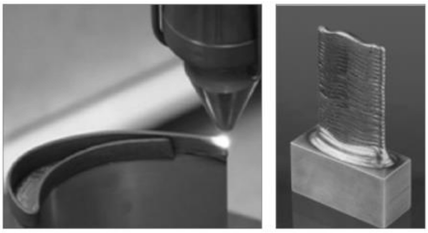

Fig. 22 Direct Energy Deposition process for blade repair or building (courtesy Fraunhofer ILT)

Benefits of Direct Energy Deposition process can be summarized as follows:

- New topological features possible
- Repair of parts that up to now were impossible
- Addition of functionalities on existing parts with either the same or a different material
- No dimensional limits (apart from the machine size)
- Excellent metallurgic quality at least as good as foundry
- Control of the material deposited (gradients, multi-materials, monolithic ...)

Further treatments and variants

Post processes are important in additive manufacturing such as removal of powder, support structures and platform, heat treatment and surface finishing, polishing, etc., and they can represent a significant part of the actual process. One of the most important post processes in Additive Manufacturing is HIPing. The density of parts produced by metal powder based additive manufactured is usually very high, but there is always the risk of defects in the material such as micro porosity or cracks, depending on the machine used as well as the type of powder. AM parts can contain a small amount of porosity for instance due to:

- Scanning calibration mismatch
- Key-hole beam-weld interaction
- Entrapped gas (can be internal to individual powder particles)
- Shrinkage as previous layers solidify
- Micro-cracks.

Eliminating the microporosity that forms during building can significantly improve fatigue life, impact toughness, creep strength and ductility. Besides, HIP provides stress relief to remove as-built residual stresses and reduces the extent of as-built segregation due to recrystallisation and homogenization of the microstructure.

Materials and typical applications

A very wide range of alloys are used on additive manufacturing machines thanks to the availability of suitable metal powders:

- Steels: stainless like 316L, 17-4PH etc., and also low alloy steels
- Nickel and cobalt base superalloys: 625, 718, CoCr F75 etc.
- Titanium alloys: Ti6Al4V, CPTi etc.
- Aluminium alloys: AlSi10Mg etc.

Many other metals are also evaluated and developing:

- Copper alloys
- Magnesium alloys
- Precious metals such as gold, silver, platinum
- Refractory metals such as Mo alloys, W and WC
- Metal Matrix Composites, etc.

Regarding the applications, additive manufacturing technology is strongly developing in many different industries such as:

- Aerospace
- Energy
- Medical, in particular in surgical implants and dental applications
- Tooling, in particular for plastics processing (and even MIM)
- Automotive and transportation
- Consumer goods

Fig. 23 shows the TRLs (Technology Readiness Levels) of AM in various industries. First four levels represent the evolvement of an idea until the lab-work, 5 to 7 until the prototype demonstration and 10 being system proven in operational environment.

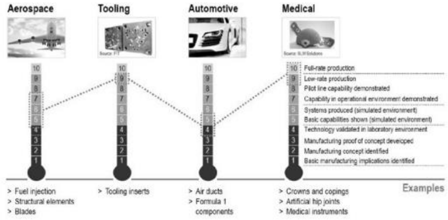

Fig. 23 Manufacturing readiness level of AM in various industry sectors (courtesy Roland Berger)

EXAMPLES OF PM PARTS FOR AEROSPACE APPLICATIONS

As already anticipated, aerospace is an industrial sector where powder metallurgy continuously finds new applications [20]. On one hand the technologies have evolved into high density-capable processes (and even P&S is improving the maximum density and consequently properties, although still distant from the full density performances that are usually needed), on the other hand the materials portfolio is now so wide that the designer can safely find good candidates, and reliable suppliers, even for very demanding applications.

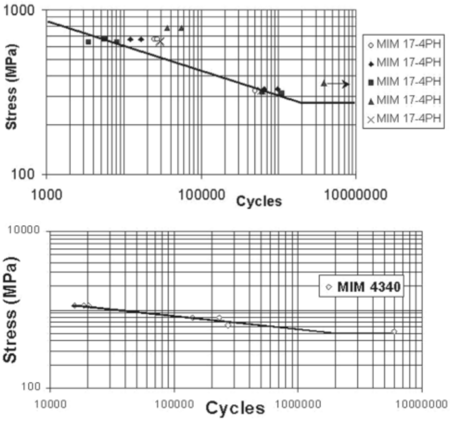

Fig. 24 Top: axial fatigue test plot for MIM-17-4 PH (R = 0); bottom: axial fatigue plot for MIM-4340 (courtesy LNEG)

High density implies lower and smaller porosities, and rounder pores: this is very helpful in reducing stress concentration around these defects and boosting the fatigue properties of the PM materials to reach, and sometimes go beyond the conventional materials. In fact, the use of fine powders, the isotropy of the composition, and the fine tuning of the microstructures achievable by microalloying sometimes allows the PM parts to outperform the wrought and machined counterpart. This is unfortunately still not the case of P&S materials, unless they are treated to full density (powder forging, HIPping), because of the limits in composition and the irregular pores normally left by the "incomplete" sintering experienced, but it is the case of many MIM (Fig. 24) and AM (Fig. 25) parts, especially after post-HIPping treatments.

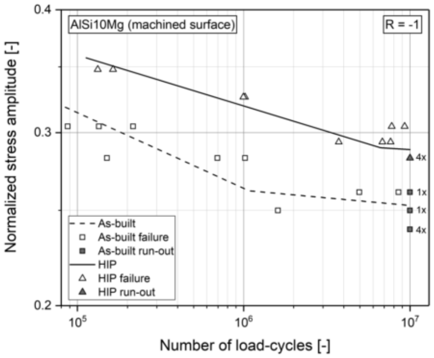

Fig. 25 The effect of HIP post processing on fatigue resistance of parts made by SLM (Laser Beam-AM) in AlSi10Mg [20]

PM, and especially AM but not only, is also increasingly used to produce special materials that can have application in aerospace. These are commonly referred to as "Functional Materials" as they are normally not use merely for their mechanical properties, but for their physical properties, like electrical, magnetic, thermal, etc. An outstanding example also in terms of market size is the already mentioned sector of the hard magnets; high temperature alloys are also to be included in this functional materials category, and biomaterials of different kinds. A very interesting family of functional materials is being developed for hydrogen storage in the solid state, using the characteristics of some metal hydrides [22]. With hydrogen becoming more and more a viable solution for mobility, including flying vehicles, PM materials might play a role in the future, even if the weight issue when considering aircraft applications is much more severe that for sea, rail or road transportation. Also in battery production powder metallurgy can be used to prepare e.g. sintered sheets of the battery materials, so PM is likely to play a major role in the electrification process.

In the following paragraphs some specific examples of PM parts (MIM, HIP and above all AM components) applied in aerospace are shown.

MIM part: high pressure compressor vane

This MIM application by the German producer Schunk Sintermetalltechnik GmbH is the first serial fabrication of a high pressure compressor (HPC) of a turbine engine. The part, a vane, substitutes a forged part without any reductions in performance, fulfilling all requirements of aerospace industry in quality assurance, reproducibility and traceability. The most important challenge was the guarantee the shape stability of the aerofoil and the prevention of contamination of the material with carbon, oxygen and nitrogen along the process, from powder production up to the sintered part. Additionally, the part had to go through a process of several gates and engine tests before being released for use in aerospace industry.

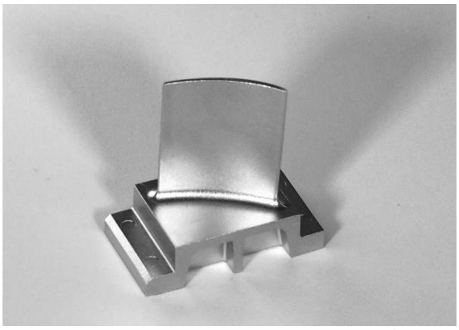

Fig. 26 The high pressure compressor (HPC) vane of a turbine engine (courtesy Schunk Sintermetalltechnik GmbH)

HIP part: Impeller for the cryogenic engine of Ariane V space rocket

Fig. 27 shows an example of HIP part. It is an impeller used in the Ariane 5 Rocket, produced by Aubert&Duval for Safran SA. The material is a Ti6Al4V alloy; the size of the part (larger diameter) is 100 mm. By using this powder metallurgy route, the customer obtained more freedom in vane design, as the shapes were impossible to machine. With a high dimensional reproducibility, the surfaces were in fact produced net shape. The material showed useful mechanical properties at the typical use temperature of only 20 K (-253.16°C).

Fig. 27 The Ti64 impeller for the cryogenic engine of Ariane V space rocket (courtesy Aubert&Duval and Safran)

HIP part: Near net shape hipped Astroloy casing for high speed turbine

Current high speed turbine casing constitutive materials are designed to work at ca. 650°C, so that superalloys like Inconel 718 or Waspaloy are typically used. All aeronautic propulsion producers are trying to find materials and manufacturing routes capable to provide casings which can operate at higher temperatures, 700 to 800°C, a range of temperature that pushes conventional materials to the limit, to improve performances and efficiency, at the same time reducing emissions. Aubert&Duval used HIP to produce this part (Fig. 28) out of Ni-based alloy Astroloy, obtaining properties that exceed those of the competing forged Waspaloy AMS5704.

Fig. 28 The Astroloy casing for high speed turbine (courtesy Aubert&Duval)

These are some of the properties of the material produced by HIP:

- Density (g/cm^3): 7.92
- Tensile Strength (MPa): > 1300 MPa
- Yield Strength (MPa): >900 MPa
- Hardness: 340 HB10; 410 HV0.5
- Elongation (%): >25 from room temperature up to 760°C

AM part: Titanium insert for satellite sandwich structures

As weight reduction in space applications has an enormous driving force due to the cost of sending material to orbit (each kilogram put into orbit costs around $20,000), AM can help by providing lighter structures that could not be easily produced otherwise. Materialise & Atos used an optimized design to develop the new inserts (Fig. 29), produced by Laser Powder Bed Fusion out of Ti6Al4V. They are weighing just one-third of the initial weight of 1454g, that is 500g, with some improved properties added in. The obvious benefits compared to carbon fiber structures are:

- Weight reduction by using topology optimization and lattice design
- Reduction of thermo-elastic stress issues during the curing process of carbon fiber reinforced polymers
- Increased lifetime

Fig. 29 The titanium inserts for satellite sandwich structures (courtesy Atos and Materialise)

AM part: Support for a satellite antenna

By making use of the topology optimization feature in the AM process, this support for a satellite antenna (Fig. 30) has been produced at Poly Shape by Laser Powder Bed Fusion with a weight reduction of 55% from the original design. The material is Ti6Al4V, the part is about 300 mm high and weighs 3.3 kg now.

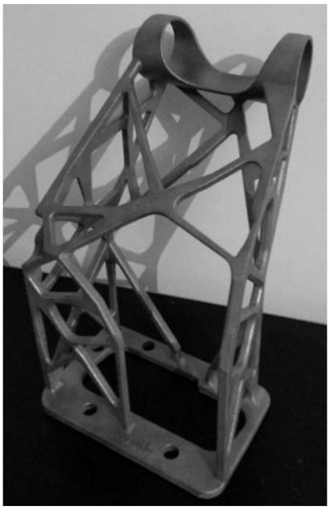

Fig. 30 The support for a satellite antenna (courtesy Poly Shape)

AM part: Bionic partition

Another example of the topology optimization feature in the AM process is this new Scalmalloy (AlMgSc) bionic partition for an A320 Airbus plane (Fig. 31). The use of topology optimization led to a huge weight saving, paving the way to new generations of aircraft cabin components that are more valuable, lighter, and thus create less impact on the environment. The material properties are:

- Density (g/cm^3): ~2.7
- Tensile Strength (MPa): 490
- Yield Strength (MPa): 450
- Hardness: 177 HV0.3
- Elongation (%): 8

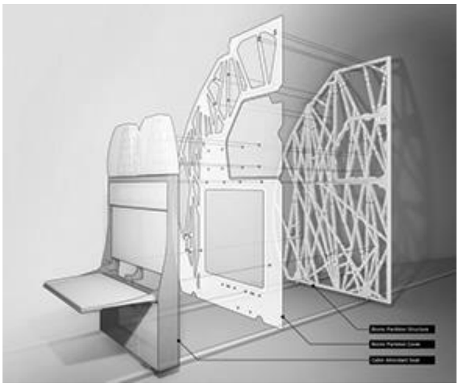

Fig. 31 The bionic partition (first object from the right) for an Airbus A320 (courtesy Airbus)

AM part: Borescope bosses for A320Neo geared Turbofan^{TM} engine

The bosses (Fig. 32) are made by selective laser melting (SLM) on an EOS machine with Inconel 718 powders. They form part of MTU’s low-pressure turbine case and allow the blading to be inspected at specified intervals for wear and damage using a borescope. The part volume is 15.600 mm³, and sizes are 42 x 72 x 36 mm.

Benefits of the AM technologies demonstrated here are the possibility of a series production of up to 2,000 parts per year, lower development production lead times and lower production costs, suitability for producing parts in materials that are difficult to machine, as, for example, nickel alloys, and for complex components that are extremely difficult, if not impossible to manufacture using conventional methods, and tool-free manufacturing and less material consumption.

Fig. 32 The boss for a borescope for the A320Neo geared Turbofan^{TM} engine (courtesy MTU Aero Engines)

AM part: Bracket

The AM technology allowed Airbus and MBFZ Toolcraft GmbH to redesign a 30% lighter bracket for a cabin door (Fig. 33). Produced out of Ti6Al4V with Laser Powder Bed Fusion, the part has dimensions of 225 x 225 x 120 mm.

Fig. 33 The bracket for cabin door (courtesy Airbus and MBFZ Toolcraft GmbH)

AM Rocket parts

In recent years, space agencies have been investigating with increasing interest te use of AM for the fabrication of critical parts for space vehicles. For example, there have been wide reports of the activities to develop special nozzles for rocket engines. Stimulated from work done by GE Aviation for their GE9X engine [160], AM gave the chance to NASA to develop a new series of rocket engine components [24], including a bimetal (Cu/Inconel) rocket igniter [25], using a wide range of AM techniques, most of which based on powder metallurgy. ESA is working on similar programmes, for instance for the Ariane launcher.

In Germany, an interesting example is the demonstrator rocket engine developed by Fraunhofer IWS and TU Dresden, all made by Laser Powder Bed Fusion or L-PBF [26]. The engine is thought for microlaunchers that carry smaller payloads (about 350 kg) and uses incoming fuel to cool the nozzle structure by conformal cooling channels that are built by the AM technique. The design allows for a reduction of fuel consumption of about 30%.

Fig. 34 Aerospike nozzle for microlaunchers (courtesy Fraunhofer IWS and TU Dresden)

CONCLUSION

Powder Metallurgy is a set of technologies, continuously evolving but with a wide and established core, allowing the fabrication of solid, reliable and performant metal parts that can be used in several sectors, including aerospace.

Although decades ago the only widespread technology was Press&Sinter, with some limitations in terms of available compositions and properties, mainly because of the reduced ability to achieve low residual porosity, nowadays PM offers a variety of fabrication routes that deliver high quality, high density, high complexity parts, with specific compositions that can also be tuned to customer needs because of the ease of alloying given by the powdered raw materials.

In aerospace, the examples shown indicate a large amount of applications have already been demonstrated, and that great potential for further development can be envisaged especially in the emerging net and near net shape technologies, like AM and

MIM. Topology optimization in AM can drive further weight reduction, and improve sustainability in aerospace, at no expense of performance. This justifies the increasing interest of aircraft producers and space agencies in this field.

Acknowledgments
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