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WHAT WILL BE THE FUTURE OF POWDER METALLURGY?

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Abstract
Traditionally, powder metallurgy has been based on two major industrial sectors – ferrous precision parts and hardmetals. Both of them relied heavily on the automotive industry, with focus on internal combustion engines. Today, there is an increasing trend towards alternative drivetrain systems, and powder metallurgy faces the challenge to find new applications to replace those lost with the decrease of classical internal combustion drives. In this presentation it is shown that the main strength of powder metallurgy lies in its enormous flexibility regarding materials, geometries, processing and properties. This enables PM to adapt itself to changing requirements in a changing industrial environment. Examples given are PM parts in alternative drivetrain systems, new alloying concepts and processing routes offering distinct advantages. With hardmetals, innovative microstructures as well as sophisticated coatings offer increased lifetime, applications ranging from metalworking to rockdrilling and concrete cutting. A particularly wide area is found in functional materials which range from components for high power switches to such for fuel cells. Soft and hard magnets are accessible by PM with particularly good properties, PM having in part exclusivity in that respect, such as for NdFeB superhard magnets as well as soft magnetic composites (SMCs). Metal injection moulding (MIM) is gaining further ground, e.g. in the medical area which is a fast-growing field, due to demographic effects. Finally, most additive manufacturing techniques are powder based, and here, the knowledge in powder handling and processing available in the PM community is essential for obtaining stable processes and reliable products. Conclusively it can be stated that PM is on the way to fully exploit its potential far beyond its traditional areas of applications.
Keywords: Powder metallurgy, trends, precision parts, hardmetals, functional materials, additive manufacturing.

INTRODUCTION

Powder metallurgy is usually linked to two major product and application ranges – ferrous precision parts, mostly for automotive purposes [1-3], and hardmetals for tools [4, 5]. These product groups in fact make up for the major tonnage produced – PM parts – and the major turnover – hardmetals. Both product groups have started in the 1920s to 1930s and encountered tremendous growth after WW II, in particular with the expansion of automobile production, since the car industry is not only the major customer for precision parts, it also uses large quantities of hardmetal tools.

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With the increased skepticism towards the internal combustion engine – in part as a consequence of the "diesel crisis", resulting in diesel engines cars being banned from city centres - these traditional markets for PM parts are at least not as stable and predictable as they used to be. Electric or hybrid cars are subsidized by numerous governments and through they are still a small minority in the streets – except maybe from Norway - , it cannot be taken for granted that the internal combustion engine will be the main drivetrain at the end o the next decade. Therefore, the powder metallurgy industry has to be prepared for a fundamental change of its product range and its customer basis. The first to feel the change will be the ferrous parts manufacturers, but also other branches of PM will be affected by the change in car drivetrains.

On the other hand it must be remembered that one of the main features of powder metallurgy is its enormous flexibility regarding processes, materials, shapes and products [6]. In that respect, PM is like nature in which also many mutations occur, thus offering chances for survival also in a changing environment. Although the numbers for tonnages and turnover are dominated by the main product groups, there are numerous other PM products that are less spectacular quantitatively but are unbeatable qualitatively, PM being either the only or at least the most effective technique to manufacture them. In Fig.1 the variety of processes available in PM is graphically depicted.

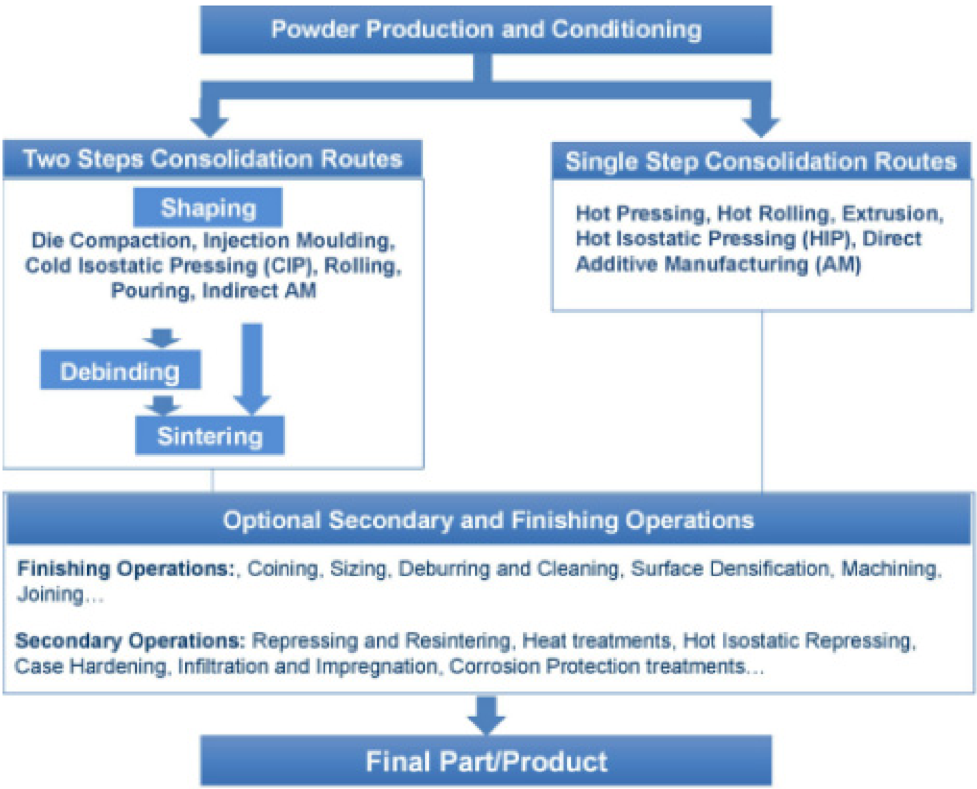
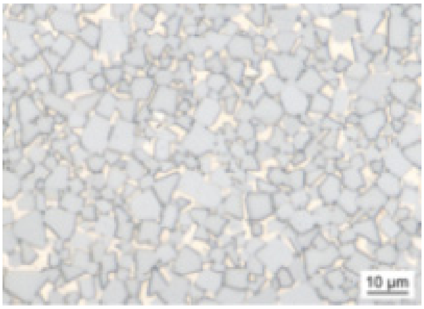


Fig.1. Powder metallurgy processing routes [6]

Furthermore, it must also be considered that many PM products offer high added value. This can already be seen when comparing ferrous parts with hardmetals; for the former a price of 15.- EUR/kg can be estimated as an average while for the latter rather 200.- EUR/kg are calculated. Of course this includes the cost of the more expensive starting materials, but nevertheless.

When assessing PM products there are in principle 2 groups: those for which shape and precision are essential and those for which the material and its properties are the basis for existence. For the former, a camshaft belt pulley in an automotive engine is a good example, for the latter it is WC-Co hardmetal with its specific microstructure that is inaccessible e.g. by ingot metallurgy. Both examples are given in Fig.2.


a) Camshaft belt pulley (MIBA)



b) Microstructure of hardmetal

Fig.2. Examples of the major product groups of PM

In practice, both are frequently combined, as e.g. in hardmetal cutting inserts which exhibit not only the special microstructure of hardmetals but feature also intricate shapes and excellent geometrical precision. Other examples are self-lubricating bearings and filters.

In the present article, several product groups of PM – by far not all of them - are discussed, from traditional parts to additive manufactured components, and their perspectives are estimated as far as this is possible today.

FERROUS PRECISION PARTS

Today, sintered precision parts are used to a large extent in classical internal combustion engines and transmissions. However, also alternative drivetrain systems such as add-on hybrids need a sort of transmissions, components for which are accessible through powder metallurgy [7, 8]. In particular for electrically driven vehicles, the noise-damping capacity of PM gears might be a definite asset since without the noise caused by the internal combustion engine, other sources of unwelcome noise become prominent [9]. Also the trend to downsizing of combustion engines is favourable for PM, applications such as clearance-free gears and camphasers for the camshaft drive being already in service here (Fig.3).

A very important feature is the increasing load-bearing capacity of ferrous PM parts. This is in part due to material development, new alloying systems being used [10]. Here, in particular cost-effective and non-toxic alloy element, such as Cr, Mn and Si are attractive. PM steels such alloyed are more difficult to sinter, as a consequence of the high oxygen affinity of the alloy elements [11, 12], but today the sintering furnace as well as the atmospheres can afford the required cleanliness of the sintering environment regarding oxidizing compounds, and at sufficiently high sintering temperatures which are desirable anyhow regarding the mechanical properties – also fairly stable oxides are reduced.

a) Clearance-free PM gear b) Camphaser stator c) Camphaser rotor

Fig.3 PM components for modern internal combustion engines (MIBA Sinter Austria)

In particular Cr is introduced mainly through the prealloying route since this element does not too much affect the compressibility of the powder. With Mn and Si this is more of a problem. An elegant method to introduce these elements is the masteralloy route, i.e. using a base iron powder – with excellent compressibility – and adding the alloy elements though a fine high-alloy powder that contains the desired elements in combination with Fe. By this way the compositional flexibility is superior to the prealloyed grades while the oxygen affinity is lowered by the lower chemical activity of the alloy elements. Using e.g. Fe-Mn-Si masteralloys, sintered steels with excellent properties can be attained [13].

A further, already established, way to improve the load bearing capacity in particular of PM gears is surface densification by rolling, e.g. [14]. By this method, the mechanically loaded tooth flanks and roots obtain the load-bearing capacity of a fully dense steel while the remaining part is porous, thus being 10-15% lighter than a fully dense steel part and also offering better NVH (noise-vibration-harshness) behaviour. Surface rolling is usually combined with thermochemical treatment, low pressure carburizing being particularly suitable here since the carburizing depth is hardly affected by porosity, and thus the fully dense functional surfaces can be properly carburized without overcarburizing the porous faces, which would hardly be possible by standard gas carburizing [15,16].

HARDMETALS

With hardmetals, the classical WC-Co type is still absolutely dominating, despite objections about the availability of W and the frequently temperamental behaviour of the Co price. However, since Co has been classified cancerogenic by the EU, at least increased cost must be expected by the hardmetal industry. Alternative binders have been studied for a long time, but replacing Co by the equally critical Ni is not the optimal solution, and Fe based binders suffer from a very narrow two-phase region, which makes proper carbon control extremely tricky [17]. Furthermore, also the phase stability of the Fe-based binder is an aspect to be considered, phase transformations during service being usually undesirable. Therefore, WC-Co will remain the standard hardmetal base at least for the next years to come.

Hardmetals based on other hard phases than WC, usually TiCN, the so-called cermets, have been used for decades, but have found widespread application only in Japan, in Europe and North America the market share is below 20%. The main incentive, a possible scarcity of W, is not a problem today, also as a consequence of systematic recycling of spent cutting tools and of the more focused use of hardmetals, this expensive material being used only where it is really needed, e.g. just on the tips of rock drills (Fig.4).

Hardmetals are less dependent on the automotive industry, esp the internal combustion engine, than are ferrous PM parts. Although the carmakers are important customers, e.g. machining of jet engines consumes a lot of HM inserts, as do rock drilling and concrete cutting (Fig.4).

Fig.4 Hardmetal-tipped rock drill (HILTI AG)

From the material viewpoint, ultrafine hardmetal grades tend to further grow in market share [18]. In particular for metal cutting, coatings applied by PVD or CVD consistently increase cutting performance and lifetime [19], thus enabling economical machining of tricky materials such as heat treated steels, Ti base materials or Ni base superalloys.

REFRACTORY METALS

This group of metals has been at the beginning of modern PM, the main product at that time being W lamp filaments [20]. In these early days, attaining the melting temperature of these metals was not possible technically, PM being the only feasible route. Currently, melting also of W is possible, However, also today, PM is the main production route for W, Mo and Ta [21], the microstructures obtained by PM being more favourable than those of ingot metallurgy specimens. This holds still more for refractory-based pseudoalloys, i.e. two-phase materials such as W heavy alloys or W-Cu contact materials, and these very special but essential groups of materials will be used also in the future. Fig.5a shows a heavy alloy collimator for radiotherapy, while Fig.5b depicts contacts for high voltage/high current switched tipped with W-Cu pseudoalloys which are inaccessible by other means than PM. For medium voltage vacuum switches, Cu-Cr contacts are used which can also be produced by ingot metallurgy routes; here, however, the shaping capability of PM is a distinct advantage for manufacturing the very complex contact ends of these switches.

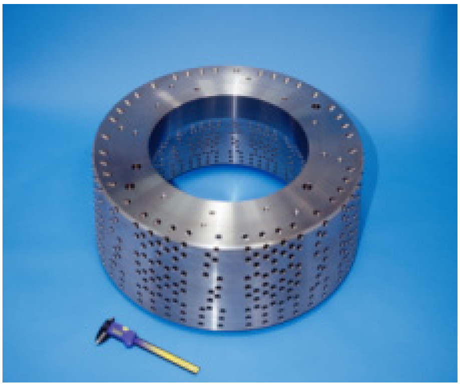


Fig.5a Heavy alloy collimator for radiotherapy (mass approx. 2 tons)(Plansee SE).

Fig.5b W-Cu-tipped contacts for high voltage/high current switches (Plansee SE).

Another application for PM refractory metals and superalloys are components for solid oxide fuel cells [22], the metal-based SOFCs being more robust mechanically than e.g. anode or electrolyte-supported variants. Here, Cr interconnects have been manufactured by the press-and-sinter route, as have been supports with defined, open and interconnected porosity for introducing fuel and oxygen as well as removing the reaction products. In this case, the capability of PM to manufacture metallic bodies with well defined and regular porosity is a distinct advantage.

METAL INJECTION MOULDING, MIM

The MIM is a success story of powder metallurgy, exhibiting sales growth rates of about 10% annually in the last decades; not even the crisis of 2008 had much impact here. The combination of the geometrical flexibility of polymer injection moulding with the material flexibility offered by PM has shown to be highly attractive for numerous applications, such as machinery, medical, automotive, [23, 24]. In Figure 6 some examples are given.

In the MIM, the major fraction of the products still consist of stainless steel, but also low alloy steels, hardmetals and Ti base materials are used, the difficulties associated with the tendency of Ti to absorb O, N, C and H into the lattice, with resulting embrittlement, having been overcome. Also MIM of Mg is being studied, as a consequence of the difficulties to obtain intricate-shaped Mg parts by machining. MIM of Al is still in the experimental state, but encouraging results have been reported, the main problem being complete removal of carbon rather than the oxide layers on the Al powder particles [25].

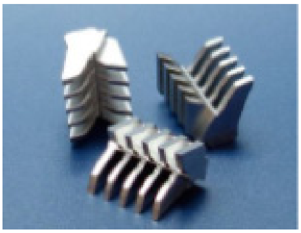


Fig.6a MIM parts for machinery (itb)

Fig.6b MIM parts for automotive (GKN)

Fig.6c MIM parts for bicycles (OBE)

Fig.6 Examples of MIM Parts (Courtesy Fraunhofer IFAM).

PM MAGNETIC MATERIALS

Today, by far the major proportion of the total tonnage of soft magnetic materials (18.5 Mto) consists of electrical steel sheet, either isotropic (81%) or oriented (14.5%)[26]. Only 4.5% make up for the rest, such as FeNi, FeCo, ferrites, ... Once more, however, PM is an attractive route for special products. This may include shaped soft magnetic parts obtained by the press-and-sinter route [27]; here, Fe, Fe-P, Fe-Si and Fe-Si-P are common materials. The role of porosity on the magnetic properties is fairly well known today, for soft magnetic parts the coercive force being particularly critical.

One advantage of PM is that the poor deformability of Fe-Si with >4%Si does not play a role with sintered materials if starting from powder mixes. The homogenization of Si in the matrix during sintering is strongly enhanced by the ferrite-stabilizing effect of Si, i.e. the homogenization is a self-accelerating process. Another material for which the shaping capability of PM is a definite asset is Fe-Co, the magnetic material with the highest saturation magnetisation but with very poor mechanical properties and machinability ("Crackalloy"). Using the net shape production by PM is a clear benefit here.

A clearly unique group of materials are the so-called soft magnetic composites (SMCs), which are attractive for AC applications at high frequencies. Alternating magnetic fields, as induced by AC, cause eddy currents in electrically conductive materials that result in energy losses by heating. Traditionally this is remedied by using laminated steel sheets – each sheet being electrically insulated from its neighbours - , as common e.g. in transformer cores, but their efficiency markedly decreases at higher frequencies. SMCs, in contrast, consist of powder particles which are electrically insulated by a surface layer. The powders are coated by organic or inorganic layers, then pressed and cured or annealed, but not sintered. In order to keep the resistivity as high as possible – to keep eddy current losses low - ´damage to the insulating layers during pressing or curing/annealing has to be minimum, and for low coercive force, annealing has to be done to eliminate work hardening due to pressing but without damage to the insulating layers, which compromise is not easy to be found.

The SMCs compete with laminated steel sheet [26, 28]: at lower frequencies the laminates are superior with regard to magnetic properties, mainly because of the better saturation as a consequence of being fully dense; at higher frequencies, in contrast, SMCs offer benefits because of their higher resistivity. However, also the shaping capability of the PM route has to be considered; complex-shaped parts are more easily produced as SMC. Also 3-dimensional magnetic flux can be easily realized using SMCs. Although SMCs have been known and investigated for about 20 years, today, with the increasing trend to electrical drives, it has become also industrially attractive, and all major PM manufacturers are working on this topic.

On the other end of the ferromagnetic product range are the superhard (rare earth) magnets, based mainly on NdFeB. Here, PM is the exclusive production method [29], although the very high oxygen affinity of Nd makes the handling of powder tricky to avoid undesirable oxygen pickup. Both monolithic (= sintered) and polymer-bonded NdFeB magnets have been on the markets for a number of years, consolidation in the magnetic field being standard; recently, also production e.g. by MIM has been done, and additive manufacturing has been tried [30]. The problem of raw materials supply, exaggerated by the fact that China is the principal – and almost exclusive – supplier of RE elements such as Nd and Dy, is being tackled by developing recycling techniques that enable reclaiming at least a significant fraction of the RE magnets used in Europe and America. Also for new, RE-free hard magnetic materials such as FePt, CoPt and MnAl, PM manufacturing offers interesting perspectives.

ADDITIVE MANUFACTURING

Today, AM, also known as 3-D-printing, is the most rapidly expanding manufacturing technology, and a very large proportion of it is powder based. The Figure 7 shows the different variants of AM; and it is evident how many routes are available there. For many of them, metal powders are the starting materials, and powder knowhow is therefore essential for successful production. AM enables manufacturing of structures that are inaccessible by other techniques, at least without complicated joining processes [31].

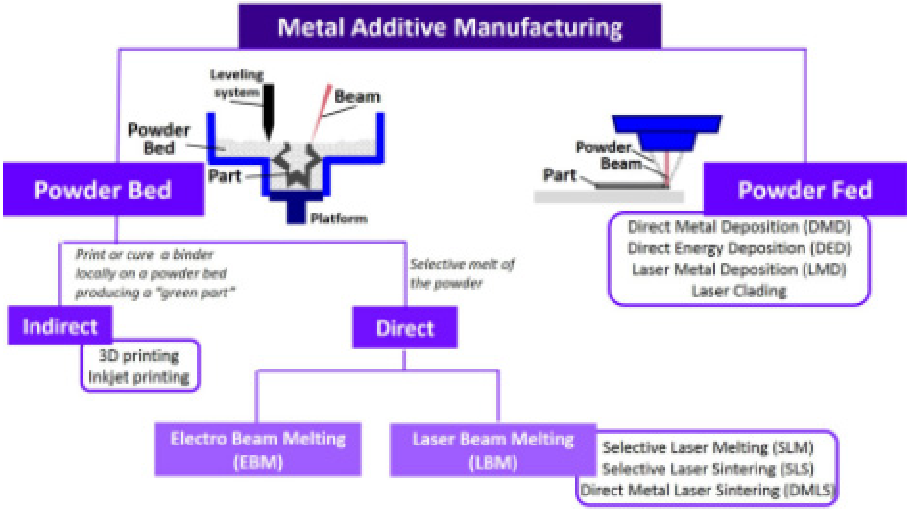
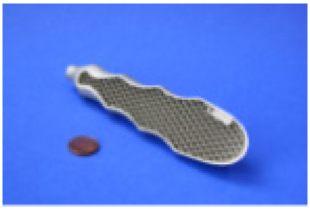
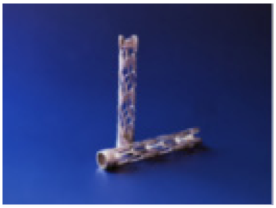


Fig.7. Variants of Additive Manufacturing routes for metallic products [6].

Today it is mostly the direct processes that are in the focus of public attention, in particular Direct Laser Melting (DLM) and Electron Beam Melting (EBM), since the aerospace components thus produced are in part already in service which is widely publicized. In Fig. 8 some components manufactured by DLM are shown.


a) Handle for medical tool


b) Stent


c) Hollow airfoil

Fig.8. Components manufactured by Direct Laser Melting (Fraunhofer IFAM Bremen).

However, also the indirect techniques which use organic binders to consolidate the powder assembly, such as inkjet printing, photolithography or screen printing, offer benefits. Although they need further steps such as debinding and sintering, the isothermal processing lowers the risk of distortion – which is very critical with the direct processes - , and much experience gained from MIM can be used. Also the option of implementing a desired surface finish before sintering should be acknowledged. Finally, the AM equipment for the indirect processes is in part significantly cheaper than DLM or EBM machines.

In any case it can be predicted that the Additive Manufacturing techniques will gain further ground in the future, and PM knowhow will be essential here. Applications will be widespread, from automotive [32] to aerospace [33] and many others There are several open questions, e.g. the effect of recycling powders or feedstock [34], the fatigue properties and how the required surface quality can be attained in an economical way. However, regarding the huge number of research groups and the money invested it can be expected that these problems will be solved in the near future, e.g. by combining AM with other techniques such as HIP [35].

CONCLUSIONS

In general the following predictions can be made:

- Combining special material and net shape technologies will become still more important, to ensure production with minimum material and energy consumption
- In the years to come, classical PM precision parts will be further used in automotive drivetrains, new opportunities being found both in downsized combustion engines and in alternative drive systems such as hybrids.
- PM functional materials will gain more and more importance, esp. for electrical and magnetic applications
- This holds in particular for Soft Magnetic Composites; in this field the primary mover for further development originates from the sector electromobility.
- Powder based additive manufacturing processes will make further progress and will find increasingly use in practice; this holds for both the direct and the indirect manufacturing routes.
- In addition to the classical direct processes such as Direct Laser Melting and Electron Beam Melting, also indirect, i.e. metal powder + binder-based routes will find increasing use, in part because of the more cost efficient equipment.
- As with other manufacturing techniques, also for PM tools for simulation and modelling will find increasing use, also because of more reliable and comprehensive input data being available.

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