

ADVANCES IN APPLICATIONS OF GAS ATOMISED METAL POWDERS IN NEAR NET SHAPE MANUFACTURING

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Abstract

In the face of ever-increasing materials costs, net shape manufacturing routes for large volume manufacture of small parts by Metal Injection Moulding (MIM) and small volume manufacture of larger parts by e.g. Rapid Manufacturing and HIP'ping are gaining popularity. Gas atomised powders offer unique advantages for manufacturers using these technologies in terms of cleanness, flow properties and high packing density. These chemical and physical properties translate into higher mechanical properties, improved tolerances and more consistent and cost effective processes. We present here examples of applications in each of these near net shape manufacturing technologies which illustrate these principles and demonstrate how these methods are maturing technically and commercially.

Introduction to Gas Atomised Powders

Powder Metallurgy (PM) is a well established production technology consuming more than USD6bn of metal powders each year. It is dominated by the manufacture of 'press & sintered' near net-shape ferrous components for automotive applications, including transmission gears, powder forged con-rods and self-lubricating bearings. The powders used in these applications are irregular in shape made by e.g. water or air atomising and confer good green strength after compaction. After sintering, refined, homogeneous microstructures are obtained with good mechanical properties at relatively low manufacturing costs. Gas atomised (GA) powders on the other hand are used in more specialised processes for the manufacture of high performance products where the same benefits of high materials utilisation and homogeneity are obtained, but in addition improved shape capability and higher finished part densities are achieved (~96-100% as opposed to 90-93% in press & sintered products). The impressive performance achievable using GA powders is illustrated with reference to three consolidation processes: (a), Hot Isostatic Pressing (HIPing) to produce fully dense parts in special steels, (b), Metal Injection Molding (MIM) of fine powders to produce small, complex parts and (c), Rapid Manufacturing using laser and electron beam melting to produce net shape products.

The GA powders used in these processes are clean (low oxygen), spheroidal in shape and have good flow characteristics but have very different particle size distributions designed for their respective processes. These characteristics may be contrasted with water atomised (WA) powders which have irregular shapes, poor flow and higher levels of oxygen and other impurities. Figure 1 shows SEM images of (a) 17-4PH GA MIM and (b) an equivalent WA 17-4PH powder.

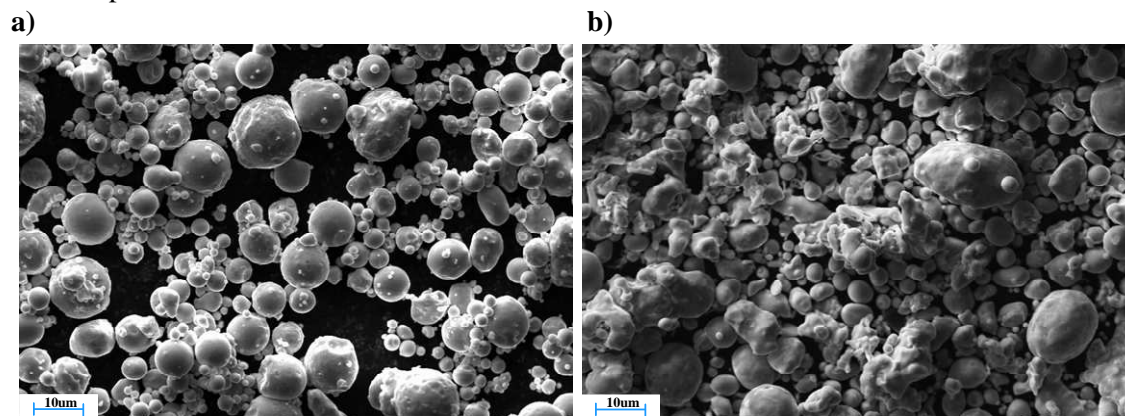


Fig 1: SEM images of 17-4PH (a) gas and (b) water atomised powder

GA powders are produced by disrupting a stream of molten metal with high pressure inert gas under controlled conditions. Sandvik Osprey has refined its atomising technology over its 35 year history and offers a comprehensive range of alloys and particle size distributions. The company has five gas atomising units, each fitted with interchangeable melting furnaces and equipped with an inert gas protective enclosure. Three of these units are specifically designed to make fine powders (median size < 15µm), which are ideally suited for MIM and higher-resolution laser Rapid Manufacturing technologies. The two remaining atomising plants are used to make coarser powders (median size ~ 40-90µm) which are suitable for HIP'ping, Rapid Manufacturing using electron beam technology and thermal spray/PTA applications. Figure 2 shows a schematic illustrating the relative positions of each consolidation route in terms of typical 'component size vs component numbers'.

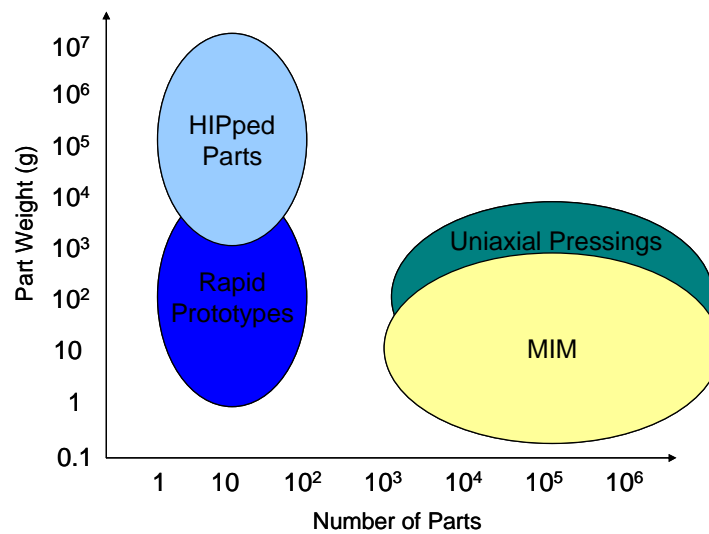


Fig 2: Schematic showing specialisation of consolidation routes vs part size and quantity

HIP'ping of Gas Atomised Powders

While HIP'ping is used routinely to enhance properties of castings by removing porosity, it is being used increasingly to manufacture near net shape parts by consolidation of gas atomised powders. It is well recognised that HIP'ping allows designers to make fully dense parts with refined, segregation-free microstructures. The extended solubility made possible by the rapid solidification of the alloy that takes place during powder production can also offer additional performance benefits. From a manufacturing standpoint, improving capabilities to model shape changes during consolidation mean that net shape HIP'ping is being employed on larger and more complex components. In many cases this means a dramatic reduction in manufacturing costs through higher materials utilisation and many fewer thermo-mechanical processing and machining steps. Examples from Sandvik PowderMet include sub-sea hubs/manifolds for the oil & gas industry and steam chests found in power generation plants (Fig. 3).



Fig 3: Sandvik PowderMet steam chest for power generation & sub-sea hub for oil & gas industry

Once installed, it is important that such components achieve maximum life in order to minimise operational costs and HIP'ping helps ensure plant integrity. The service environments for these parts typically feature high pressure, highly corrosive and abrasive fluids and therefore high mechanical strength and corrosion resistance are essential. Sandvik offers a range of advanced stainless steel grades including duplex, super duplex, austenitic and Ni-based alloys for diverse environments.

For successful HIP'ping, it is important that powders are clean and have good flow and high packing density to enable effective filling of the capsule and to minimise shrinkage and distortion that occurs during consolidation. This generally dictates that a broad, coarse size distribution is favoured, with low surface area to adsorb minimum impurities and therefore ease high temperature degassing. A recent study by the Indian Defence Metallurgical Research Laboratory [1] compared the performance of HIP'ped 304L stainless steel parts with the wrought alloy with a view to using the technology in the aerospace industry. They used Osprey GA 304L powder (Bal Fe, 0.045% wt. C, 0.045% wt Si, 0.95% wt Mn, 0.006% wt P, 0.007% wt S, 18.2% wt Cr, 9.0% wt Ni, and 400ppm O) with a particle size -180um and D₅₀ of 88um. Following degassing, capsules were consolidated by HIP'ping at 1200°C and 120MPa for 3hours. Room temperature tensile properties, reproduced in Table 1, show the superiority of the HIP'ped steel compared with minimum values specified for the wrought material. The improvement in strength was attributed to the high degree of compositional uniformity and enhanced diffusion across the powder particles during HIP'ping, resulting in improved cohesive strength of the particle boundaries. Furthermore, the fine grained microstructure and uniform dispersion of very fine oxides was believed to contribute to increased alloy strength. However, it is critical that low levels oxygen are maintained in the GA powder otherwise prior particle boundary networks will compromise properties. The DMRL study concludes that the HIP route is suitable for manufacture of near net shaped components for aerospace applications.

TABLE 1: Room temperature tensile properties of as hipped stainless steel

Material Condition	0.2% Yield strength(MPA)	UTS (MPa)	Elongation (%)	Reduction in Area (%)
As HIP'ped Osprey 304L	280	660	85	85
Specification for wrought steel (ISO:6603-1972)	200	490	40	40

Gas Atomised Powders for Metal Injection Molding

While coarse GA powders are used to manufacture large HIP'ped parts (e.g. up to 10MT), at the other end of the size spectrum, fine GA powders (typically 10 µm median but down to 5µm) are, not surprisingly, exploited in Metal Injection Molding (MIM). This manufacturing process is suitable for the high volume manufacture (e.g.>1000parts) of relatively small (<200g), complex parts.

Global sales of MIM powder were reported to be approaching 6000Mt/year in 2008 with a 10-15% growth rate [2]. Japan was an early adopter of the technology and Asia has continued to grow at a faster rate than other parts of the globe, now accounting for an estimated 50% of the total market. The MIM market in Asia is dominated by consumer, computer and communication-related devices (so-called 3C) where fast response is critical, but impressive growth in manufacture of automotive parts is also evident.

MIM components are produced using a three stage process: (a), feedstock formulation by kneading of alloy powders with a polymer binder components (typically 6wt% binder) (b), injection molding of the feedstock into multi-cavity tools and finally (c), the most critical stage, binder removal and high temperature sintering during which linear shrinkage of 10-15% occurs. Binder removal can be completed separately or in a combined cycle depending

on the feedstock formulation. Batch or continuous sintering furnaces produce sintered components with high densities (>97%) that usually require very few finishing operations. The requirement for finishing operations, such as polishing of watch cases or coining to meet precise tolerances can be influenced by the choice of starting powder size: finer sizes giving higher density and better surface finish.

MIM components manufactured using GA powders generally exhibit superior physical properties to components made with equivalent WA powder including, e.g. higher density and correspondingly lower porosity. This is demonstrated in Fig 4 which shows micrographs of surface finish on 316L components manufactured using identical particle size fractions of 90%-22um. The superior surface finish shown by the GA MIM component is critical for consumer applications where a highly polished finish is often required.

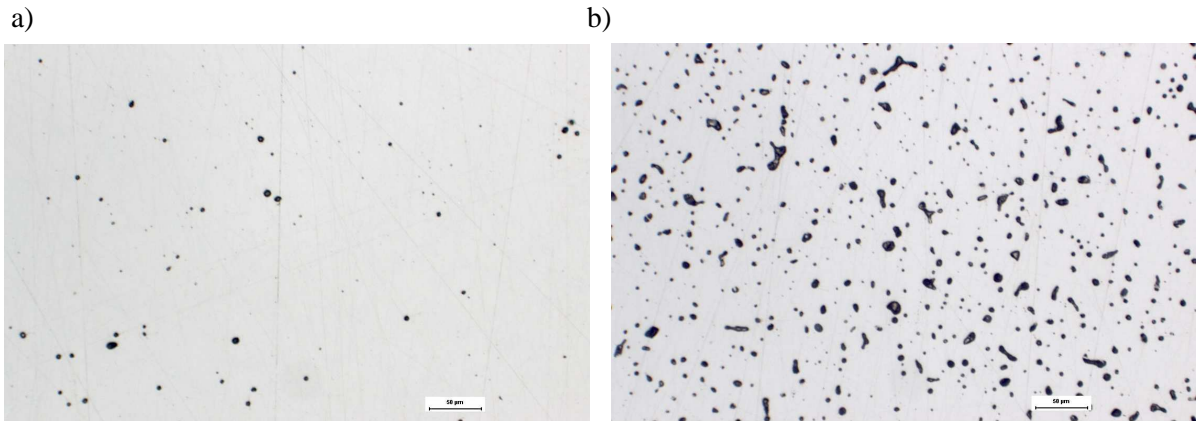


Fig 4: Example of surface improved surface finish and reduced porosity with: (a) GA powder 0.4% porosity, as compared to (b) WA powder and 4% porosity.

Conventional austenitic stainless steels remain very popular for 3C markets, but as demands on performance, such as wear resistance and strength, have increased, alternative alloy systems are being assessed. Recent research carried out separately by Krug and Zachman [3] and Hwang [4] shows that the physical properties of 316L components can be improved by sintering in a cracked ammonia atmosphere to increase the nitrogen content in the final component and by using finer particle sizes. Work has also been done on alternative alloys including the Nitronic family of alloys. These are fully austenitic, non-magnetic alloys which contain Mn as the primary austenite stabiliser (e.g. Nitronic 60 has composition; Bal Fe, 16-18% Cr, 8-9% Mn, 3.5-4.5% Si, 0.08-1.8% N, 0.1% C) and typically contain high levels of nitrogen which confer higher strength and hardness than 316L making them particularly suited to the 3C market.

GA powders have also been used extensively in the challenging automotive sector where design for dynamic loading is critical. In this case, powder cleanliness is an issue and work has been done to determine the benefits of GA MIM powders. Gülsoy et al [5] demonstrate that

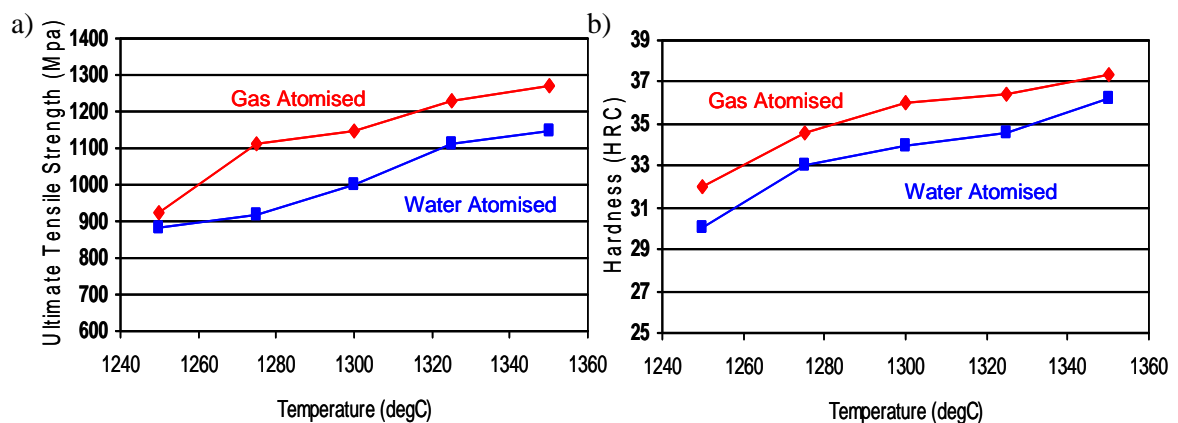


Fig 5: a) Ultimate tensile strength and b) Hardness for MIM parts produced with GA and WA powder

improved mechanical properties may be expected even when using a coarser GA powder (D50 10.65 μm) compared with finer WA powder (D50 8.75 μm). It was found that GA 17-4PH showed superior tensile strength, hardness and elongation compared with WA (Fig 5).

Perhaps the largest single volume application for MIM parts worldwide is in components for diesel auto turbochargers including roller bearings, vanes and nozzle rings. Prior to adoption of MIM, conventional casting and machining was the established fabrication route but this was very costly because of low material yield and high machining costs. While the vast majority of turbochargers are currently deployed in diesel engines operating at max 850°C, there is a desire to develop MIM'ed parts for gasoline engines which will require development of new alloys with higher temperature capability (>1050°C). Candidate alloys include IN713C, the established investment casting alloy, and other advanced Ni base alloys. The application of MIM to production of high temperature auto turbine wheel manufacture (Fig 6) has the potential to reduce component costs and improve performance though developments are still at an early stage.



Fig 6: Turbocharger turbine wheel, currently manufactured by investment casting but a target for MIM manufacturers

One example where MIM technology has largely displaced investment casting as the preferred manufacturing method is in the dental sector, in particular orthodontic applications. Traditional investment cast F75 (CoCrMo alloy) orthodontic brackets have for many years been replaced by MIM components which are produced far more cheaply by virtue of the reduced number of process steps and radically reduced scrap rate.

Gas Atomised Powders for Rapid Manufacturing

Rapid Manufacturing (RM) is a generic term embracing a number of technologies for making near net shape parts from metal powders. For example, Selected Laser Melting (SLM) and Electron Beam Melting (EBM) have in common the use of a powder bed which is acted upon by a rastered laser or electron beam respectively. The raster pattern and the build up of layers is driven by Computer Aided Design (CAD) files, CAT scan or MRI data. The parts are built up layer by layer in the powder bed with fresh powder layers deposited by rolling or wiping across the bed surface. The process is repeated and the file is translated into three dimensions with each successive layer of powder (Fig 7 (a)). Final part resolution depends on the RM process and reflects the size of powders used typically in the process. This can be ~ 20 μm for SLM up to 50 μm for EBM.

GA powders are ideally suited for use in all RM processes and have been adopted by all of the leading machine manufacturers. The critical powder characteristics include good flow, high packing density and low surface oxide levels. It is essential that when applying fresh powder layers to the powder bed, that a uniform layer of powder is deposited to ensure uniform and consistent part build.

Good flow characteristics are inherent in the spheroidal particle shape of GA powders, but flow is enhanced by removing the very fine component of the powder distribution by classification. The spheroidal nature of the powder also ensures good packing which means that parts build uniformly with high density and minimal distortion.

These new techniques are able to produce complex 3D parts quickly and in small numbers which is ideal for making functional prototypes, bespoke items and production runs of a few tens or hundreds of parts. Indeed it is possible to make complex parts with internal detail which are impossible to make by conventional metal forming methods.

The surface finish of RM parts is dependent on powder size and power input and control of surface texture is an important attribute for certain components, in particular for the medical sector. Here, the rough surface can encourage early in-growth of bone and tissue which can speed recovery after implantation of bespoke items for reconstructive surgery. Biocompatible materials such as Titanium and CoCrMo-based alloys are among those most in demand for RM processes.

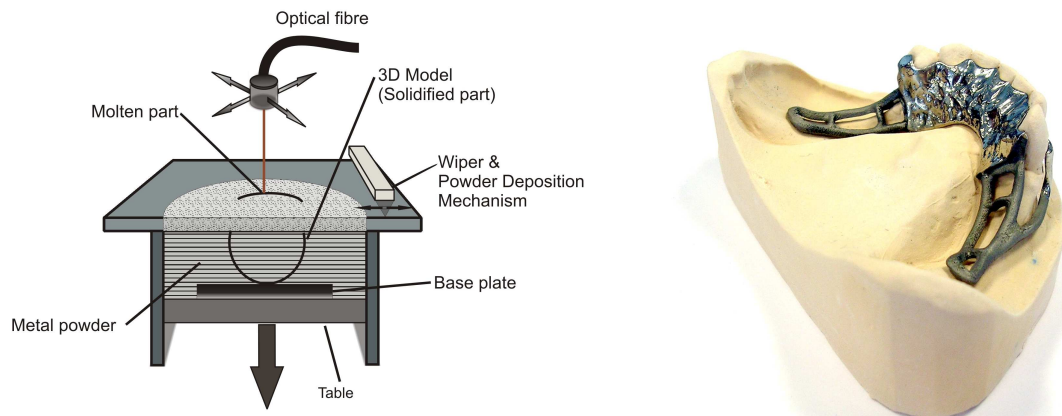


Fig 7: a) Schematic diagram of the SLM process and b) an example of a removable partial denture frame- work produced by SLM

Rapid manufacturing of medical devices using SLM has been employed successfully in various applications, including osteotomy and drilling guides. Commercialization of the SLM technology is progressing with orthodontic applications including manufacture of customized prostheses, including crown and bridge frameworks and removable partial denture frame work.

Summary and Conclusion

Gas atomised powders are essential precursors for high performance net shape manufacturing routes such as HIP'ing, Rapid Manufacturing and Metal Injection Moulding. Each fabrication route demands distinct powder size ranges for optimum performance and these can be achieved by tuning atomising conditions as appropriate. Net shape technologies such as those described are efficient in reducing manufacturing time and increasing materials utilisation. Strong growth in these areas is therefore set to continue.

References

1. G. Appa Rao, D.V.V. Satyanarayana, M. Srinivas and D.S. Sarma, "Structure property correlations in hot isostatically pressed AISI-304 stainless steel, *Powder Metallurgy*, Vol. 52 pp 244- 249 (2009)
2. BASF presentation, *PM Asia 2009 conference proceedings* (2009)
3. S. Krug, S. Zachmann, "Influence of sintering properties and furnace technology on ...", *Powder Injection Moulding International*, Vol. 3, pp 66-70 (2009)
4. K.S. Hwang, National University of Taiwan, *PMAROC proceedings* (2009)
5. H. Ö. Gülsoy, S. Özbek and T. Baykara, "Microstructural and mechanical properties of injection moulded gas and water atomised 17-4PH stainless steel powder", *Powder Metallurgy*, Vol. 50, pp 120-126 (2007)