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Powder Metallurgy Hot Isostatic Pressing: Titanium Done Differently for Defence

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ABSTRACT

Powder metallurgy hot isostatic pressing (PM HIP) is a novel manufacturing process extensively utilized in oil & gas and aerospace industries. With the evolution of this advanced manufacturing process, many other industrial sectors including defence are benefiting from the clear strategic advantages of PM HIP compared to conventional manufacturing processes. This paper is intended to give an overview of PM HIP technologies and highlight the potential of this process for the manufacture of components for land based military systems. The study will focus on a brief introduction of PM HIP technology followed by more detailed description of some key benefits of adopting PM HIP in defence sectors. These include easier processability of Ti-alloys, generation of high-performance metal matrix composites (MMCs), manufacturing of complex shape parts and generation of multi-materials structures via HIP diffusion bonding (DB). Finally, the paper will focus on future prospectives of PM HIP.

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1. INTRODUCTION

Powder metallurgy hot isostatic pressing (PM HIP) is an advanced manufacturing process which can be exploited to consolidate a wide variety of powders into fully dense complex structures with reduction of buy-to-fly ratio while maintaining excellent mechanical properties.

In PM HIP, a capsule, commonly called canister is filled with the desired powder. After filling procedure, the canister is degassed, sealed and then HIPed by applying temperatures between 0.5 - 0.7 T_m and pressures between 100 – 200MPa. After the HIP stage, the canister is removed via machining or by acid attack (pickling). A schematic of PM HIP process is reported in **Error! Reference source not found.**.

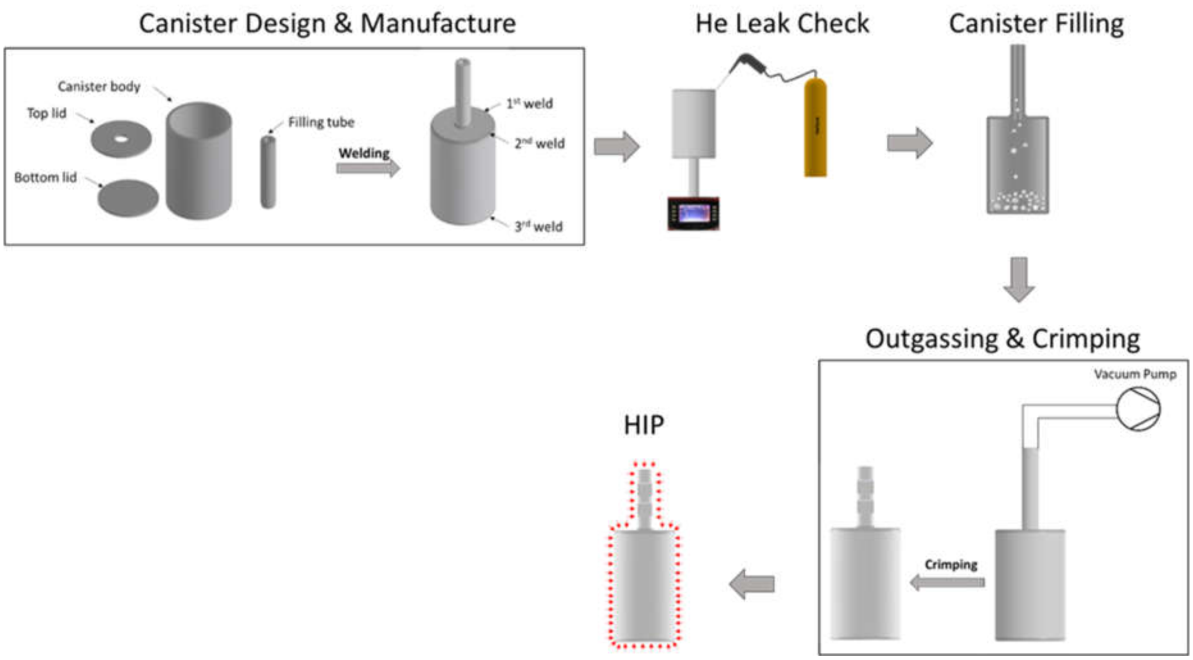

Figure 1 Schematic of PM HIP Process.

PM HIP is becoming increasingly popular due to the following advantages if compared to conventional manufacturing processes such as casting and forging:

- **Reduction of buy-to-fly ratio:** if compared to conventional manufacturing processes, PM HIP results in a drastic reduction in material waste.
- **Increasing of design flexibility:** it is possible to tailor the design of a component and at the same time the properties by generating multi-materials structures and novel materials such as metal matrix composites (MMCs).
- **Improving mechanical properties:** PM HIP generates an isotropic fine-grained structure with enhanced properties often comparable or superior to the forged counterpart.
- **Reduction of machining operations:** the manufacture of near net-shape components is a direct consequence of reduced machining operations to obtain the final product. Additionally, it was proven that machinability of PM HIP material leads to a 60% improvement of cutting tool life compared to wrought material.
- **Drastic reduction of lead time:** PM HIP technology relies on the manufacture of sacrificial canisters via sheet manufacturing which is often quick and flexible. This results in a drastic reduction of lead time compared to large forgings.

All the abovementioned characteristics are well-aligned with the defense industry demands of reliable high-performance structures, flexible design and supply chain readiness. The PM HIP advantages for defense industry are clearly mentioned in different studies. In fact, Rao et al. discusses the use of PM HIP technique for the development of components in defence and for other strategic applications [1]. Other studies also focus on the development of conventional and advanced armour using PM HIP of Ti-alloys and Ti-based metal matrix composites (MMCs) [2], [3], [4].

However, despite the potential shown in these studies, more needs to be done in the validation of PM HIP technology and its exploitation for land based military systems.

To highlight further the use of PM HIP for land based military systems, the paper will focus on some specific topics including PM HIP of Ti-alloys, MMCs, complex shape manufacturing and HIP diffusion bonding (DB) providing some insights and case studies.

2. PM HIP of Ti-Alloys

Ti-alloys are one of the most suited classes of materials for PM HIP, due to the high specific cost, reactivity and difficulties with processability as well as machining. Hence production of Ti-alloys components via PM HIP gives unquestionable advantages including the possibility of generating a material with superior mechanical properties. An example of the properties of PM HIPed Ti6Al4V processed at Proxima is reported in **Error! Reference source not found.**. PM HIPed Ti6Al4V shows superior strength if compared to wrought, without compromising on ductility. This is a consequence of a fine and isotropic microstructure if compared with the wrought counterpart (**Error! Reference source not found.**).

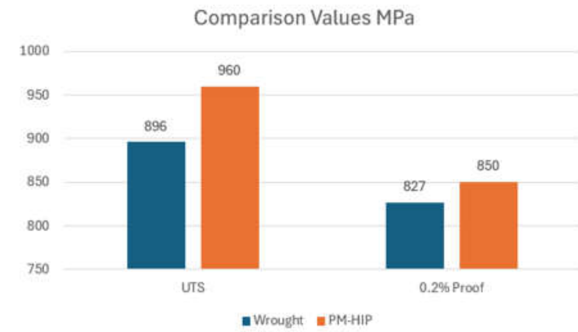

Figure 2 Room temperature tensile properties of wrought Ti6Al4V vs PM HIP Ti6Al4V. (elongation 18% versus 10%)

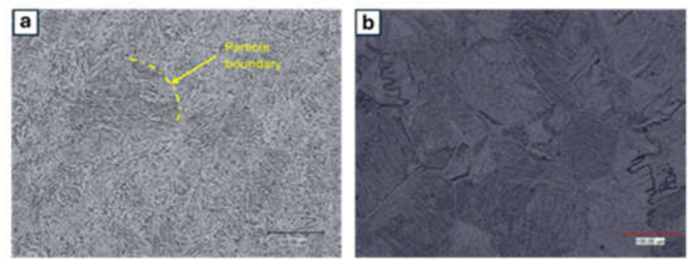

Figure 3 Optical microscopy micrographs for PM HIPed Ti6Al4V (a) and wrought Ti6Al4V (b).

Although most of the PM HIP Ti-alloys are adopted for aerospace applications, there is a clear advantage and examples of Ti-alloys being used in military applications especially for the manufacture of ballistic armour for land based systems [5], [6], [7].

One of the main advantages offered by PM HIP of Ti-alloys is the reduction machining operations. In fact, machinability of Ti6Al4V is extremely challenging and it is affected by various aspects including low elastic modulus, high reactivity and low thermal conductivity. Not only PM HIP reduces the amount of machining but also contributes towards a drastic increase in cutting tool life. In fact, it was demonstrated in a study conducted by Proxima in collaboration with Nikken an increase of tool life up to 60% for PM HIP Ti6Al4V if compared to the wrought counterpart (**Error! Reference source not found.**). This increase in tool life is linked with the more uniform microstructure of PM HIP material, and the absence of inclusions if compared to wrought Ti6Al4V.

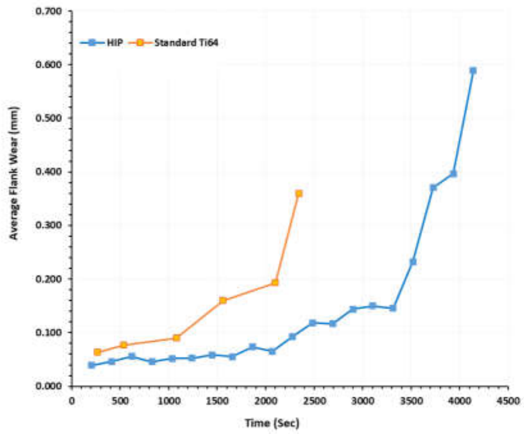

Figure 4 Comparison of pocketing average tool wear for wrought Ti6Al4V and PM HIP Ti6Al4V

3. Metal Matrix Composites

Metal matrix composites (MMCs) are a class of materials combining the properties of metals such as toughness and ductility with the ones of ceramics including high hardness and strength, higher Young Modulus and lower coefficient of thermal expansion (CTE) [8]. MMCs can be generated via PM HIP via blending a metallic matrix with ceramic particles. There are many studies available in literature related to PM HIP of MMCs. Markosky et al. exploited PM HIP technology to generate Ti-based MMCs for ballistic armours, in particular Ti6Al4V with the addition of various concentrations of TiC and TiB was HIPed and characterised. The ballistic results performed on Ti6Al4V – 40%TiB show an excellent response with no significant damage of the plate and a disintegrated bullet due to the high hardness of the plate [2].

A similar approach was used by Sergi et. al to develop Alloy 625 based MMCs. In this study SiC and TiB_2 with various concentrations were adopted. Also in this case, the MMCs resulted in a considerable increase in hardness and wear properties if compared to the base material as witnessed in **Error! Reference source not found.** [9].

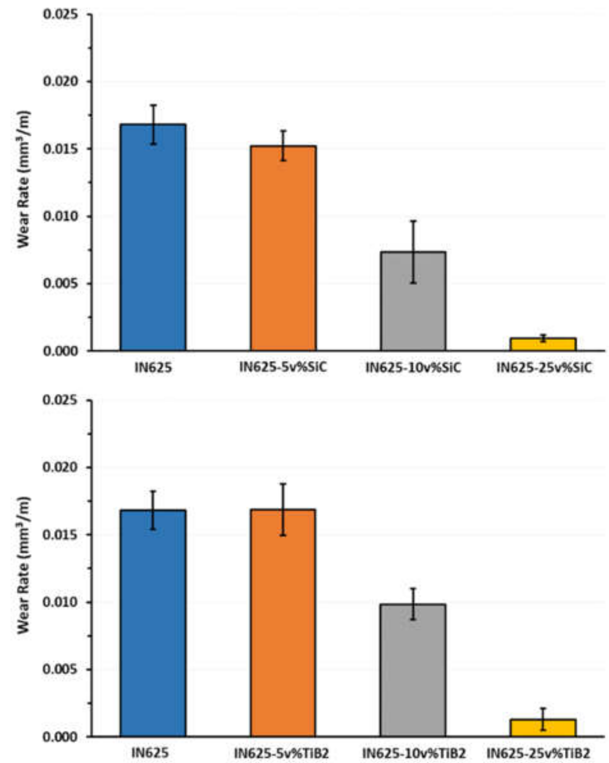

Figure 5 Effect of ceramic reinforcement on wear rate for IN625-MMCs produced via PM HIP [9].

The above examples provide an understanding of the successful use of PM HIP for the generation of MMCs with enhanced properties, and there are many other studies available on this topic [10], [11], [12], [13]. The studies demonstrate also the suitability of MMCs materials for defence applications due to enhanced wear resistance, higher temperature capabilities and lower density if compared to base materials.

4. Complex Shape Manufacturing

PM HIP technology can manufacture high integrity complex shaped parts with a drastic reduction of buy-to-fly ratio and consequent reduction in material wastage. Some excellent examples of near-net-shape manufacturing of large complex components via PM HIP is reported in the work of Mashl et al. where a large steam chest for a counterrotating, radial-flow turbine with an intricate internal geometry was manufactured. The paper also shows other large components including a steel valve body and a nuclear reactor cooling panel [14].

The rapid development of near-net-shape manufacturing via PM HIP has accelerated in recent years due to the advancements in capsule manufacturing and in shape simulation and prediction.

Different research was conducted over the years to manufacture complex shaped demonstrators via alternative advanced manufacturing processes including hydroforming, spin forming, investment casting etc. An example of investment casting canister is shown in **Error! Reference source not found.**. This represents a civil aerospace primary structure demonstrator made by Proxima PM Ltd using Ti6Al4V powder encapsulated in a cast capsule. The technology is proprietary of Proxima and is described in the following patent [15].

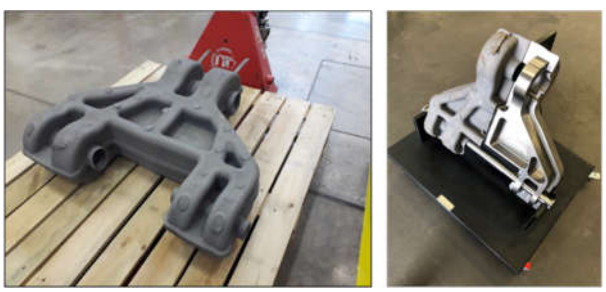

Figure 6 Example of cast canister for the manufacture of civil aerospace primary structure. Casted canister after HIP (left), half machined part (right).

Other advanced forming techniques were employed to manufacture complex shape components. A recent project by Oak Ridge National Laboratory (ORNL) and partnered with Electric Power Research Institute (EPRI) looked at using hydroforming to make near-net shape canisters for PM HIP. Industrial trials confirmed that hydroforming can produce canister halves that work for HIP. The main outcome is that tool geometry needs tweaking (gentler radii, air evacuation features), and surface finish matters to avoid imprinting defects on thin blanks [16].

Other technologies such as electroforming and additive manufacturing can also be used in conjunction with PM HIP to manufacture extremely complex near net-shape parts with drastic improvement in buy-to-fly ratios.

Together with advanced canister manufacturing, shape prediction is also making considerable advantages. This is demonstrated by a recent study performed by Brockmann et. al where a complex shaped canister shape post-HIP was predicted with high accuracy using discrete element modelling (DEM) and an iterative model [17].

5. HIP Diffusion Bonding

HIP DB is a solid-state joining technique, capable of joining multi-materials structures via the application of high temperature (0.5 – $0.7T_m$) and high pressure (100-200MPa) [18].

The advantages of HIP DB compared to conventional joining technologies such as fusion welding and brazing are:

- Generation of joints with similar microstructure of the base material. HIP DB guarantees a strong joint with the absence of heat affected zone (HAZ), which represents a detrimental characteristic of the fusion welding techniques.
- Possibility of joining dissimilar materials. A wide range of materials can be successfully joined using DB, including ceramics.

- Joining reactive metals including Zr, Ti and refractory metals with reduced chances of contamination.

HIP DB for military land-based vehicles can offer some advantages as it is possible to generate multi-layered structures with higher properties if compared to a monolithic material structure. This is particularly relevant for armours where a multi-layered approach can result in better ballistic properties with a hard surface backed by a more ductile core as demonstrated by Markovsky et al. [2]. The use of multi-layered structures can also be adopted in context where high temperature and high wear and corrosion resistance is needed. This could be for example in a gun barrel where the low alloyed steel can be coated on the inside by a hard layer such as Stellite via HIP DB resulting in a more reliable, higher performance structure [19]. Some examples of HIP DB include the joining of pure Nb with Ti6Al4V proposed by Sergi el al., resulting in a joint with no evident defects and reported in **Error! Reference source not found.** [20]

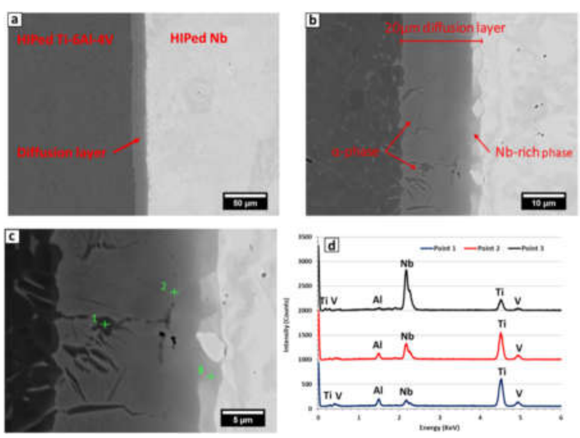

Figure 7 SEM backscattered micrographs and EDX of Nb-Ti6Al4V diffusion bonding; a) low magnification SEM micrograph, b) high magnification micrograph, c) EDX spectra [20].

All the abovementioned examples showed the possibility of generating a high-performance joint via HIP DB for different applications. The use of HIP DB could lead to an advancement in military industry due to the generation of multi-material structure with enhanced ballistic response or, the muti-materials approach can also be adopted for high corrosion and high-temperature environments such as gun barrels or leading edges.

6. Conclusion

The paper provides a generic overview of the PM HIP process focusing on the advantages of PM HIP for the manufacture of military land-based systems.

PM HIP is proven to be a suitable manufacturing process that can enhance the properties and performance of high values military components via generation of isotropic fine-grain structure, generation of multi-materials systems and novel materials such as MMCs or high entropy alloys (HEAs). Specifically in this paper it was proven the possibility of manufacturing high performance MMC armour, Ti-alloys with superior mechanical properties and enhanced machinability, near-net shape manufacturing of complex high-value components and generation of reliable high-strength joints obtained via HIP DB technique.

Additionally, the use of PM HIP can lead to much shorter lead times and a drastic reduction of machining operations making it a valid alternative to traditional manufacturing processes for defence applications.

The authors strongly believe that this technology will become increasingly widespread in the military industry due to the multiple advantages covered in this paper.

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9. ACRONYMS

HIP	Hot Isostatic Pressing
PM HIP	Powder Metallurgy Hot Isostatic Pressing
Ti6Al4V	Alpha-Beta Titanium Alloy
HIP DB	Hot Isostatic Pressing Diffusion Bonding
MMCs	Metal Matrix Composites