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A Review Paper Powder Metallurgy Process on Ti-6al-4v Combine with Metal Injection Moulding

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ABSTRACT

Metal Injection Moulding (MIM) of Ti-6Al-4V is an advanced manufacturing technique aimed at producing complex titanium alloy parts with high precision, minimal waste, and reduced costs. Ti-6Al-4V, a titanium alloy known for its excellent strength-to-weight ratio, corrosion resistance, and biocompatibility, is extensively used in aerospace, biomedical, and automotive applications. However, traditional methods for shaping titanium are costly and time-intensive. MIM offers a solution by combining the design flexibility of plastic injection moulding with the strength of metal alloys. This process involves mixing fine Ti-6Al-4V powder with a binder, injecting it into a mould, and subsequently debinding and sintering the part to achieve full density. Critical parameters, such as powder size, binder composition, sintering temperature, and atmosphere, play a crucial role in determining the mechanical properties and surface quality of the finished product. The study focuses on optimizing these parameters to minimize defects and achieve desired properties, making MIM a viable, cost-effective alternative for producing high-quality titanium alloy components. Results indicate that MIM can produce Ti-6Al-4V parts with mechanical properties comparable to those of traditionally manufactured components, supporting its potential for broader application across industries.

KEYWORDS;-

Pre-alloyed method, blended elemental method,Ti-6Al-4V,boron carbide.

INTRODUCTION

we chosen to write a journal on powder metallurgy specifically focusing on Titanium due to its unique combination of properties, including high strength-to-weight ratio, excellent corrosion resistance, biocompatibility, and thermal stability. Titanium's growing demand in aerospace, medical, energy, and automotive industries further sparked my interest. Powder metallurgy offers significant advantages in producing titanium components, such as near-net-shape production, improved microstructural control, reduced material waste, and increased design .our objective is To investigate the effects of powder characteristics, sintering conditions, and alloying elements on the microstructure and mechanical properties of titanium .To develop and optimize titanium powder metallurgy processes for specific industrial applications. To explore the potential of titanium powder metallurgy in emerging fields, such as energy storage, biomedical devices, and advanced aerospace systems.

For powder metallurgy (PM) of titanium, several methodologies are commonly employed, and each has its advantages depending on the specific requirements (such as cost, material properties, and final part geometry). The main methodologies include:

Metal Injection Moulding (MIM)

MIM combines powder metallurgy with plastic injection moulding. Titanium powder is mixed with a binder, injected into a mould, and then sintered to remove the binder and consolidate the metal. there are several advantages for (MIM) like it is Suitable for mass

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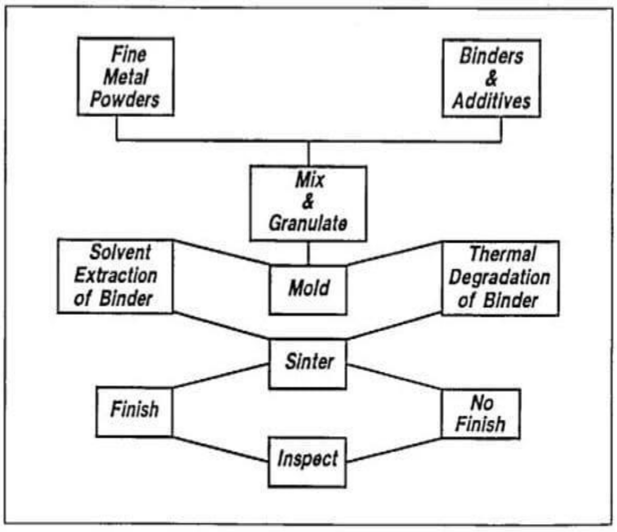
production of small, complex parts. and offers High material utilization and less waste . and Cost-effective for large volumes. MIM is the most cost-effective method when producing a large number of small, intricate parts.The Metal Injection Moulding (MIM) process is an advanced technique in powder metallurgy (PM) that combines the benefits of plastic injection moulding with the strength of metal alloys. Using finely powdered titanium, MIM produces complex shapes with high precision, allowing for near-net shaping that minimizes material waste. This process yields mechanical properties on par with or exceeding those of components made through traditional ingot metallurgy, while significantly reducing costs. MIM is especially valuable for applications requiring strong, lightweight, and corrosion-resistant materials, such as aerospace and biomedical implants, where titanium's properties can be fully utilized without the high costs of traditional methods.



Flow diagram of MIM process

13.2.1 powders and powder handling

Titanium and titanium alloy powders are available in all four grades of commercial purity and specific Ti-6Al-4V grades (grades 5 and 23). For Metal Injection Moulding (MIM), fine powders are generally preferred for better sintering and surface quality, though finer powders risk oxygen contamination. While steel powders for MIM often range from −22 µm to −6 µm, titanium powders are commonly sieved to −45 µm for optimal handling and reduced contamination**.** The primary titanium powder for MIM, sized at −45 µm, is produced by gas or plasma atomization, creating spherical particles that minimize surface area and contamination from oxygen, nitrogen, and carbon. This powder shape is advantageous as it allows high metal content in the feedstock. In gas atomization, alloy rods are melted and atomized with argon gas, while in plasma atomization, alloy wires are melted in plasma, cooled, and transported to the collection chamber. To reduce contamination, initial alloy material for atomization contains lower oxygen and nitrogen levels than required for final parts. Achieving grade 5 quality requires using grade 23 powder, with an oxygen increase of about 0.08% typically expected, though careful handling can lower it to 0.03–0.05%.For precise part replication and improved finishes, finer −25 µm powders can be sieved from −45 µm powder. However, due to their larger surface area, finer powders are more susceptible to oxygen contamination, necessitating more stringent handling measures. This has driven efforts to produce Ti-6Al-4V powder as fine as −15 µm, though protective argon atmospheres are costly and thus less common industrially. Alternative titanium powder sources include titanium hydride (TiH_2) and hydride-dehydride (HDH) powders. TiH_2 is produced by hydrogenating titanium, rendering it brittle for milling into the desired particle size, which can then be used directly or dehydrated to form HDH powder. However, these powders have angular particles that increase binder requirements and easily absorb oxygen, complicating efforts to meet low oxygen specifications. A recent study examined the influence of powder size and mould roughness on MIM, using Ti-6Al-4V powders of maximum diameters 25 µm (powder A) and 15 µm (powder B). The study used a wax-polymer binder and tested various mould cavity surface finishes (Ra values of 0.4 to 9.0 µm). Finer powder B better replicated mould cavity roughness, while coarser powder A exceeded the cavity roughness. After sintering, however, both powders showed no significant difference in surface roughness.

FIG 13.1 Moulded green parts with four areas of different surfaces

Table 13.2 Result of surface roughness measurements (Ra in µm).

			Green parts		Sintered parts	
Cavity number	Specification	Tool	Powder A	Powder B	Powder A	Powder B
1	0.4	0.90–1.00	1.81	0.91	1.20	1.18
2	0.8	1.40–1.46	1.93	1.19	1.16	1.17
3	1.6	2.37–2.49	2.64	1.86	1.81	1.89
4	9.0	7.41–11.74	9.94	9.42	8.63	8.56

13.1.2 BINDER SYSTEMS

In Metal Injection Moulding (MIM), binders are essential for shaping metal powders into desired forms before sintering. A typical MIM binder consists of three main components: a polymer backbone, a plasticizer, and surfactants. The polymer backbone provides structural strength during moulding and is later decomposed during thermal debinding. Plasticizers, the largest component by volume, reduce the backbone’s viscosity, enhancing the flowability of the mix. During the initial debinding stage, the plasticizer is removed through solvent extraction, catalytic debinding, or evaporation. Small amounts of surfactants are also included to ensure proper interaction between the metal powder and binder, and these are typically removed during solvent extraction or thermal debinding**.** The ideal MIM binder for titanium would enable thorough mixing and moulding with the powder and be entirely removed without leaving any residual carbon or oxygen contamination in the final sintered part. However, in practice, even the best binders impart small amounts of carbon and, to a lesser extent, oxygen. This carbon pickup is a consequence of incomplete binder decomposition, which can lead to carbon residuals being incorporated into the sintered material. Oxygen pickup can also occur, especially if the binder components contain oxygenated groups, although it is typically less significant than the oxygen introduced by the sintering atmosphere. The ideal MIM binder for titanium would enable thorough mixing and moulding with the powder and be entirely removed without leaving any residual carbon or oxygen contamination in the final sintered part. However, in practice, even the best binders impart small amounts of carbon and, to a lesser extent, oxygen. This carbon pickup is a consequence of incomplete binder decomposition, which can lead to carbon residuals being incorporated into the sintered material. Oxygen pickup can also occur, especially if the binder components contain oxygenated groups, although it is typically less significant than the oxygen introduced by the sintering atmosphere.

13.1.3 Debinding and Sintering

Solvent debinding for Metal Injection Moulding (MIM) involves immersing the parts in solvents at temperatures typically ranging from room temperature to 60°C. Common solvents include hexane and heptane for dissolving paraffin waxes, and warm water for extracting PEG-based binders. Contamination is not a major issue during this step, but when using waxes, explosion-safe equipment is necessary. The parts must be dried slowly to prevent cracking.

After solvent extraction, the parts undergo thermal debinding, often in an argon atmosphere with reduced pressure (200–600 mbar). This method efficiently decomposes the polymer binder and removes the decomposition products. The peak debinding temperature depends on the binder's polymer backbone, with wax-polymer binders generally debound at around 450°C for optimal results. The thermal debinding cycle is typically integrated into the sintering process, though the furnace

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must be equipped to trap binder residues outside the hot zone.

Titanium sintering is commonly carried out in high vacuum or argon atmospheres. High vacuum sintering yields better results, particularly in terms of final density and reduced oxygen contamination, since argon can be trapped in the sintered part's pores, hindering densification. Impurities in the argon may also contaminate the titanium. For enhanced results, getter materials such as titanium scrap or sponge are used to trap oxygen, especially when the furnace is not fully loaded.

Sintering typically occurs at around 1250°C with a dwell time of about 3 hours. Higher sintering temperatures can improve density and tensile strength but may reduce ductility, possibly due to grain growth or increased oxygen absorption. The ASTM F 2885-11 standard specifies mechanical properties for sintered Ti-6Al-4V at densities of 96% and 98% theoretical density (TD). Additionally, Hot Isostatic Pressing (HIP) at temperatures between 850–1100°C can optimize density and microstructure if the density is above 95% TD.

For titanium sintering, substrates made from alumina are unsuitable. Instead, zirconia or yttria substrates are preferred. A cost-effective alternative involves using alumina substrates coated with a yttria layer through plasma spraying.

PROPERTIES OF SPECIFIC ALLOYS PROCESSED BY MIM

Titanium processed through Metal Injection Moulding (MIM) merges the strength and unique properties of titanium with the design flexibility and efficiency of injection moulding, making it ideal for producing complex, high-performance parts. MIM titanium parts achieve densities close to 96-99% of their theoretical maximum, providing strong, durable components for industries like aerospace, medical, and automotive. Although the sintering process in MIM reduces porosity significantly, some micro porosity may remain, which can slightly affect overall strength and toughness compared to fully dense, wrought titanium. Despite this, MIM titanium retains a well-balanced set of mechanical properties that meet the demands of many applications. titanium exhibits high tensile strength, though it can be marginally lower than that of fully dense titanium due to residual micro porosity or variations in the phase of the material from the sintering process. Ductility in MIM titanium is generally favourable and can be tailored further with post-processing techniques, such as heat treatments or alloying with elements like aluminium and vanadium. These treatments improve the material's ductility and flexibility, which are critical in applications requiring toughness and formability. Additionally, MIM titanium has moderate hardness, which can be enhanced through alloying and thermal treatments to increase wear resistance and strength, creating an optimal balance for different applications. Titanium's inherent corrosion resistance and lightweight nature further contribute to its appeal, allowing MIM to produce parts with complex geometries without the need for costly machining. Overall, MIM titanium offers an efficient alternative to traditional manufacturing methods, particularly for applications where high material performance, lightweight, and intricate shapes are required. This process opens new possibilities in design and application, making MIM titanium valuable in various industries with stringent performance demands.

Condition	Porosity (%)	YS (MPa)	ε_f (%)	Endurance limit (MPa)	Study
As sintered	1.1	740	12	380	Niinomi et al.
As sintered + solution treatment	1.1	920	5	280	Niinomi et al.
As sintered + HIP	0.5	850	13	420	Niinomi et al.
As sintered + hot rolling	0.4	900	3	200	Niinomi et al.
As sintered	n/a	750	10	180	Muterlle
As sintered + shot peening	n/a	810	9	330	Muterlle
As sintered	3.6	720	14	350	Ferri et al.
As sintered + shot peening	3.6	720	14	450	Ferri et al.
As sintered + HIP + shot peening	0.0	841	17	500	Ferri et al.

Ti-6Al-4V is a titanium alloy known for its favourable mechanical properties, making it the most commonly used titanium alloy in metal injection moulding (MIM). Given its balance of strength, biocompatibility, and corrosion resistance, it's particularly suitable for medical applications and high-stress environments. MIM has become a commercially viable method for processing Ti-6Al-4V over the last decade, as well as other alloys like Ti-6Al-7Nb and modified versions of Ti-6Al-4V, owing to its cost-effectiveness and ability to produce complex shapes. The MIM process for Ti-6Al-4V typically includes sintering at high temperatures, between 1200 and 1350°C, in the single beta-phase region. Upon cooling, alpha phase forms as the alloy passes through the beta transus temperature (approximately 980°C, though this can vary depending on the oxygen content). This results in a microstructure characterized by alpha grains with beta lamellae, where alpha phase often forms at colony boundaries. Residual porosity in these structures generally falls within a range of 3–4%, although finer powders or extended sintering times can reduce porosity, resulting in pores less than 10 µm in diameter. As shown in table (13.1).

Standards for medical MIM components made of Ti-6Al-4V, outlined in ASTM F 2885-11, establish mechanical and chemical requirements similar to those of ASTM B 348-02 for wrought material used in general applications. ASTM F 2885-11 recognizes both "sintered" and "densified" conditions, with the latter achieved through hot isostatic pressing (HIP) to enhance density. This standard aligns with the chemical requirements of Grade 5 titanium and the mechanical properties of Grade 23. With proper processing, MIM-produced Ti-6Al-4V can achieve mechanical properties comparable to wrought materials, although the actual tensile strengths of fine-grained, thermos-mechanically treated wrought materials often exceed the minimum standards. The final properties of a Ti-6Al-4V MIM component are influenced by factors like porosity, grain size, and interstitial content. These properties, however, vary across studies because the effects of individual factors are difficult to isolate. Factors such as raw material characteristics (powder and binder systems) and processing conditions during DEbinding and sintering can significantly impact the resulting porosity, colony size, and interstitials in the alloy, and thus, the mechanical properties. Consequently, MIM Ti-6Al-4V components can be tailored for specific applications, with their mechanical performance largely meeting the demands of various industrial and medical uses.

(13.2.2) Influence of porosity

Residual porosity significantly impacts the tensile properties of sintered materials. To minimize connected porosity and achieve better mechanical properties, porosity should ideally be below 5%.As shown in graph (13.2).The best properties are obtained with additional Hot Isostatic Pressing (HIP), but the exact relationship between tensile properties and porosity levels from 5% to 0% remains unclear. Residual porosity is influenced by powder characteristics, sintering conditions, and temperature. Sintering under vacuum increases density by avoiding trapped gases that prevent further shrinkage. Studies using gas-atomized Ti-6Al-4V powder in Metal Injection Moulding (MIM) reveal that tensile properties strongly depend on residual porosity, with nearly full density achieved via HIP. Further studies, such as those by Zhang et al. and Niinomi et al., explored long sintering times to reach porosities as shown Fig (13.4) as low as 1-2%, showing a similar trend in tensile strength but with variations due to differences in oxygen content. The specimens in Obasi et al.'s study had consistent oxygen levels (~0.22 wt%), but other studies showed increased strength and lower ductility, likely due to higher interstitials, illustrating the challenges in comparing results across different studies.

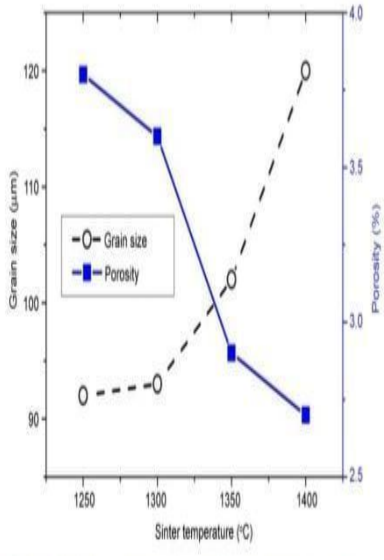


Fig 13.2 Influence of the sintering temperature on grain size and porosity of MIM-processed Ti-6Al-4V. sintering time was 2 h for all samples.

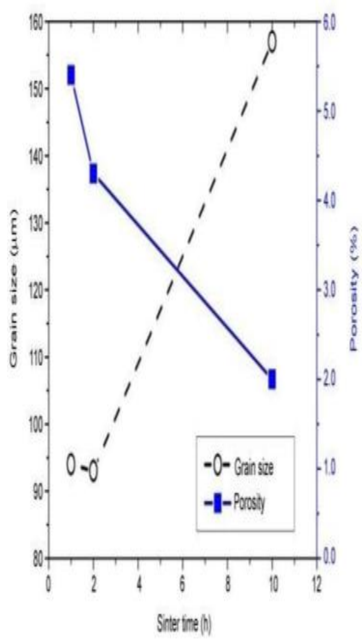


FIG 13.3 Influence of the sintering time on grain size and porosity of MIM-processed Ti-6Al-4V.Sintering temperature was 1350 degree Celsius. For all samples

FIG 13.4 Influence of porosity of MIM-processed Ti-6Al-4V on strength and plastic elongation of MIM-processed prealloyed

Ti-6Al-4V and blended Ti and 60Al-40V powders (zhang et al,Niinomi)

13.3.1 Fatigue

MIM (Metal Injection Molding) titanium alloys, like Ti-6Al-4V, generally exhibit lower fatigue resistance compared to wrought alloys due to inherent issues such as porosity, surface flaws, and coarse microstructure resulting from the sintering process. These flaws, including pores, oxide inclusions, and grain coarsening, can act as sites for crack initiation, reducing fatigue performance.

However, studies show that the fatigue resistance of MIM titanium can be significantly improved through post-processing treatments. Shot peening introduces beneficial residual stresses, which shift crack initiation from the surface to more homogenous material beneath, reducing the impact of surface defects. Additionally, Hot Isostatic Pressing (HIP) further enhances fatigue resistance by reducing porosity and improving material homogeneity.

While MIM titanium alloys typically show fatigue properties between those of cast and wrought materials, shot peening and HIPing can bring their fatigue resistance closer to that of wrought alloys, making them suitable for high-cycle fatigue applications.

Table 19.4 Overview of mechanical properties of MIM-processed Ti-6Al-4V

Condition	**Porosi (%)**	**YS (MP**	**ε_f (%)**	**End ran limi (MI**	**Study**
As sintered	1.1	740	12	380	Niinomi al.
As sintere solution treatment	1.1	920	5	280	Niinomi al.
As sintere HIP	0.5	850	13	420	Niinomi al.
As sintere hot rolling	0.4	900	3	200	Niinomi al.
As sintered	n/a	750	10	180	Muterlle
As sintere shot peening	n/a	810	9	330	Muterlle
As sintered	3.6	720	14	350	Ferri et a
As sintere shot peening	3.6	720	14	450	Ferri et a
As sintere HIP + s peening	0.0	841	17	500	Ferri et a

Another possibility to improve the fatigue resistance is to perform alloy modification. This was also done by Niinomi et al. and Ferri et al. and the results are shown in Table 19.5. While Niinomi et al. added 3 wt% Mo powder, Ferri et al. mixed the prealloyed Ti-6Al-4V powder with elemental boron powder.

Interestingly, the addition of Mo results in a significant increase of the yield strength, but not a corresponding growth in fatigue resistance in the same amount.

Table 19.5 Mechanical properties of MIM-processed or modified Ti-6Al-4V alloys

Alloy, condition	Porosit (%)	YS (MPa	ε_f (	Enduran limit (M	Study
Ti-6Al-4V-3Mo, as sintered	1.1	880	11	385	Niinom et al.
Ti-6Al-4V-0.5B, as sintered shot peenin	2.3	787	12	640	Ferri et

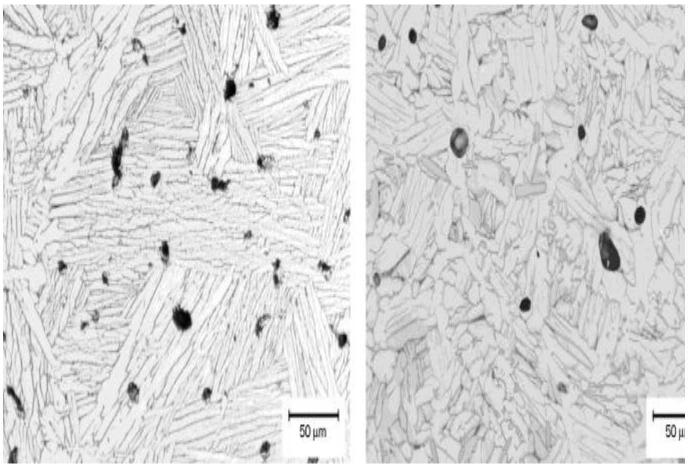


Figure 19.9 Comparison of typical microstructures of MIM-processed Ti-6Al-4V (left) and Ti-6Al-4V-0.5B (right).

The addition of boron to MIM-processed Ti-6Al-4V significantly enhances its fatigue resistance, particularly the endurance limit, without drastically affecting its tensile strength. Boron reacts with titanium during heating to form TiB (titanium boride) particles. These TiB particles hinder grain growth during sintering, similar to what is observed in casting processes. Additionally, the TiB particles act as nucleation sites for the alpha phase during cooling, leading to the formation of smaller alpha colonies. This results in a finer microstructure, with colony size reduced from 120 µm in pure Ti-6Al-4V to 18 µm in the boron-modified alloy.

The enhanced microstructure and the resulting refinement of the grain structure help improve the fatigue resistance of the alloy, with the endurance limit reaching approximately 400 MPa. When combined with shot peening, which induces beneficial residual stresses, and Hot Isostatic Pressing (HIP), which further reduces porosity, the fatigue performance of the alloy improves even more.

In summary, MIM-processed Ti-6Al-4V, especially when modified with 0.5 wt% boron, shows fatigue properties comparable to wrought materials, making it suitable for applications in aerospace, automotive, and medical implants, even with some degree of porosity present. Simple alloy modifications like boron addition can significantly boost the material's fatigue resistance, positioning it as a viable option for demanding, fatigue-loaded applications.

19.6.2 MIM of beta-titanium alloys

One reason for using metastable beta-titanium alloys is their capability of optimizing mechanical properties like strength or fatigue resistance by heat treatments. Here, the basic mechanism is to control alpha phase forming after fast cooling from the pure beta-state. This makes the alloys suitable for highly loaded applications, for example, in the aerospace sector. Furthermore, beta-titanium alloys show a reduced Young's modulus compared to pure titanium or Ti-6Al-4V, and can be composed completely from biocompatible elements. Even aluminum can be avoided. Therefore, this alloy class is especially attractive for manufacturing permanent bone implants in order to reduce the risk of stress shielding and toxic reactions.

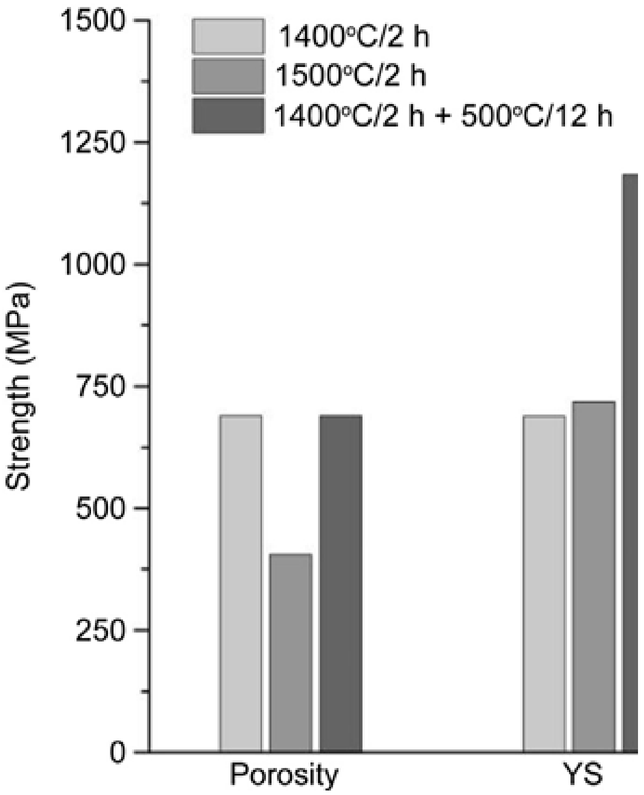


Figure 19.10 Typical tensile properties and porosity of Ti-15V-3Al-3Sn-3Cr processed by MIM under different sintering conditions

There are limited studies on MIM (Metal Injection Molding) of beta-titanium alloys, but some attempts have been made using alloys such as Ti-15V-3Al-3Sn-3Cr (a technical alloy) and Ti-24Nb-4Zr-8Sn and Ti-Nb (medical alloys). These studies generally used a binder system based on paraffin-wax, polyethylene-vinyl acetate, and stearic acid, similar to the binder used in Ti-6Al-4V MIM processing.

Key Findings:

1. Ti-15V-3Al-3Sn-3Cr Alloy:

Sintering Results: MIM-processed specimens made from gas atomized Ti-15V-3Al-3Sn-3Cr powder showed that increasing the sintering temperature reduced residual porosity, which resulted in higher strength. However, ductility decreased due to increased interstitial content in the specimens.

Heat Treatment: Samples subjected to a heat treatment at 500°C for 12 hours, aimed at partially transforming the beta phase to alpha phase, showed a significant increase in strength but also became more brittle. This suggests that while heat treatment can enhance strength, it may lead to embrittlement if not carefully controlled.

Microscopic Analysis : Carbide precipitates were observed at the grain boundaries in MIM-processed Ti-15V-3Al-3Sn-3Cr, which were not present in Ti-6Al-4V. These carbides were also seen in other beta-titanium alloys, such as Ti-Nb or Ti-Mo alloys, where elements like Nb or Mo act as beta stabilizers.

2. Ti-24Nb-4Zr-8Sn and Ti-Nb Alloys:

Study Overview : A study on Ti-24Nb-4Zr-8Sn powder and Ti-Nb alloys for medical applications showed similar trends. MIM processing of these alloys resulted in promising mechanical properties, although the details of sintering and heat treatment were not provided in full in the summary.

Conclusion:

MIM processing of beta-titanium alloys, such as Ti-15V-3Al-3Sn-3Cr and Ti-Nb-based alloys, can lead to materials with good mechanical properties, but their performance is highly dependent on the sintering temperature and post-sintering heat treatment. While increasing sintering temperature reduces porosity and improves strength, it also tends to reduce ductility. Heat treatments can further enhance strength but may result in embrittlement, particularly in alloys that undergo phase transformations (such as beta to alpha). Carbide precipitates at grain boundaries are commonly observed, and their presence may affect the mechanical properties, especially in beta-stabilized alloys. These alloys show potential for high-performance applications, especially in the aerospace and medical fields, but further optimization is needed, particularly in terms of heat treatment processes.

Table 19.6 Microstructural, chemical, and mechanical data of MIM-processed beta-titanium alloys based on the system Ti-Nb

	Po sit (%	Oxy n (wt%	Carb (wt%	Y (MP	UT (MPa)	ε_f (%)	Young's modulus (MPa
Ti-10Nb	3.6	0.20	0.056	55	63	10.5	85.2
Ti-16Nb	5.2	0.26	0.060	58	68	3.6	
Ti-22Nb	5.8	0.23	0.059	64	75	1.4	
Ti-22Nb HIP	0.0	0.23	0.065	6	83	1.3	
Ti-24Nb 4Zr-8Sn	3.9	0.32	0.067	6	65	9.2	

MIM processing of beta-titanium alloys, such as Ti-Nb-based alloys (e.g., Ti-24Nb-4Zr-8Sn), shows potential for strong mechanical properties, including high strength, but presents challenges in terms of ductility and carbide formation.

Effect of Nb Content: Increasing Nb content improves strength but reduces ductility and Young's modulus due to the stabilization of the beta phase. Higher Nb content also leads to more porosity, and even HIP processing does not significantly improve ductility.

Carbide Formation: The addition of elements like Nb or Mo reduces carbon solubility in the titanium matrix, leading to carbide precipitation, which contributes to embrittlement. This is a key difference compared to Ti-6Al-4V, where no carbide precipitation is observed.

-Sintering and Heat Treatment: Sintering temperatures between 1400°C to 1500°C are required for effective MIM processing, which can enhance strength but also increase the risk of carbide formation. Heat treatments can further improve strength but may worsen embrittlement.

In conclusion, while MIM-processed beta-titanium alloys offer high strength, their ductility is lower than expected, and carbide formation poses a challenge. Further optimization of sintering and heat treatment processes is needed to address these issues and improve the material's performance, particularly for applications in medical and aerospace industries.

19.6.3 MIM of titanium aluminides

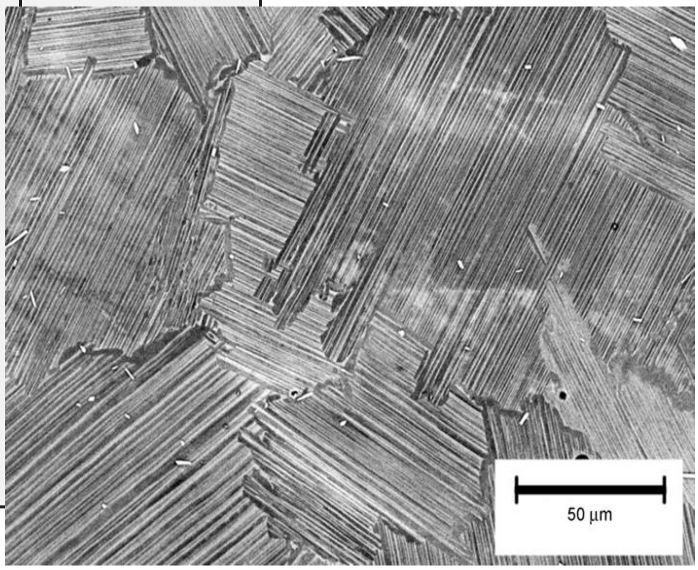


Figure 19.11 SEM micrograph of the typical microstructure of MIM-processed TNB-V5 (Ti-45Al-5Nb-0.2B-0.2C).

Titanium aluminides are attractive for high-temperature applications, such as gas turbines, jet engines, motor valves, and turbochargers, due to their lightweight properties compared to Ni-based alloys. These alloys primarily consist of two hard and brittle intermetallic phases, α_2 and γ, which present challenges in processing. Despite their commercial use, there is no standardized processing technique for titanium aluminides, particularly because of their inherent difficulties in being processed using conventional methods.

MIM Processing of Titanium Aluminides:

Powder Metallurgy (PM) techniques like Metal Injection Molding (MIM) are promising alternatives for processing titanium aluminides. However, MIM faces significant challenges due to the need for very high sintering temperatures close to the solidus temperature of the material, owing to the low diffusivity of titanium aluminides. Additionally, the resulting microstructure is highly sensitive to the sintering profile, requiring precise control over the process to achieve optimal properties.

Recent Developments:

In recent years, significant progress has been made in MIM processing of titanium aluminides. For example, Ti-45Al-5Nb-0.2B-0.2C (at%) alloy, also known as TNB-V5, was sintered at 1500°C for 2 hours under high vacuum, achieving a residual porosity of only 0.2%. The resulting lamellar microstructure showed a colony size of approximately 80 µm, which is characteristic of titanium aluminides processed by MIM. These results demonstrate the potential for producing near-net-shape parts with controlled microstructure and minimal porosity.

Impurity Control:

Controlling impurities during MIM processing is challenging, but efforts have been made to limit oxygen content. In one study, the oxygen content was reduced to 0.12 wt%, which is an acceptable level for maintaining the mechanical properties of the alloy. Tensile tests of MIM-processed Ti aluminides, conducted both at room temperature and at 700°C, yielded results comparable to those of cast materials, which had been HIPed, machined, and polished to standard geometry. While the MIM samples were tested as-sintered, their tensile properties were nearly equivalent to those of the cast counterparts.

Conclusion :

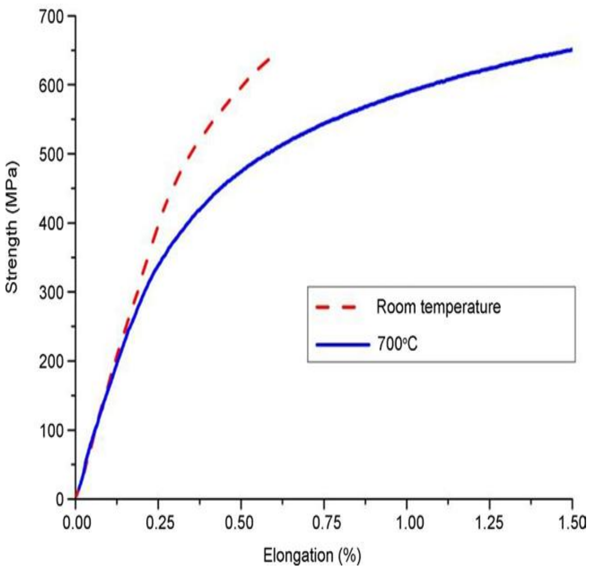
Although processing titanium aluminides via MIM presents challenges, particularly in terms of sintering temperature and impurity control, recent developments show promising results. With careful optimization of the sintering process, MIM can produce titanium aluminide components with near-net-shape geometries, low porosity, and mechanical properties that are competitive with those of cast materials, making it a viable option for high-performance, high-temperature applications.

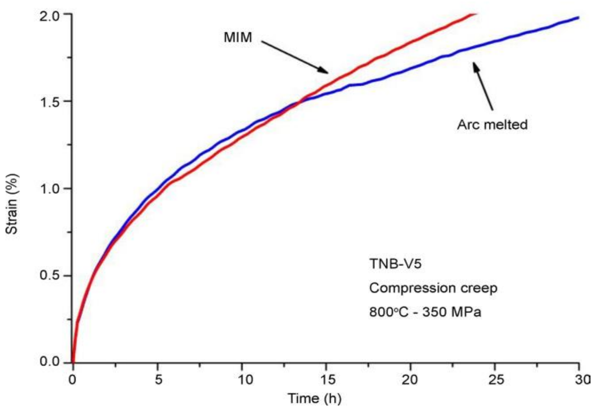
Table 19.7 Results from tensile tests on MIM-processed and cast TNB-V5 alloy at room temperature (RT) and at 700°C

Temper ure	Sample	UTS (MPa	ε_f (%)
RT	MIM	630	0.2
	Cast	745	0.1
700°C	MIM	650	1.0
	Cast	720	1.4

MIM processing of titanium aluminides, such as Ti-45Al-5Nb-0.2B-0.2C (TNB-V5), has shown promising results in producing materials with ductile behaviour in the as-sintered state and good mechanical properties. Tensile tests revealed that the MIM samples exhibit ductility, which is unusual for titanium aluminides. Compression creep tests indicated that MIM-processed and arc-melted TNB-V5 materials have comparable performance, especially at low strain values, suggesting that MIM can produce high-temperature, high-performance components like turbine blades or turbocharger wheels.

Despite these promising results, MIM processing of titanium aluminides still faces challenges, particularly with optimizing sintering conditions and controlling impurities. Further research is needed to refine processing parameters before MIM can be widely used in industrial applications. However, the potential for MIM to produce titanium aluminide components with high strength, ductility, and creep resistance makes it a promising method for manufacturing fast-rotating, high-temperature components.





19.7 Perspectives

Metal Injection Moulding (MIM) is not yet a standard manufacturing technique for titanium and its alloys, but its use is growing commercially, and excellent mechanical properties, including sound fatigue resistance, are now achievable. While there are still concerns regarding residual porosity and potential production flaws, particularly for aerospace components, MIM has already been successfully used for medical applications, including permanent implants, and ASTM standards specifically target this market.

MIM is also making inroads in the aerospace industry, with titanium components under testing for critical applications in aero-engines. The rapid growth of additive manufacturing, which shares similarities with MIM due to its use of powders, could accelerate the development and adoption of MIM titanium components.

The increased familiarity with powders in this field, along with faster development cycles, may help address some of the challenges MIM faces.

Additionally, the rise of carbon fiber–reinforced polymer (CFRP) usage in lightweight applications presents a potential new opportunity for MIM titanium. Since aluminium, a common material in lightweight structures, can corrode when in contact with CFRP, titanium connectors made via MIM could offer a solution, further expanding the potential applications of titanium MIM.

Ongoing research into MIM-specific titanium alloys, the development of porous components for medical implants, and efforts to reduce powder costs are all contributing to the technique’s advancement. Success in the demanding medical and aerospace sectors will likely spur broader adoption, driving the need for better, potentially cheaper powders and enabling more cost-effective applications. The next decade could see significant growth in the use of titanium MIM, expanding its impact across various industries.

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