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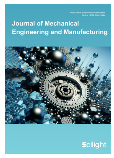

Review

Exploring Post-Processing Operations of Ti Alloys Using Hybrid Manufacturing Systems

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Abstract: This article provides an insightful overview of titanium alloys, focusing on their production, key applications, and the challenges in machining and processing. It delves into the extraction methods like the Kroll and Hunter's processes, the formation of alloys with elements like aluminum and vanadium, and their use in aerospace, biomedical, and automotive industries due to their excellent strength-to-weight ratio. This issue also addresses the difficulties in machining titanium, efforts in enhancing its properties, and the role of advanced manufacturing techniques, especially Hybrid Manufacturing, in improving efficiency and reducing costs. This study intended to perform a comprehensive literature analysis on titanium and its alloys, encompassing extraction, manufacturing, and post-processing, while examining contemporary advancements, employed approaches, and resultant findings in this domain. This work seeks to provide organized information on research pertaining to titanium, specifically the Ti6Al4V alloy, encompassing its extraction, manufacturing processes, post-processing, applications, and identified challenges, thereby facilitating the rapid knowledge acquisition of emerging researchers in this domain. Additionally, a SWOT analysis is included as a method for scenario analysis.

Keywords: Ti alloys; Ti6Al4V; additive manufacturing; hybrid manufacturing; post-treatments

1. Introduction

Titanium alloys play a crucial role in revolutionizing various industries due to their unique combination of properties [1]. Titanium and its alloys, due to their excellent properties and characteristics, are increasingly used in various applications. They generally have a high modulus-to-weight ratio, high corrosion resistance, excellent mechanical properties, the ability to retain their mechanical properties at high temperatures, and biocompatibility [2–4]. Therefore, this material is widely used in industrial, marine, chemical, and energy applications [5–7]. They are manufactured by CNC machining from cast or forged bars [8].

The Titanium metal is primarily produced from titanium tetrachloride using processes like the Kroll's or Hunter's method. It is often alloyed with elements like aluminium [9], vanadium, molybdenum [10], and iron [11] to enhance its mechanical and physical properties, like high strength-to-weight ratio and resistance to high temperatures. The focus of this work is on Ti6Al4V alloy, widely used in applications in aerospace [12], automotive [13], biomedical [14], military [15], and petrochemical industries [16], and known for its high strength-to-weight ratio, corrosion resistance, and biocompatibility [17].

AM techniques, such as Selective Laser Melting (SLM) and Electron Beam Melting (EBM), have gained prominence in the aerospace industry for manufacturing complex parts with low production volumes and minimal weight. Machining titanium alloys can be challenging due to toughness and wear resistance, leading to increased tool wear and machining time. This challenge has a higher importance in applications for aerospace industry, where is well known that fatigue and crack propagation under high-stress cyclic loading is a regular condition of working [1]. Hybrid manufacturing, combining additive manufacturing (AM) and subtractive processes, is explored to optimize production, achieve complex geometries, and improve surface finish. Challenges of this type of manufacturing include dealing with residual stresses, recycling considerations, equipment costs, and training requirements [18].

Moreover, post-processing of titanium alloys is essential and faces challenges such as machining difficulties, oxidation in atmospheres containing oxygen, and the need for heat treatment [19]. Ongoing research focuses on developing alloys with higher service temperatures and better wear resistance for demanding environments. Thus, this work contains a comprehensive overview of the production, properties, and applications of titanium and its alloys. It also delves into the challenges associated with machining and post-processing of titanium alloys, as well as the emerging field of AM, especially in the aerospace industry. The information provided in this article gives a comprehensive understanding of the production, properties, and challenges associated with titanium and its alloys, shedding light on both traditional and advanced manufacturing processes. Although current literature has established the feasibility of additive manufacturing of titanium alloys and the associated post-processing requirements, critical research on the integrated optimization of these processes in hybrid systems remains fragmented. There aren't many studies that review and evaluate how AM and post-processing parameters directly impact the microstructural and mechanical properties of components. This is especially true for the complexity needed in industries like aerospace. Therefore, the primary objective of this review article is to explore, synthesize, and critically analyze the post-processing operations of titanium alloys using hybrid manufacturing systems, outlining research trends, points of debate, and existing gaps in the literature to guide future investigations.

2. Literature Review

2.1. Extraction of Titanium

Titanium, a silver-coloured transition metal, was discovered in 1791. The metal was named after the titans because it's very reactive with oxygen and nitrogen, which makes it difficult to extract. Research and industry have adopted different strategies to overcome this, such as processing in an environment with inert gas. Using an inert gas prevents titanium from reacting with oxygen and nitrogen. Sealed chambers control the environment during melting and cooling in additive manufacturing. If contamination has occurred, remove the contaminated layer through machining. While effective, this approach is costly as it increases processing time, material waste and tool wear. Acid pickling is another option. An acid bath removes the contaminated layer without damaging the main material. This method is used for complex geometries or surface finishing.

It has since emerged as a vital material in various industries, thanks to its unique combination of strength, lightness, and corrosion resistance [20]. Obtaining these alloys involves several steps, from extracting Ti ore to producing the final alloy. First, titanium ore is extracted from ilmenite ($FeTiO_3$) and rutile (TiO_2) minerals. Ore deposits are found in igneous, metamorphic and sedimentary rocks in over 20 countries. Once extracted, the ore is purified to produce Ti dioxide, which is then converted into titanium tetrachloride ($TiCl_4$) through a process called the chloride process. This involves reacting the titanium dioxide with chlorine and coke at high temperatures.

Titanium metal is produced from titanium tetrachloride using either the Kroll or Hunter (Figure 1) process. The Kroll process is more widely used and involves reducing titanium tetrachloride with magnesium in a large and sealed reactor [21,22]. This process yields titanium sponge, which is then melted and formed into ingots [23]. The Hunter method is an older process. It also uses the reduction of titanium tetrachloride ($TiCl_4$), but with liquid sodium (Na) instead of magnesium. The reaction takes place in a steel bomb. The end product is a sponge of titanium (Ti) and sodium chloride (NaCl). Both methods produce a titanium sponge, but Hunter's is less efficient and more difficult because of the reactivity of sodium. Kroll's method is the industry standard.

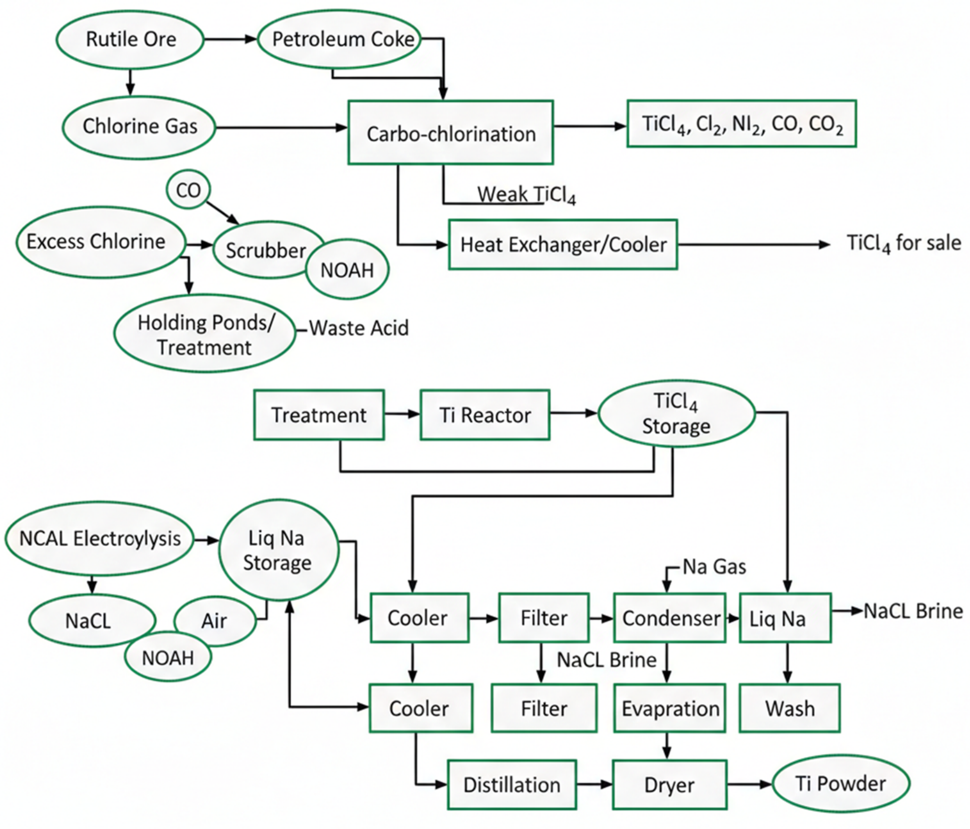

Figure 1. Hunter Process Diagram. Based from [23].

2.2. Titanium Alloys

To produce titanium alloys, pure titanium is alloyed with other elements such as aluminum (Al), vanadium (V), molybdenum (Mo) and iron (Fe). This is typically done in a vacuum arc remelting furnace, where precise control of temperature and atmosphere is possible [24]. The addition of these alloying elements enhances the mechanical and physical properties of the final alloy [25]. The final step involves processing the titanium into sheets, bars, or tubes, using heat and machining. Titanium is known for its exceptional strength-to-weight ratio, which is approximately 45% lighter than steel yet comparable in strength, making it an essential material in applications where weight is a critical concern. In fact, while being only 60% heavier, titanium alloys are twice as strong as soft aluminum alloys [16].

Titanium alloys are used to make advanced engines, which use less fuel and are more efficient. Titanium alloys are key to making safer, lighter parts in heavy machining systems. The resistance to corrosion makes it ideal for use in environments exposed to sea water, aqua regia, and chlorine [26]. Titanium alloys are resistant to corrosion and exhibit high fracture toughness and high-temperature strength. Their high melting point of 1668 °C makes them suitable for high-temperature applications. Its biocompatibility makes titanium a favored choice for medical implants and prosthetics [27]. Datta et al. [28], evaluated a methodology that could predict the strength and modulus of elasticity of titanium alloys to design alloys suitable for orthopedic and dental applications. The paper concludes that combining imprecise knowledge with experimental data can effectively lead to rule-based models for designing titanium alloys. In turn, Niinomi [29], described Young's modulus, wear properties, notch fatigue strength, fatigue behavior in relation to aging treatment, resistance to fatigue crack propagation, and ductility based on titanium's biocompatibility. The study concludes that specific nontoxic alloying elements lead to low-rigidity titanium alloys with proven benefits in bone healing. Conforto et al. [30], examined the microstructure of titanium and titanium alloys that underwent sandblasting treatment to improve surface roughness, thereby improving osseointegration, fixation, and implant stability.

In the aerospace industry, titanium alloys have been pivotal [31]. Their use has revolutionised aircraft design and construction, providing lightweight yet strong materials that improve fuel efficiency and performance. However, there is an ongoing challenge to produce even stronger titanium alloys. New research and development are focused on creating alloys with higher service temperatures and better wear resistance, making them more suitable for demanding environments [32]. One of main disadvantages of using Titanium alloys can be the susceptibility to fatigue and crack propagation under high-stress cyclic loading, which is a concern in aerospace applications [33]. Williams et al. [34] described recent developments involving Ti and its alloys in aerospace components, citing, for example, the cast and machined low-pressure turbine blades in the GE engine (GEnx) used in the Boeing 787, to those to be developed by A.M. for the GE90X engine, which will power the Boeing B-777X. Gomez-Gallegos et al. [35] focused their study on the Ti54M alloy, from which the authors addressed the validation of a model capable of estimating the behavior and grain size evolution of titanium alloys under superplastic conditions. In turn, Boyer & Briggs [36] investigated Beta titanium alloys and their applications in the aeronautical and aerospace industries through a review article.

Titanium alloys have many applications including the aerospace, automotive, biomedical, military, chemical, marine and sports industries. For example, Gurrappa [37] evaluated the corrosion of Ti6Al4V in chemical, marine and industrial environments at various temperatures, verifying that the alloy is suitable for the manufacture of components intended for use in these environmental conditions. This wide-ranging applicability is a testament to the versatility and effectiveness of titanium alloys in various industrial and technological contexts [38]. Titanium's advantages extend beyond its physical properties, but its cost is high due to complex extraction and processing. Machining titanium also requires specialised equipment. Machining titanium alloys can be challenging due to their toughness and wear resistance, leading to increased tool wear and machining time [39]. In his article, Pramamik [40] described the main challenges encountered in machining titanium alloys, which, according to the author, include varying chip thickness, high thermal stress, high pressure loads, spring back, and residual stresses responsible for wear and surface quality. Furthermore, the author highlights the high machining costs.

Titanium alloys are strong, lightweight, corrosion-resistant and biocompatible. However, they are costly, difficult to machine and sensitive to fatigue. Research and technology are working to address these issues. Titanium alloys can be sub-divided into near-α and metastable β alloys [41], as shown in Figure 2:

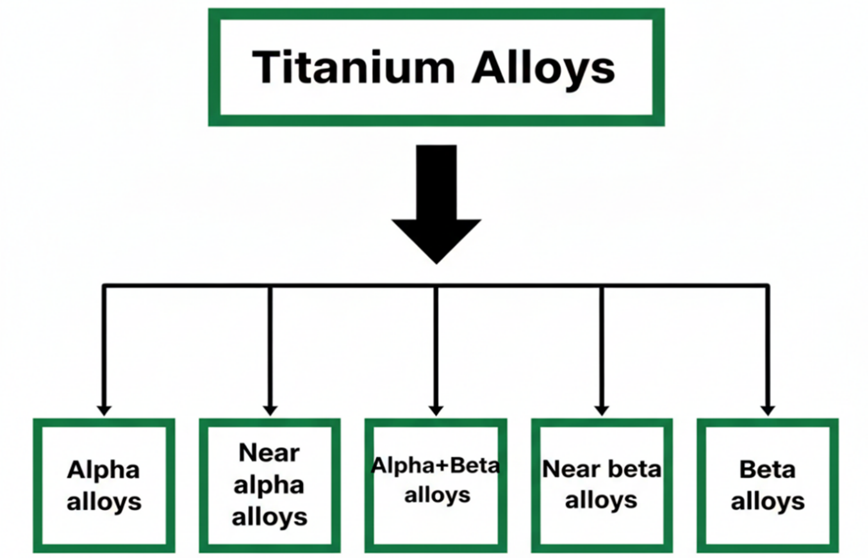

Figure 2. Classification of titanium alloys. Based from [16].

Alpha (α) titanium alloys are composed primarily of the α phase. The alpha phase has a hexagonal close-packed (HCP) crystal structure. This structure is stable at lower temperatures and is responsible for titanium's high-strength, low-ductility properties. However, they are generally less strong than β or α-β alloys. α alloys are often used in environments where corrosion resistance is crucial, such as in chemical processing and marine applications. An example of an α alloy is commercially pure titanium (ASTM grade 1, 2, 3 and 4 Ti/Pd alloys, ASTM grade 7 and 11). When considering a near alpha alloy, Ti–6Al–Mo–1.5V–2Zr, Lavrys et al. [42], investigated the corrosion behavior of the same alloy being manufactured by EBM and laser metal deposition (LMD), observing lower corrosion resistance than manufacturing through conventional methods.

β alloys are mainly composed of the beta phase (body-centred cubic, BCC) and can be heat treated, increasing strength significantly. β alloys are stronger and more ductile than α alloys. They can be easily processed and are used in high-strength-to-weight ratios applications like aerospace. Ti15V3Cr3Sn3Al is an example of β alloy. Pesode & Barve [43] reviewed metastable β-titanium alloys that could be used as viable alternatives in the development of dental implants, emphasizing their excellent biocompatibility properties. In turn, Ballor et al. [44], from a beta alloy, investigated the generation of a new phase, called ω, and thus verified the influence of the ω phase on the mechanical properties of β-titanium alloys. The ω phase is a metastable phase that forms in some alloys during rapid cooling. Its precipitation can increase the material's hardness and strength, but can also cause embrittlement. Controlling its formation is critical.

α-β alloys combine the best properties of both α and β phases. They can be heat treated for a balance of formability, strength and ductility. These alloys are versatile and used in aerospace due to their properties at a range of temperatures. Ti6Al4V is the most widely used titanium alloy, falling into this category [16]. The Ti6Al4V alloy, was developed in 1940, and stands out as one of the most popular and widely used titanium alloys. It demonstrates the low-density characteristic of titanium—60% less than that of steel and superalloys—which, when combined with alloying and deformation processing, results in significantly improved strength. This grade 5 titanium alloy is well known as a lightweight material for aerospace structure combining very good metallurgical and physical properties. Ti6Al4V presents a high strength to weight ratio, a low density, elevated temperature properties up to 400 °C, and a low modulus of elasticity [45].

This alloy has received considerable interest due to its excellent properties, making it vital for commercial use in numerous industries, including aerospace, biomedical, and automotive sectors [46]. The composition of Ti6Al4V, particularly the 6% Al and 4% V, contributes to its superior strength, lightweight, and corrosion resistance. These attributes make Ti6Al4V especially suitable for critical applications where reliability and performance are important parameters. In the aerospace industry, Ti6Al4V is extensively used in the manufacturing of aircraft components due to its high strength-to-weight ratio and resistance to high temperatures. This makes it ideal for parts that are subject to extreme stress and environmental conditions. The Ti6Al4V alloy, also known as Grade 5 titanium, possesses a combination of properties that make it well-suited for biomedical implants. These include high strength, excellent corrosion resistance, and biocompatibility. Biocompatibility is a crucial factor, ensuring that the material is compatible with the human body and does not induce adverse reactions. In the biomedical field, the biocompatibility of Ti6Al4V is a significant advantage [47]. It is commonly used in the production of medical implants, such as joint replacements and dental implants. The alloy's compatibility with the human body and resistance to bodily fluids make it an excellent choice for long-term implantable devices [48]. Although the Ti6Al4V alloy is generally considered biocompatible, vanadium (V), one of its main alloying elements, is known to be cytotoxic. Leaching of vanadium ions from implants can lead to adverse reactions, including inflammation and localized toxicity, especially over time. To mitigate this risk, researchers and manufacturers have explored alternative alloys. The Ti-6Al-7Nb alloy, for example, replaces vanadium with niobium (Nb), which is considered more biocompatible and less cytotoxic. Other alloys, such as Ti-13Nb-13Zr, are also promising because they do not contain vanadium. The issue of toxicity is crucial for post-processing, as heat or surface treatments can influence the stability and release rate of vanadium ions. Future research should focus on optimizing these processes to ensure that the implant surface remains stable and does not release potentially toxic elements. The automotive industry also benefits from the use of Ti6Al4V, particularly in high-performance vehicles. Additionally, its strength ensures the durability and reliability of automotive components [49]. Based on this, the choice of titanium alloy for this review study focuses primarily on Ti6Al4V. This dual-phase alloy is often referred to as the 'workhorse' of the titanium industry because it is the most widely used in critical applications, as previously mentioned. The focus of this review on post-processing is highly relevant and applicable to most high-value components produced by hybrid systems, given the alloy's popularity in Additive Manufacturing processes, such as SLM and EBM. To inform subsequent discussions on post-processing, the crucial properties of the Ti6Al4V alloy are specified in Table 1.

Table 1. Chemical and mechanical properties of the Ti6Al4V alloy [50].

Property	Typical Value (AM/Wrought)
Chemical Composition (Nominal) [%]	6%Al, 4%V, balance Ti
Density [g/cm^3]	4.43
Yield Strength (σ_y) [MPa]	880–1000
Ultimate Tensile Strength (σ_{UTS}) [MPa]	950–1100
Young's Modulus (E) [GPa]	110–115

2.3. Mechanical Processes

Several mechanical processes are employed in the production of titanium alloys, and these processes vary depending on the desired final product and application. Here are listed some common mechanical processes used with titanium alloys and the resulting products [51]:

- Machining: Used to obtain components with intricate shapes, such as aerospace parts and medical implants [52]. Muthuramalingam et al. [53] assessed the impact of machining parameters on surface performance in the machining of titanium alloy utilizing the Taguchi-Grey relational method. Research has shown that laser power is very important. It is important for determining the quality measures of surface roughness and taper angle in Laser Beam Energy. This is because of its impact on plasma energy. In turn, Airao et al. [54], evaluated the post-processing through micro milling of selective laser cast (SLM) and forged Ti6Al4V, comparing the wear performance based on the verified wear mechanisms. Kaltenbrunner et al. [55], focused their work on the difference between up and down milling in relation to thermomechanical load and tool wear in the milling of Ti-6Al-4V, with the highest wear rate in up milling.

- Forging: It improves the mechanical properties and grain structure of titanium alloys. Mainly used for production of aircraft components, automotive parts, and structural components [19]. Ranjan et al. [56], evaluated the impact of microstructure heterogeneity on Ti-6Al-4V forging based on the development of a processing route for bimodal microstructure. The bimodal microstructure, which has a higher lamellar fraction, was found to have weaker texture intensity and enhanced fracture toughness.
- Extrusion: It is commonly used to produce long and uniform profiles, such as tubes, rods, and other long sections used in various applications. Slámečka et al. [57], evaluated the high-cycle fatigue behavior of new titanium scaffolds produced by additive manufacturing by material extrusion used mainly in biomedicine with regard to bone implants. In turn, Zhang et al. [58], investigated the tensile properties and deformation mechanism of a hot extruded near α-Ti alloy. An adequately high oxygen content (0.36% by weight) can provide superior tensile strength and excellent ductility in a powder metallurgy near α-Ti alloy.
- Rolling: Sheets, plates, and foils for applications in aerospace and industrial sectors are commonly produced by this process [59]. Considering the ultrasonic rolling process, Luo et al. [60] evaluated its effect on the microstructure and properties of the surface layer of Ti6Al4V alloys, such as surface roughness, surface topography, microhardness, and residual stress. The authors found lower surface roughness and greater plastic deformation, as well as a decrease in the grain size of the surface layer, and a consequent increase in hardness and residual stress.
- Investment casting or precision casting is a process where a wax pattern is coated with a ceramic shell, melted, and replaced with molten metal. It allows for complex and near-net-shape components. Used for obtaining complex and intricate components for aerospace, medical, and industrial applications [61]. For example, Li et al. [62], considered the hot isostatic pressing (HIP) process in Ti6Al4V alloy castings based on the evolution of the material microstructure around the porosities. HIP closed 96% of porosity in Ti6Al4V (mostly in first phase, driven by fluid flow and diffusion near grain boundaries). Also, longer HIP times led to spheroidization of α lamellas around the pores, via dynamic recrystallization and twisting. On the other hand, Ismail et al. [63], evaluated investment casting (IC) for the fabrication of artificial hip joints made of Ti6Al4V based on mechanical strength, hardness, impact strength, and the influence of oxygen. The low oxygen content after IC caused a decrease in strength and hardness, but resulted in a significant increase in ductility (elongation).
- AM: the process involves the use AM machine that deposit titanium material in successive layers, following a three-dimensional digital model. Adding material layer by layer makes it possible to create complex parts and intricate geometries that would be difficult or impossible to produce using traditional methods [64]. The industrialization of metal additive manufacturing has made significant strides in recent years, experiencing rapid growth [65]. This evolution commenced with the production of dental items and medical implants, subsequently extending its reach to the aerospace sector [66]. There is a lot of work and research in this area as it is very promising, and titanium alloys are not left out of this aspect.

2.4. Additive Manufacturing

AM offers a myriad of advantages, including reduced waste, expanded design possibilities, enhanced product functionality, and increased production flexibility [67]. Noteworthy instances include the fabrication of intricate components that are either costly or unfeasible to produce through traditional methods. Additionally, AM facilitates the creation of single components by consolidating numerous separate pieces, a feat difficult to achieve using other manufacturing techniques [18].

Another notable application involves the development of tools featuring curved cooling channels for optimized cooling. Furthermore, AM enables the production of lightweight parts with topology optimization, leading to substantial reductions in weight, as well as significant decreases in lead times, costs, and waste compared to conventional manufacturing methods. Exemplary cases from various corners of the globe underscore the remarkable achievements in weight reduction, along with the considerable benefits of diminished lead times, costs, and waste when contrasted with traditional manufacturing processes. This underscores the transformative impact and potential of metal additive manufacturing in diverse industries [68].

The aerospace industry has indeed witnessed significant advancements in metal Additive Manufacturing, and two notable techniques, Selective Laser Melting (SLM) and EBM, have stood out prominently [69]. These techniques have proven highly effective, particularly in the aerospace sector, where the demand for manufacturing complex parts with low production volumes and minimal weight is crucial [70]. The choice of raw materials in metal Additive Manufacturing for aerospace applications commonly includes titanium, aluminum alloys, and specific types of steel [71]. It is interesting to also note that, according to the information provided, approximately 14% of Metal Additive (MA) parts produced for the automotive industry in series production find application in vehicle engines. This highlights the growing integration of metal Additive Manufacturing technologies in the automotive sector, where the unique capabilities of these techniques are leveraged for manufacturing engine components with enhanced performance characteristics [72].

The techniques that are most used to metals are four: powder bed fusion (PBF), direct energy deposition (DED), binder jetting (BJ) and sheet lamination (SL) [73]. When using SLM the absorption reactions of the laser beam differently for each type of metal, leading to surface tensions and increasing thermal stress, which can cause cracks being this a disadvantage of this technique. There are several studies focus on new emerging techniques for AM, like wire arc additive manufacturing (WAAM), and cold spraying additive manufacturing (CSAM), demonstrating that parts produced by WAAM exhibit lower accuracy due to factors such as wire deposition and heat transfer. Conversely, surfaces produced by WAAM tend to be rougher due to larger deposition sizes [19]. On Table 2 some of the main characteristics of parts obtained by this manufacturing process is compared, relative differences between additive manufacturing processes, based on the typical properties of each technology. To provide rigor to the comparative analysis presented in Table 2, the qualitative terms used to evaluate the AM processes are defined based on common industry benchmarks and technical literature:

- Density: The term "high" in "high density" refers to a relative density above 99.5%, which is often comparable to wrought or forged material and essential for critical structural applications. The term "moderate" alludes to a relative density that generally falls within the range of 95% and 99.5%, where the management of porosity may emerge as a matter of paramount importance.
- The term "small" is used to describe print sizes that are generally limited to small-to-medium cubic envelopes, typically measuring below 250 × 250 × 300 mm. These dimensions are characteristic of powder-bed systems, such as SLM and EBM. "Large" in this context refers to WAAM processes capable of producing components with dimensions exceeding 500 mm in at least one axis.
- Accuracy: "High" means that the final part will have a tolerance of 0.1 mm or better. 'Low' implies a requirement for significant material removal during post-processing to achieve design tolerances, often with deviations greater than 1 mm.
- Surface Quality: "High" suggests a surface finish that is near or within the operable range (IT7 to IT11). "Moderate" indicates the need for additional finishing operations, whereas "High" for WAAM refers to the quality of surface deposition rather than the final finish.
- Residual Stress: "High" indicates that a specific heat treatment process is mandatory. This process is costly and time-consuming. It is also known as a heat treatment process, or HIP, or annealing. The purpose of this process is to prevent warpage or failure of the part. The term "low" indicates that stress relief treatment may be optional or less intensive due to better thermal management (EBM).
- Cost: 'Low' refers to the cost of raw material/equipment setup relative to EBM. 'High' is primarily associated with the capital cost of the specialized equipment

Table 2. Qualitative properties of parts produced by SLM, EBM, and WAAM processes [19].

	SLM	**EBM**	**WAAM**
Density	High (comparable to forged)	High (similar of SLM)	Moderate (may have porosity)
Print Size	Small	Small	Large
Accuracy	High	High	Low
Surface quality	High	Moderate	High
Residual Stress	High	Low	High
Cost	Low	High	Low

The analysis of Table 1 effectively contrasts the qualitative properties of parts produced via SLM, EBM, and WAAM processes, highlighting crucial design trade-offs. Both powder-bed fusion methods, SLM and EBM, excel in producing parts with High density and High accuracy, making them suitable for small, high-integrity components. However, SLM presents High Residual Stress, demanding subsequent stress relief, while EBM is categorized by its High Cost. In stark contrast, WAAM is distinguished by its capacity for Large print sizes at a

Low Cost, yet this comes at the expense of Low Accuracy and only Moderate Density (with potential porosity). Ultimately, the choice of the Additive Manufacturing process hinges on the application's priorities: SLM for high precision, EBM for lower residual stress, and WAAM for large-scale, cost-effective production, often necessitating extensive post-processing due to its inherent limitations.

The Ti6Al4V has emerged as one of the pioneering alloys manufactured through the EBM process [74]. This advancement was primarily driven by the biomedical industry, which recognized the substantial potential of the Ti6Al4V alloy for creating personalized surgical implants. The ability to produce customized surgical implants tailored to the specific needs of individual patients has been a transformative aspect of using Ti6Al4V alloy in the EBM process. This not only enhances the overall performance and longevity of implants but also contributes to better patient outcomes [75]. The EBM process involves selectively fusing metal powder layer by layer using an electron beam. Along with other techniques such as L-PBF (Laser Powder Bed Fusion), this additive manufacturing method enables the creation of complex, custom designs, making it especially suitable for biomedical applications requiring patient-specific implants [76].

Some studies demonstrate that using BJ and as the processes is carried out at room temperature, for the metal to have structural resistance, it is necessary to carry out a post-processing to remove the bonding agent and, at the same time, have a resistant metal part. For this post-processing that can be used two techniques: infiltration and sintering. In the infiltration technique first the binding agent is removed, leaving a porous structure. Further heating solidifies this structure, which already has internal porosity, and then filled with the molten metal, resulting in a bimetallic part. The sintering method the binding agent is "burned off" on a furnace leaving the metal powder particles, the remaining metal powder particles are then sintered or fused together at high temperatures, resulting in a solid, high-density part [70].

Direct Energy Deposition (DED) processes are most used to repair parts or add metal to manufactured parts. The technique is promising for use in components requiring structural strength, as it produces parts with high resistance and there are many materials that can be used. On the other hand, its disadvantages include poor geometric accuracy and difficult control of the weld puddle.

Recently, the researchers have demonstrated that AM processes can produce metal parts with mechanical performances different from the wrought ones [77]. In particular, the hardness and wear resistance of the AM metals have revealed to be superior to conventional casting ones because the AM techniques can produce excellent surface wear properties due to low levels of residual stresses induced by the process itself [70]. The continual progress in additive manufacturing (AM) technologies underscores the dedication of researchers and industry experts to overcoming challenges, paving the way to produce metal parts that closely emulate or even surpass the properties of traditionally manufactured components. The dynamic and collaborative nature of additive manufacturing positions the industry to deliver metal parts that not only rival but often surpass the properties of traditionally manufactured components, marking a significant stride towards the future of advanced manufacturing [78].

AM parts are often compared to castings, as a reasonable facsimile, since melting of powder with a laser, plasma or an electronic beam is comparable to what happens in a casting on a micro scale. But that can be also the same micro porosity problems; they have to be fed with liquid metal to avoid porosities. Another problem refres to when liquid metal turns to solid and it shrinks and dimensions needs to be adjusted. The shrink is not equal in all 3 dimensions since parts are not allowed to shrink freely in space but are obstructed by geometry. So rules have to be made for each part to compensate for shrinkage. Nowadays, the AM processes use scale factors which are used to scale the part to compensate for this shrinkage in each dimension [79].

Table 3 compares the surface roughness values from differents processes of metal parts production. The dimensional accuracy is also a challenge on demand for the AM technology comparing with some of the most commonly used traditional processes. The color coding on the matrix represents the range of dimensional accuracy typically achievable. Lighter colors indicate better accuracy; darker colors (red) indicate poorer accuracy, often requiring additional machining.

Standard ISO 286-1 is part of a series of international standards that establish tolerances for linear dimensions of mechanical parts. It provides a table of dimensional tolerances for shafts and bores in metric systems. Tolerances are specified in terms of tolerance classes numbered IT-01 to IT-18. The lower the number, the tighter the tolerances. It is easy to understand that AM processes have is limitation when the goal is dimension accuracy. Even when using an additive manufacturing technique, post-processing is commonly required to conform and give the parts the desired shape, dimensions and mechanical properties. Despite its geometric flexibility, Additive Manufacturing consistently falls into the worst surface quality range (IT-12 to IT-16), emphasizing the critical need for post-processing (e.g., using Grinding or Milling) to achieve the required tolerances and surface finishes for high-performance applications. In the Ti Alloys it can be a very difficult task [80]. The combination of porosity, columnar grain structure and residual stresses makes machining AM parts from titanium alloys a more complex and demanding process than that of their cast/forged counterparts, which have a more homogeneous and predictable microstructure.

Table 3. Dimensional accuracy after various manufacturing processes.

Process	**IT-Classes (ISO 286-1)**											
	5	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Casting							■	■	■	■	■	■
Sintering					■	■	■	■				
Forging								■	■	■	■	■
Precision forging						■	■	■				
Extrusion			■	■	■	■	■					
Rolling				■	■	■	■					
Cutting								■	■	■		
Jiggering			■	■	■	■						
Drilling								■	■	■		
Milling			■	■	■	■	■	■				
Planing				■	■	■	■	■				
Broching			■	■	■	■	■					
Grinding	■	■	■	■								
Additive Manuf.								■	■	■	■	

The post-processing of titanium alloys, after AM or even casting, can pose specific challenges due to the unique properties of titanium and the extreme processing conditions [81]. Some common problems in the post-processing of titanium alloys can include:

- Machining difficulties due to the low thermal conductivity and high chemical reactivity of the Ti alloy, that can lead to rapid tool wear and demand of specific machining techniques [82];
- During machining, titanium can form sharp edges, which can compromise the quality of the machined part and increase the risk of injuries to operators [83];
- Atmospheres containing oxygen leads to oxidation and the formation of undesirable surface layers, compromising part integrity [84];
- Heat treatment of titanium parts may be necessary to enhance their mechanical properties [85];
- Plastic deformation at low temperatures can be employed to improve the mechanical properties but may lead to increased brittleness and the need for subsequent heat treatments;
- In additive manufacturing processes, thermal processing anomalies may occur, leading to variations in properties that require careful consideration in design and post-processing;
- Due to the anisotropy, mechanical properties may vary in different directions, necessitating careful considerations in design and post-processing [86];
- Post-processing of titanium alloys can be costly due to specialized techniques, high-quality machining tools, and additional quality control measures.

To address these challenges, it is crucial to employ specific techniques and processes tailored to titanium and to use appropriate tools and equipment. Collaboration between materials engineers, manufacturers, and processing experts is essential to optimize the post-processing of titanium alloys and ensure the quality of the final parts.

The machining of Ti6Al4V is however possible, even without lubrication [87]. Titanium alloys are easily damaged during machining. The damage appears as micro cracks, build up edge, plastic deformation, heat affected zones and tension residual stresses manufacturing. Post-process methods such as heat-treatment (HT), machining (M), HIP, and different combinations thereof have been explored to enhance the mechanical as well as the fatigue properties [88]. Making sturdy and budget-friendly metallic parts with tricky shapes is a big deal for aerospace, medical, automotive, tooling, and consumer product folks. To speed things up, simplify the whole manufacturing deal, and slash costs for these industry goodies, researchers are digging into combining lots of manufacturing steps into just one machine. The end goal is to reduce production space, time, and manpower requirements. Integrated systems are increasingly being recognized to meet these goals [89].

Hybrid processes were developed to reply to this issue, based on a principle of addition of material followed by the removing of material on the same machine. The deposition process allows reaching a "near net shape" and the process of machining a "final form". Figure 3 presents a comparative analysis of AM and traditional processes.

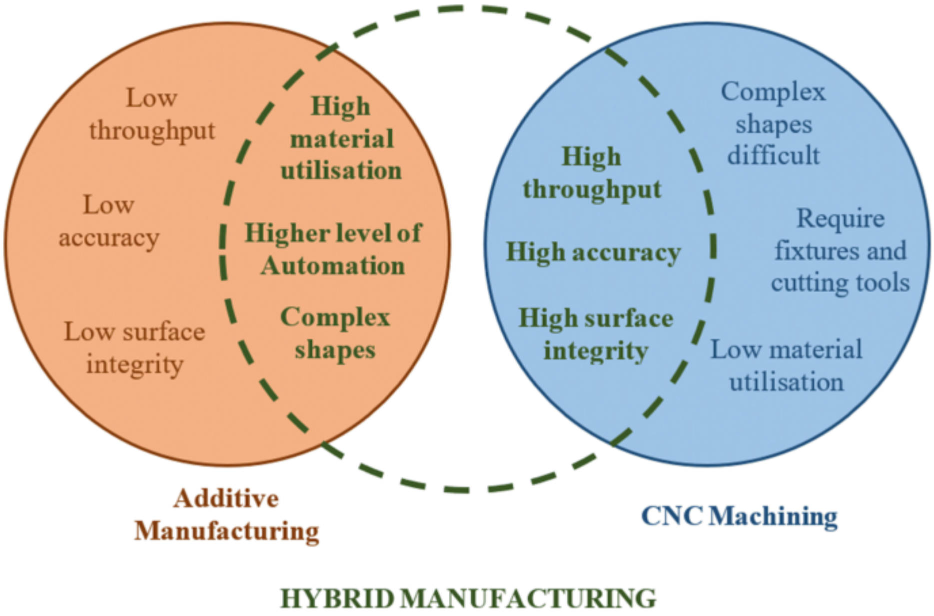

Figure 3. Synergy and Trade-offs of Key Characteristics in Hybrid Manufacturing. Reproduced from [90].

Hybrid processes become economically competitive when deposited materials are rare, expensive, and difficult to machine, like titanium alloys, ranked among the most difficult-to-machine materials [45]. Hybrid manufacturing leverages the advantages of both AM and machining to create parts that have complex geometries, and a demand for tight tolerances and excellent surface finish. The residual stresses created by the two processes is a challenge. AM generates very high residual stresses due to the thermal history imposed by the process. These stresses can cause the part to crack and separate from the build plate or to distort significantly, causing the part to fail or not meet the design requirements. Also, In the post-processing of additively manufactured parts, the propagation of geometric errors can impact the machined surface accuracy of the final product [91].

The high stresses may induce distortion that can damage the part during the AM process, and it leads to unexpected problems during machining. Some studies were found on works about the residual's stresses caused by Laser Powder Bed Fusion process on stainless steel cylinders. The distortion was calculated and estimated by measuring the outer diameter before and after the machining process. This allowed to anticipate the distortion before the machining process and adjust the parameters programmed on the machine [91].

Hybrid additive/subtractive manufacturing is a process that combines both additive manufacturing (AM) and subtractive manufacturing, to create parts with high complexity, tight tolerances, and good surface finish [92]. This processing can be done in the same equipment, where both AM and machining operations are performed [93]. The AM processing enables complex geometries to be created while the machining creates better geometric accuracy and surface finish. While AM processes inherently create parts with high residual stresses that, hybrid manufacturing removes portions of the stressed material [91].

Hybrid manufacturing involves the integration of different manufacturing processes to create products or components. In the context of titanium alloy processing, the hybrid approach can be employed to leverage the unique characteristics of this material and overcome specific challenges. Hybrid manufacturing plays a crucial role in tool molds and reconstruct of pieces with damage areas. For example, die casting molds can be provided with a core made of a bronze alloy and provided with a layer of hot-work tool steel. Or repair of tool molds where material is first applied to a damaged and with a subsequent milling process a finish machining is carried out to restore the original quality of the piece [18].

It is crucial to consider the specific challenges associated with titanium, such as machining difficulty and chemical reactivity, when developing hybrid approaches. The effective integration of processes can result in titanium components with improved properties and enhanced production efficiency [81]. Some hybrid manufacturing approaches for titanium alloys may include:

- Additive Manufacturing with post-processing machining to achieve tight tolerances, remove imperfect surface layers, or refine fine details;
- Integrated welding to join titanium components and machining operations to ensure dimensional accuracy and surface integrity [94];
- Combined hot and cold working to optimize the mechanical properties of titanium. This may include hot forming followed by cold working operations to enhance strength and toughness [95];

- Customized heat treatment such as quenching, tempering, and other treatments to adjust the mechanical characteristics of titanium [96];
- Combination of different AM processes to involve the use of multiple materials or deposition methods to create more complex components.
- However, there are also some necessary disadvantages when using a hybrid manufacturing. Some are listed above [97]:
- Residual stresses from additive step can be reviled on the subtractive step;
- Recycling of the powder, liquids and, oils and cutting fluids;
- Protection of the machine (cooling system);
- Training of qualified technicians;
- Costs of the equipment;
- Costs of the powder metal;
- High setup time;
- Possibility of interference of the cutting or milling fluids.

A SWOT analysis was conducted to provide a concise assessment of the hybrid manufacturing setting of titanium alloys, particularly Ti6Al4V, focusing on its development and expansion, as illustrated in Table 4.

Table 4. SWOT analysis about hybrid manufaturing Ti alloys.

	Positive Factors	**Negative Factors**
Internal factors	**Strengths** Single equipment, high surface quality and dimensional accuracy, reduced time of fabrication.	**Weakness** Residual stress, training, costs, high setup time.
External factors	**Opportunities** Important process in the utilization of Ti alloys. Material waste is minimized, considering more sustainable.	**Threats** Recycling of the powder, liquids and oils and cutting fluids. Possibility of interference of the cutting or milling fluids.

The technology is promising, but still faces significant internal challenges. The technology's Strengths, such as high surface quality and dimensional accuracy, demonstrate its capability to produce high-performance parts. However, the listed Weaknesses—residual stress, high costs, and long setup times—suggest that the technology is not yet fully optimized. These factors limit its widespread adoption and make it more suitable for prototypes and niche parts. The technology aligns with sustainability trends. The highlighted Opportunities—"utilization of Ti alloys" and "minimization of material waste"—indicate that titanium additive manufacturing can be a more sustainable process than traditional methods. Waste reduction is a key competitive advantage.

The technology faces external barriers. The Threats demonstrate that the production process is not a closed loop. Reusing materials such as powder, liquids, and cutting fluids remains a challenge. Furthermore, the interference of cutting and milling fluids suggests that the technology is not immune to the common problems of traditional machining. While the technology offers clear advantages in terms of quality and sustainability, costs, complexity, and waste issues still represent significant barriers. Future research should focus on mitigating these negative factors to enable the technology to reach its full potential.

The field of Hybrid Manufacturing of titanium alloys (specifically Ti6Al4V) presents an inherent contradiction that requires critical analysis. The ability to produce complex geometries and save material is the main promise of Additive Manufacturing, as seen in Figure 3. However, this benefit is frequently undermined by the demands of post-processing. Despite the design advantages of AM, Ti components produced by SLM and WAAM are not usable in their as-built form. High residual stress (characteristic of SLM and WAAM, Table 2) and low dimensional accuracy (Table 3) make post-processing (e.g., heat treatment and CNC machining) a mandatory, rather than optional, step. The cost and complexity of the manufacturing cycle are significantly increased. The high waste rate generated by CNC machining to correct surface roughness and achieve dimensional tolerances mitigates the material savings initially achieved by AM.

The majority of research views AM and post-processing as distinct entities. The ensuing machinability and tool wear are significantly influenced by the distinctive, anisotropic microstructure of Ti6Al4V after AM, which is a consequence of high cooling rates. A critical analysis that examines the direct correlation is lacking: how the optimal subsequent CNC machining parameters are influenced by the surface hardness and the various stressrelieving heat treatments. This interdependence is a central focus of hybrid manufacturing and is largely unexplored in the literature.

The optimization of hybrid systems is inefficient due to its dependence on physical trial and error. A bottleneck exists due to the absence of real-time monitoring and predictive tools. It is imperative to surpass descriptive process comparison and employ sophisticated modeling (e.g., Machine Learning) to predict the final result (mechanical properties) of the component and quantify synergy, thereby reducing the development cycle. The true innovation in the hybrid manufacturing of Ti alloys is not only the physical fusion of technologies, but also the development of an integrated optimization model that treats AM and post-processing as a single, interdependent manufacturing cycle, thereby resolving the contradiction between structural integrity requirements and design complexity.

In the final analysis, the genuine potential of Hybrid Manufacturing for titanium alloys is to resolve the dichotomy between the precision and integrity requirements of post-processing and the design advantages of AM (complex geometries). The literature and industrial practice show a contradiction: the material savings of AM are counterbalanced by the high costs and waste produced by the mandatory need for machining and tension alleviating. Consequently, the field's advancement is contingent upon the development of integrated optimization models that treat the post-AM microstructure and machining parameters as a single, predictive, and unified manufacturing cycle. This transition from descriptive comparison to synergistic and economically viable optimization is essential.

3. Conclusions

Based on the in-depth review of the manufacturing, characteristics and applications of titanium alloys, particularly in the context of hybrid manufacturing and post-processing systems, the main conclusions and contributions of this study are concisely presented:

- Titanium alloys are vital in transforming several sectors owing to their distinctive amalgamation of features;
- Machining titanium alloys can be challenging due to toughness and wear resistance, leading to increased tool wear and machining time;
- Additive manufacturing techniques, like Selective Laser Melting (SLM) and EBM, have become prominent in the aerospace sector for producing intricate components with low production volumes and reduced weight;
- Hybrid manufacturing, which integrates additive and subtractive methods, is investigated to enhance production efficiency, realize intricate designs, and refine surface quality;
- The post-processing of titanium alloys is crucial and encounters hurdles including machining difficulties, oxidation in oxygen-rich environments, and the necessity for heat treatment;
- Although porosity and columnar grain structure are known to affect machining, there is still a lack of predictive models that correlate these microstructures with cutting forces and tool wear. This is essential for optimizing post-processing parameters;
- The lack of studies on the impact of low-temperature post-processing on the biocompatibility of the titanium alloy Ti6Al4V is a critical gap, especially for biomedical applications. Researchers need data on how heat and surface treatments affect cell adhesion and immune response;

A thorough review of the challenges and opportunities of hybrid manufacturing establishes a solid foundation for the next phase of development. Trends identified in the literature and limitations of current processes—especially regarding residual stress management and surface roughness—clearly indicate future research priorities. To enhance the efficiency and quality control of the hybrid system, future research should prioritize integrating artificial intelligence and machine learning. These tools are essential for the predictive optimization of post-processing parameters because they enable precise predictions of microstructure and mechanical properties, thereby reducing the need for costly physical testing. Moreover, the development and implementation of real-time sensor systems for post-processing monitoring can yield crucial data for quality control and ongoing process enhancement.

An alternative promising approach involves the exploration of emerging technologies in the field of machining, such as laser or electrochemical machining, in conjunction with additive manufacturing to achieve superior surface quality with greater efficiency. Ultimately, the potential of hybrid manufacturing for titanium alloys is vast. The systematic combination of AM and post-processing is key to creating complex components with innovative geometries that are impossible to produce using traditional methods. This advancement is essential to opening doors in critical sectors—such as aerospace, automotive, energy, and biomedicine—and to creating a new framework of knowledge that empowers the industry to develop high-performance, safe, and efficient products.

Author Contributions

N.P.V.S: conceptualization; F.J.G.S., A.P., I.I., I.M.P.: methodology; N.P.V.S., F.J.G.S.: data curation, visualization; F.J.G.S., A.P., A.B., I.M.P.: writing—original draft preparation; N.P.V.S.: investigation; F.J.G.S., A.P., A.B., I.M.P: supervision; A.P., I.I.: validation; F.J.G.S., I.I., A.B., I.M.P.: writing—reviewing and editing. All authors have read and agreed to the published version of the manuscript.

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No AI tools were utilized for this paper.

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