Ti-6Al-4V ELI Alloy: Properties, Recent Developments, and Applications Across Industries

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ABSTRACT

This study provides a review study of Ti-6Al-4V ELI alloy, including its mechanical and chemical properties, biocompatibility, and process integration. As a variant of the Ti-6Al-4V family, this alloy is developed for specific applications in aerospace, biomedical, and other industries. The research discusses into the alloy's chemical composition, mechanical properties, and comparisons with other titanium alloys. It also explores technological advancements, applications, and future development areas, highlighting the alloy's potential and sustainability aspects. The findings of this study offer valuable insights for material selection and design optimization in various industrial applications. Furthermore, this research contributes to the ongoing development of advanced titanium alloys for critical engineering applications, emphasizing the importance of Ti-6Al-4V ELI alloy in meeting the demands of high-performance industries

Keywords: Ti-6Al-4V ELI, Chemical, Mechanical, Biocompatibility, Oxides and treatment.

1. INTRODUCTION

Titanium is located in the 4th period and 4th group of the periodic table, with an atomic number of 22. It is the 9th most abundant element in the Earth's crust. Titanium is the fourth major structural metal, following aluminum, iron, and magnesium. This abundance, surpassed only by aluminum, iron, and magnesium[1], makes titanium a significant material for various applications. The production of titanium alloys involves a multi-step process, which begins with the extraction of titanium ore (Fig. 1).

Titanium is primarily found in the Earth's crust in the form of titanium oxide, which occurs in crystallized structures, mainly in the rutile and anatase forms, with brookite being less common. Titanium is predominantly available as titanium oxide, and the process of obtaining it in its pure form involves several steps, including crushing, separation, titanium chlorination, reduction, melting, and casting. In contrast, Anatase features a slightly different arrangement. Furthermore, brookite has an orthorhombic crystal structure. These distinct crystal structures significantly influence the optical, electrical, and photo catalytic properties of titanium oxides, making them versatile materials for various applications.

The ingot is then alloyed with other elements to enhance its properties. It is subsequently forged and rolled into the desired shape. Finally, the alloy is heat-treated to achieve the required properties. The production of titanium metal involves several key steps. First, titanium oxides ore is crushed and ground into a fine powder. Next, the powder undergoes separation of titanium-bearing minerals. Then, the resulting material is subjected to chlorination and purification, producing high-purity titanium tetrachloride. Finally, the tetrachloride is reduced to titanium metal, which is melted and cast into an ingot.

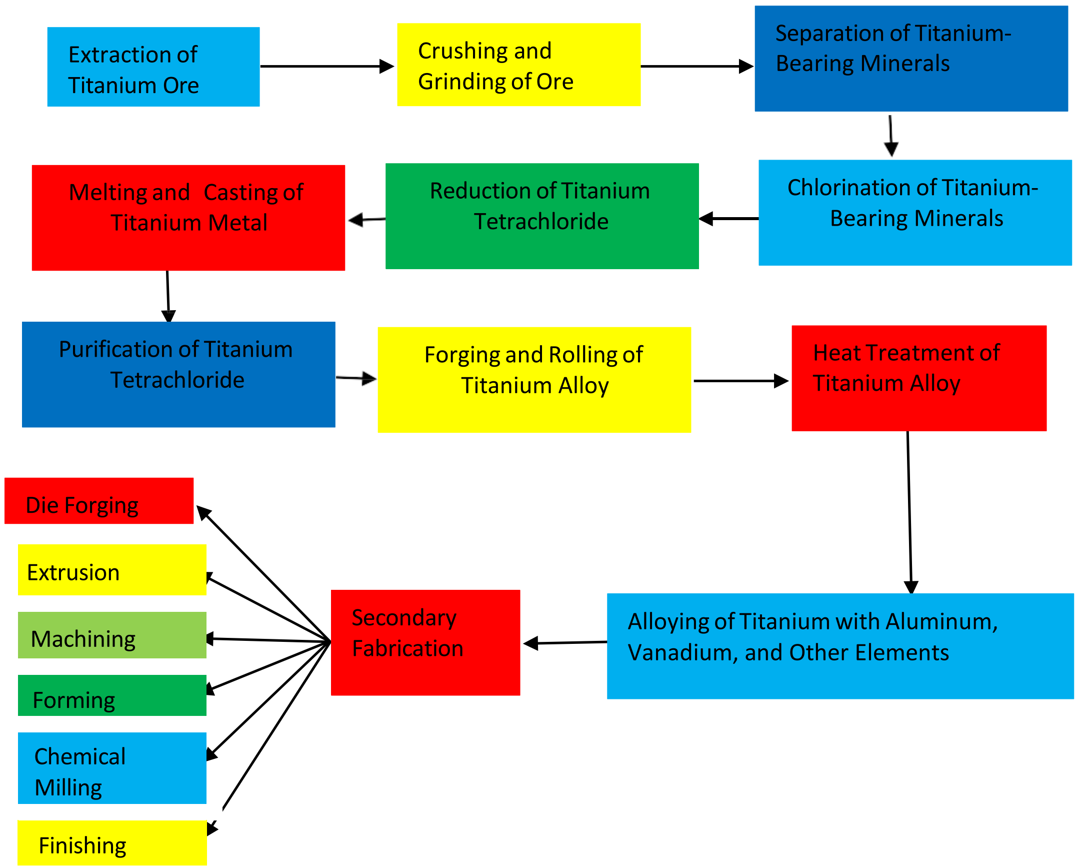


Figure 1: Flow diagram for the titanium alloy production process form ore

The alloy then undergoes secondary fabrication processes, including die forging, extrusion, forming, machining, chemical milling, and finishing. These processes are followed by rigorous inspection and testing to ensure the alloy's quality and reliability. Titanium alloys exhibit a unique crystalline structure, which transforms from a hexagonal close-packed (hcp) arrangement (α-titanium) to a body-centered cubic (bcc) structure (β-titanium) at high temperatures (Fig. 2).

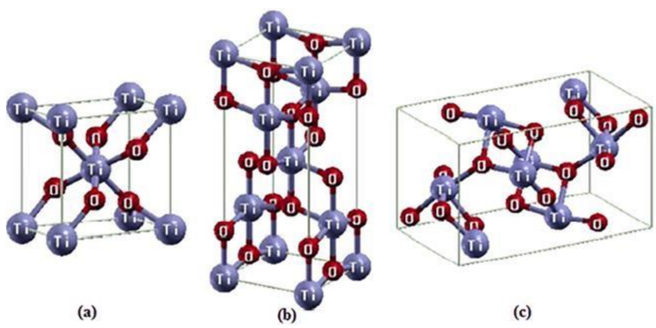
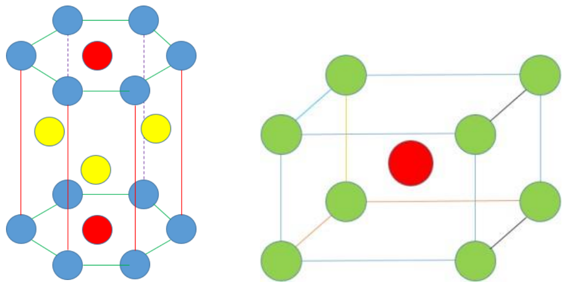


Figure 2: Titanium Oxides Crystal structure (a) Rutile (b) Anatase and (c) Brookite [2]

The α-phase has a hexagonal close-packed structure, while the β-phase has a body-centered cubic structure, affecting their ductility and deformability. The production of titanium metal involves several steps, including crushing and grinding titanium oxide ore, separating titanium-bearing minerals, chlorinating and purifying the resulting material, reducing the tetrachloride to titanium metal, and melting and casting the metal into an ingot [5]. The alloy then undergoes secondary fabrication processes, such as die forging, extrusion, forming, machining, chemical milling, and finishing, followed



(a) (b)

Figure 3: Crystal structure of (a) HCP (α) and (b) BCC (β) phase.

Titanium alloys exhibit a unique transformation between two crystal structures: alpha (α) and beta (β). At high temperatures, the alpha phase transforms into the beta phase. This transformation occurs at 882°C for pure titanium. The crystal structure of titanium alloys affects their properties, including deformation, diffusion rates, and mechanical behavior direction [3], [4]. The alpha phase has a hexagonal crystal structure, while the β-phase has a cubic structure. The α-phase is less ductile than the beta phase. By controlling the alloy's composition and heat treatment, manufacturers can create titanium alloys with specific properties [6]. The properties of titanium alloys depend on two main factors: composition and microstructure. The composition affects the properties and proportions of the α and β-phases. Titanium alloys can be classified into three categories: neutral, α-stabilizers, and β-stabilizers. For example, Ti-6Al-4V is a widely used alloy that contains alpha-stabilizers like aluminum and vanadium. This alloy offers high strength, low density, and good corrosion resistance. β-stabilizers like vanadium and molybdenum are used in other alloys to provide high strength, toughness, and resistance to fatigue. The (α+β)-alloys, such as Ti-6Al-4V, contain a combination of α and β-stabilizers, providing a balance of strength, toughness, and corrosion resistance. Titanium alloys can be broadly classified into alpha (α) and beta (β) alloys. α-Alloys, such as Ti-5Al-5Sn-2Zr-2Mo, contain high amounts of alpha-stabilizing elements and small amounts of beta-stabilizing elements, providing improved strength and toughness. Conversely, β-Alloys, such as Ti-10V-2Fe-3Al, contain high amounts of beta-stabilizing elements and small amounts of alpha-stabilizing elements, offering improved corrosion resistance and weldability [7]. Each type of titanium alloy has its unique properties and applications as discussed in next sections, and the selection of the appropriate alloy depends on the specific requirements of the intended use. The alloying element chemical composition also influence the properties of Ti-alloys. This alloy offers an excellent balance of strength, corrosion resistance (the ability to withstand degradation from environmental factors), and weldability (the ability to join the alloy using welding techniques). As a result, Ti-6Al-4V is widely used in aerospace (e.g., engine components), medical (e.g., implants), and industrial applications (e.g., chemical processing equipment).

2. PROPERTIES OF TI-6AL-4V ELI ALLOY

In this section, a review on Ti-6Al-4V ELI (Extra Low Interstitials) discussed in detail based on mechanical and chemical properties. This alloy is an advanced version of the widely used Ti-6Al-4V alloy, specifically engineered to exhibit superior performance in critical applications, such as aerospace, biomedical devices and high-performance engineering.

2.1. Chemical composition

Ti-6Al-4V ELI alloy is a high-performance titanium alloy. Its unique properties stem from the reduced levels of interstitial elements, including oxygen, nitrogen, carbon, and iron, (Table 1) which significantly influence its mechanical properties and transformation kinetics [3], [8].

Table 1: The chemical composition of Ti-6Al-4V ELI

Element	Titanium (Ti)	Aluminium (Al)	Vanadium (V)	Iron (Fe)	Oxygen (O)	Carbon (C)	Hydrogen (H)
Content (wt. %)	90.0–94.0	5.5–6.8	3.5–4.5	≤ 0.25	≤ 0.13	≤ 0.08	≤ 0.015

This alloy is specifically engineered to address the limitations of standard Ti-6Al-4V, particularly brittleness at cryogenic temperatures, by limiting the oxygen content to a maximum of 0.13%. As a result, it is optimized for extreme conditions, withstanding temperatures as low as -423°F (-253°C) in its annealed state. The reduced levels of interstitial elements enhance its performance under extreme conditions [9] [10].

2.1.1. Impact of Interstitial, Aluminium and Vanadium Elements:

Titanium alloys' strength and brittleness are affected by interstitial elements like oxygen and nitrogen. While these elements can enhance strength at high temperatures, excessive amounts can compromise ductility, particularly at low temperatures. [3], [8]. This reduction also enhances corrosion resistance, ideal for applications involving exposure to harsh environments [11]. The aluminium and vanadium play crucial roles in determining titanium alloys' microstructure and mechanical behaviour. Aluminium stabilizes the α- phase, increasing strength and oxidation resistance, while vanadium stabilizes the β-phase, improving ductility and hot workability [12]. [13]. The combination of these alloying elements results in a balanced mix of properties, enabling the alloy to withstand various operational conditions. For example, controlling the α/β-phase ratio ensures an optimal balance of toughness and machinability. The fine-tuning of these elements also mitigates stress concentration effects, enhancing the fatigue life of critical parts. Aluminum acts as a strong α-stabilizer, elevating the β-transus temperature and allowing for a broader operating range in applications subjected to thermal stress. Vanadium, as a β-stabilizer, enhances the alloy's ability to withstand rapid quenching and subsequent aging treatments, resulting in a finely dispersed secondary α-phase within the β matrix [10].

2.1.2. Impact of Trace Elements and Impurities:

Even trace elements and impurities have a profound impact on its performance. Iron present in very small amounts (≤ 0.25 wt. %), iron contributes to overall strengthening by participating in solid solution and microstructural refinements. However, excessive iron can result in the formation of brittle intermetallic phases, which are detrimental to ductility. Carbon typically limited to ≤ 0.08 wt. %, carbon enhances hardness and strength by forming fine titanium carbide (TiC) particles. Over the limit, it can lead to embrittlement. Hydrogen content is restricted to ≤ 0.015 wt. % to prevent hydrogen embrittlement, which can lead to premature failure under stress. By limiting these impurities, Ti-6Al-4V ELI maintains a uniform and fine-grained structure, vital for high-performance applications [9]. The chemical composition of Ti-6Al-4V ELI ensures precise microstructural manipulation, which is critical for optimizing its dual-phase (α+β) structure. The α-phase (HCP) provides excellent strength and creep resistance, while the β-phase (BCC) contributes to enhanced ductility and workability [6].

2.1.3. Chemical Composition Comparison with Other Ti-Alloys:

The chemical composition of this alloy is meticulously designed to meet the stringent requirements of critical applications in aerospace and biomedical fields.

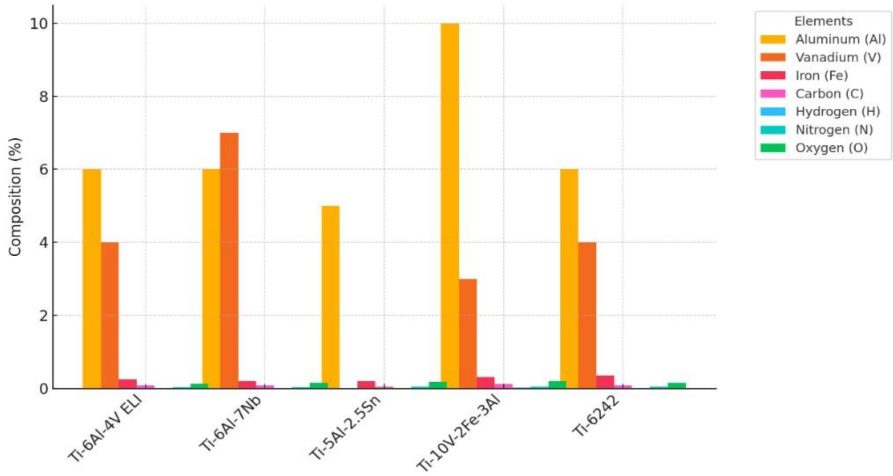


Figure 4: Chemical composition comparison of Titanium alloys

The Chemical composition comparison of Titanium alloys is shown in (Fig. 4). Unlike other α+β alloys such as Ti-6Al-2Sn-4Zr-6Mo, which tolerate slightly higher oxygen levels due to less critical toughness demands in aerospace components, this alloy strictly limits oxygen content to enhance ductility and toughness for biomedical applications [14]. The controlled hydrogen content prevents embrittlement, a common issue in alloys like Ti-5Al-2.5Sn, which prioritize corrosion resistance over toughness and permit slightly higher nitrogen tolerances [15].

The alloy restricts carbon to a maximum of 0.08%, ensuring material homogeneity and preventing carbide precipitation that could otherwise compromise mechanical properties. In contrast, β-titanium alloys such as Ti-10V-2Fe-3Al allow higher carbon levels to prioritize strength over biocompatibility [12]. The Aluminium, and α-phase stabilizer, increases tensile strength while maintaining a low density for weight-sensitive applications. Additionally, aluminium enhances resistance to oxidation and creep. Ti-6Al-4V ELI's 6% aluminium content balances strength and formability, making it superior to β-alloys like Ti-13V-11Cr-3Al, where aluminium content is lower, resulting in reduced corrosion resistance and biocompatibility [7]. The Vanadium in this alloy stabilizes the β-phase, contributing to the alloy's toughness and process ability. The 4% vanadium content ensures an optimal balance between strength and workability. While alloys like Ti-6Al-7Nb replace vanadium with niobium to address potential toxicity concerns in biomedical implants, this substitution often compromises mechanical properties, particularly fatigue resistance, making this more favourable for load-bearing applications [16]. The Iron content in this alloy is limited to 0.25%, ensuring adequate strength without sacrificing ductility. Other α+β alloys such as Ti-6242 allow slightly higher iron content to improve high-temperature performance, albeit at the expense of toughness [14]. Silicon, occasionally added in other titanium alloys to refine grain structures, is kept minimal in Ti-6Al-4V ELI to avoid embrittlement during fabrication, ensuring consistency in biocompatibility and mechanical performance [12]. The superior corrosion resistance of Ti-6Al-4V ELI is due to its ability to form a stable and protective titanium oxide (TiO_2) layer in biological environments. This passive film provides better corrosion resistance in body fluids compared to other alloys like Ti-13Nb-13Zr or TNTZ, making Ti-6Al-4V ELI more reliable for long-term implantation [17]. The low interstitial element content minimizes immune responses, while the alloy's surface properties promote superior osseointegration compared to β-alloys with a higher modulus of elasticity. This balance between rigidity and flexibility is crucial for orthopaedic implants, ensuring structural compatibility with bone tissues [18]. Ti-6Al-4V ELI remains the preferred choice for applications requiring a harmonious balance of strength, toughness, and safety.

2.2. Mechanical Properties

Ti-6Al-4V ELI alloy's unique blend of properties makes it a crucial material in industries that demand high performance, reliability, and safety. Its notable characteristics include a high strength-to-weight ratio, ductility, and resistance to corrosion and crack propagation. In terms of ductility and hardness, Ti-6Al-4V ELI alloy offers a desirable combination. The percentage application of this alloys if shown in (Fig.5). Its hardness is lower than that of Ti-5553, but higher than β-Ti alloys like Ti-15V-3Cr-3Al-3Sn [9].

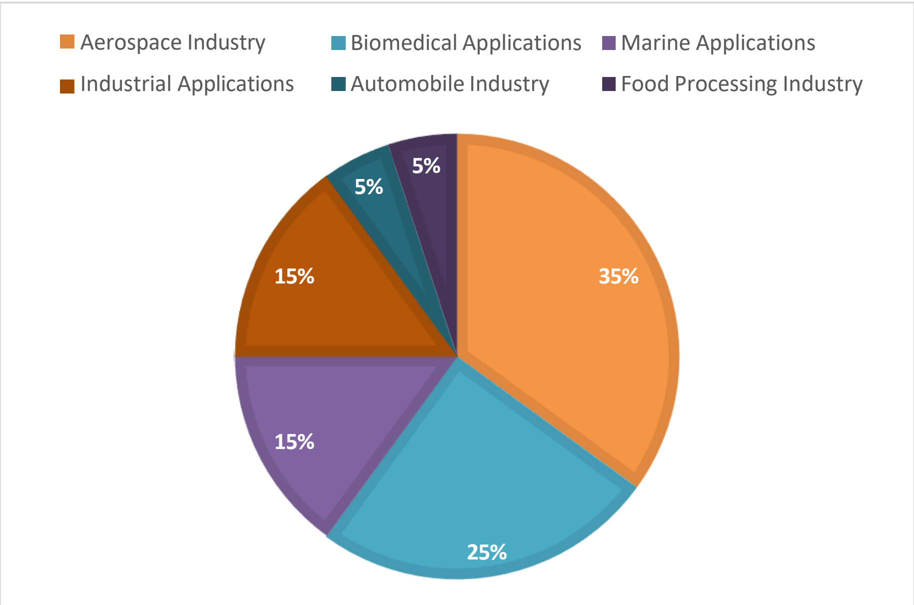


Figure 5. Ti-6Al-4V ELI percentage application in various fields

Compared to standard Ti-6Al-4V, Ti-6Al-4V ELI alloy has lower hardness but higher ductility, making it less prone to brittle failure [19]. The alloy's balance of ductility and hardness makes it suitable for demanding applications. Its enhanced ductility ensures resilience under cyclic loading, while its reduced brittleness contributes to a higher fatigue life. This makes Ti-6Al-4V ELI alloy an ideal choice for aerospace and biomedical implants [20]. Ti-6Al-4V ELI alloy shows improved creep resistance compared to standard Ti-6Al-4V. This is due to its lower interstitial content, which reduces the formation of brittle phases. As a result, Ti-6Al-4V ELI alloy maintains its structural integrity better under sustained loads.

In practical terms, this means Ti-6Al-4V ELI alloy can withstand moderate to high temperatures with relatively low creep rates [7]. However, its creep resistance is still limited compared to specialized high-temperature alloys [21], [22]. This alloy also demonstrates superior fatigue resistance under cyclic loading [23]. Its improved microstructure and reduced interstitial elements help it resist repeated stresses more effectively [13]. The alloy's high strength-to-weight ratio is crucial in aerospace applications [6]. With tensile strengths ranging from 895 to 980 MPa and yield strengths of 825 to 880 MPa, it provides robust mechanical performance. The alloy's light weight and excellent strength reduce energy consumption in aerospace applications [10]. The tensile strength of Ti-6Al-4V ELI alloy can be further improved through optimized heat treatment processes and microstructural refinement. Its improved toughness makes it more suitable for applications where resistance to crack propagation is critical[22], [25].

Table 2: Application of Ti-6Al-4V ELI industry and properties

Industry	Applications	Key Properties	References
Aerospace	Turbine blades, discs, airframes, engine mounts, lightweight parts for aircraft and spacecraft	High strength-to-weight ratio, fatigue resistance, corrosion resistance, thermal stability	[28]
Biomedical	Implants (hip, knee, dental), prosthetics, surgical tools	High fatigue resistance, biocompatibility, corrosion resistance, compliance with ASTM F136	[27], [28]
Marine	Ship structures, underwater equipment, marine fasteners	Seawater corrosion resistance, durability, and high strength	[29], [30]
Automobile	Engine parts (connecting rods, valves), safety components (roll cages, chassis), and interiors	Lightweight, corrosion resistance, excellent machinability	[31]
Food Processing	Equipment for pasteurization and sterilization, machinery exposed to acids and cleaning agents	Corrosion resistance, non-toxicity, and ease of maintenance	[22], [32]

Ti-6Al-4V ELI alloy's fatigue resistance is notable, performing well under repeated loading at various temperatures [33]. This property is beneficial in biomedical applications, where implants undergo cyclic stresses during physical activity. The alloy's high fatigue strength and refined microstructure enable it to withstand cyclic loads. Ti-6Al-4V ELI alloy demonstrates improved fatigue resistance compared to standard Ti-6Al-4V. While titanium alloys are not naturally wear-resistant, Ti-6Al-4V ELI's surface properties can be enhanced through treatments. These modifications improve the alloy's ability to withstand wear, making it suitable for biomedical implants and mechanical components. Ti-6Al-4V ELI alloy exhibits high wear resistance, with a low wear rate in dry sliding conditions. Improved wear resistance reduces debris generation, minimizing the risk of inflammatory responses in surrounding tissues. The alloy's corrosion resistance is another critical factor in its widespread use. Ti-6Al-4V ELI alloy exhibits excellent resistance to harsh environments, including seawater and body fluids, due to its stable oxide layer. Other titanium alloys, such as Ti-5Al-2.5Fe, Ti-6Al-7Nb, and Ti-15Mo, also exhibit excellent corrosion resistance. Their corrosion resistance is influenced by alloying elements, microstructure, and surface properties. Ti-6Al-4V ELI alloy's ability to withstand repeated loading is also crucial. It performs well at various temperatures, ensuring reliability under thermal cycling. In biomedical applications, implants made from this alloy endure cyclic stresses during physical activity. The alloy's high fatigue strength and refined microstructure enable it to withstand cyclic loads[23]. Compared to standard Ti-6Al-4V, Ti-6Al-4V ELI alloy demonstrates enhanced fatigue resistance. Its reduced interstitial content results in a more uniform microstructure [30], [34]. While titanium alloys aren't naturally wear-resistant, Ti-6Al-4V ELI's surface properties can be enhanced through treatments. These modifications improve the alloy's ability to withstand wear as (Table 2) shows various industry Application of Ti-6Al-4V ELI based on its properties. The alloy exhibits high wear resistance, with a low wear rate in dry sliding conditions. Improved wear resistance reduces debris generation, minimizing the risk of inflammatory responses [35], [36]. Thermal oxidation studies have shown significant improvements in wear resistance and frictional performance. These enhancements contribute to the alloy's longevity and reliability conditions [35].

2.3. Biocompatibility and Osseo-integration

Ti-6Al-4V ELI alloy is widely used in biomedical applications due to its biocompatibility. Its composition ensures superior integration with bone tissue and minimal cytotoxicity [37]. The alloy's oxide layer prevents the release of harmful ions, reducing toxicity risks. This layer also promotes osseointegration, fostering a direct bond between the implant and bone tissue. Ti-6Al-4V ELI alloy's biocompatibility makes it suitable for orthopaedic and dental implants. However, concerns about toxicity persist[38], [39], particularly regarding aluminium and vanadium[17], [40]. The other biocompatible Ti-alloys such as Ti-6Al-7Nb and Ti-13Nb-13Zr are specialized for implants but fall short in structural applications where strength and durability are vital [8], [41], [42]. Alternative alloys and surface treatments have been developed to address these concerns. Replacing vanadium with niobium improves biocompatibility, while surface treatments enhance corrosion resistance and minimize metal ion release. While β-alloys such as TNTZ and Ti-13Nb-13Zr are prized for their lower modulus of elasticity, which closely matches that of human bone, they often lack the high tensile strength and fracture toughness required for load-bearing applications. This optimized chemical composition and refined microstructure of this alloy ensure it excels for biocompatibility [15], [18]. These strategies improve the biocompatibility of Ti-6Al-4V ELI alloy and extend its applicability to sensitive patient groups[43].

Ti-6Al-4V ELI alloy is recognized as one of the most biocompatible titanium alloys due to its low toxicity, superior corrosion resistance, and excellent integration with bone tissue. Its composition enhances not only its mechanical properties but also its interaction with biological systems, ensuring superior osseointegration and reduced cytotoxicity. The alloy’s ability to maintain structural integrity in physiological environments makes it a gold standard for biomedical applications such as hip prostheses, dental implants, and orthopaedic devices. Among (α+β)-alloys, Ti-6Al-4V ELI strikes a remarkable balance between mechanical properties and biocompatibility. Its oxide layer, primarily composed of titanium dioxide (TiO_2), serves as a stable and inert barrier, preventing the release of harmful ions into surrounding tissues. This layer not only enhances corrosion resistance but also promotes osseointegration by fostering a direct bond between the implant and bone tissue. This property is critical for long-term stability and implant longevity, as it minimizes the risk of loosening or failure over time. The phenomenon, where implants with a much higher modulus of elasticity than bone lead to bone resorption, is a common issue with stiffer materials Comparatively, while alloys like Ti-15Mo and Ti-6Al-7Nb also demonstrate excellent corrosion resistance and biocompatibility, their performance in dynamic load environments and under high cyclic stress is often inferior to that of Ti-6Al-4V Studies have shown that manufacturing processes, including surface finishing techniques such as machining and polishing, significantly influence the biocompatibility of titanium alloys. The surface roughness and topography directly impact cell adhesion and proliferation, making it essential to optimize these parameters to enhance the performance of implants. Ti-6Al-4V ELI's superior response to surface treatments further solidifies its status as a leading choice for biomedical applications [9]. This biocompatibility makes it an ideal material for orthopaedic and dental implants, where the alloy must interact seamlessly with bone and soft tissues. The Osseointegration, a critical factor for implant success, is significantly enhanced by Ti-6Al-4V ELI's surface properties. This offers resistance to corrosion in the physiological environment. This resistance is crucial for ensuring that the alloy remains structurally intact over time, even under constant exposure to body fluids. At the same time, some serious concerns about this alloy is the potential toxicity of its alloying elements persist. The Aluminium, a key component, has been linked to neurotoxicity with prolonged exposure, while vanadium is associated with cytotoxic effects at high concentrations However, the naturally occurring titanium dioxide oxide layer on the alloy's surface significantly mitigates these risks. Allergic reactions to titanium alloys, although rare, have been reported, particularly in individuals with metal hypersensitivity. These reactions can manifest as localized inflammation or dermatitis. The oxide layer plays a crucial role in minimizing these risks, making Ti-6Al-4V ELI one of the safest options for medical implants. By acting as a protective barrier, this layer prevents the release of harmful ions, reducing the likelihood of toxicity To address concerns about toxicity, alternative alloys such as Ti-6Al-7Nb and Ti-13Nb-13Zr have been developed. These alloys replace vanadium with niobium, a non-toxic element, and further improving biocompatibility. Additionally, surface treatments like anodization and hydroxyapatite coating have been explored to enhance corrosion resistance and minimize metal ion release. These strategies not only improve the biocompatibility of Ti-6Al-4V ELI but also extend its applicability to more sensitive patient groups [50].

2.4. Comparison with Other Ti-Alloys

A comparison of the mechanical properties of this alloy with other Ti-alloys is demonstrated in this section (Table 3). Ti-6Al-4V offers higher strength ranges as in (Fig. 6) at high temperature compare to other but slightly reduced ductility, favoring structural aerospace applications where weight and strength are critical. Ti-5Al-2.5Sn is notable for its excellent corrosion resistance and moderate mechanical strength, making it suitable for cryogenic and high-temperature environments. The beta alloys, such as Ti-10V-2Fe-3Al and Ti-15Mo-3Al-2.7Nb, exhibit exceptional strength and corrosion resistance due to their beta-phase stabilization, with applications in landing gear and chemical processing. Ti-6Al-7Nb and Ti-13Nb-13Zr emphasize biocompatibility and low elastic modulus, making them ideal for load-bearing biomedical implants.

Table 3. Comparison of Mechanical Properties of Titanium Alloys

Material	Tensile Strength (MPa)	Yield Strength (MPa)	Hardness (HRC)	Elongation (%)	Reference
Ti-6Al-4V ELI	895 – 980	825 – 880	30 – 36	12 – 15	[44]
Ti-6Al-4V	895 – 1,100	830 – 1,000	33 – 38	10 – 14	[45] [12]
Ti-5Al-2.5Sn	830 – 960	690 – 850	28 – 33	8 – 12	[7]
Ti-3Al-2.5V	620 – 760	540 – 655	24 – 28	15 – 20	[7] [12]
Ti-10V-2Fe-3Al	1,240 – 1,400	1,100 – 1,250	36 – 44	10 – 12	[1]
Ti-15Mo-3Al-2.7Nb	900 – 1,000	800 – 900	28 – 34	12 – 18	[6] [12]
Ti-6Al-7Nb	860 – 950	795 – 850	30 – 35	10 – 14	[1]
Ti-13Nb-13Zr	790 – 890	740 – 820	25 – 30	15 – 20	[1] [12]

The table underscores the versatility of titanium alloys in meeting diverse performance requirements across industries, supported by authoritative sources like ASTM standards and leading materials handbooks.

Although ultra-high-strength alloys like Ti-10V-2Fe-3Al are stronger, they lack the ductility and versatility of Ti-6Al-4V ELI, limiting their use in safety-critical or cyclic loading scenarios. Biocompatible alloys such as Ti-6Al-7Nb and Ti-13Nb-13Zr are specialized for implants but fall short in structural applications where strength and durability are vital. Additionally, Ti-6Al-4V ELI's hardness range (30–36 HRC) ensures excellent wear resistance without compromising machinability, and its exceptional corrosion resistance enhances performance in marine and biomedical environments.

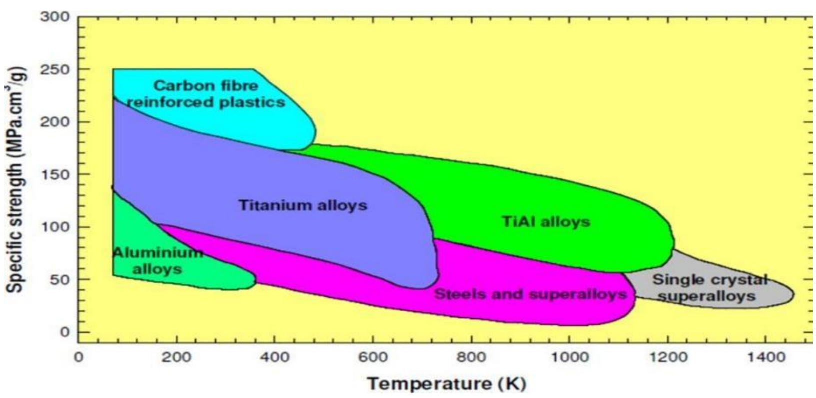


Figure 6: A plot of specific strength of titanium alloys against the thermal strength of other structural materials [46]

When compared to other titanium alloys, Ti-6Al-4V ELI exhibits competitive and often superior strength characteristics, including high yield strength (900-1000 MPa), high ultimate tensile strength (1000-1100 MPa), excellent fatigue resistance, and good creep resistance, making it a versatile and reliable choice for demanding applications in aerospace, biomedical, and other industries.Ti-6242 and Ti-6Al-4V ELI are both high-strength titanium alloys with similar applications, but they exhibit distinct differences in their mechanical properties. While Ti-6242 boasts slightly higher strength (950- 1000 MPa), Ti-6Al-4V ELI surpasses it in terms of ductility (12-15% elongation) and fracture toughness (60-80 MPa/m). This makes Ti-6Al-4V ELI a preferred choice for applications where resistance to crack propagation and fatigue are paramount [6], [12]. This alloy is preferred for applications requiring both high strength and high fracture toughness.

3. TECHNOLOGICAL ADVANCEMENTS

The ELI of this benefits significantly from various surface treatment processes (Venkatesh et al., 2009). These treatment of this alloy can markedly influence its ductility and hardness and other properties. A Summary of Surface Treatment Methods for Enhancing Ti-6Al-4V ELI Alloy Performance is given in Table 4 of this section.

3.1. Surface treatments

Solution Treatment: This process involves heating the alloy to a temperature where the β phase (a high-temperature phase) is stabilized. For Ti-6Al-4V ELI, solution treatment typically occurs at temperatures around 980-1020°C. This step dissolves α and β phases, homogenizing the microstructure and relieving internal stresses [7]. The resulting material often exhibits improved ductility as the alloy becomes more homogeneous and free from the hard, brittle phases formed during casting or fabrication. Solution treatment and annealing processes generally enhance ductility by promoting a more homogeneous microstructure and reducing internal stresses. The β-Phase Stabilization, heat treatment processes aim to stabilize the β phase to improve ductility. This treatment involves heating the alloy to temperatures above the β transus, followed by rapid cooling. By retaining a higher volume fraction of the β-phase, the alloy can achieve higher ductility, though it may sacrifice some hardness and tensile strength [48]. This process is particularly useful in applications where flexibility and resistance to deformation are more critical than hardness.

Annealing: Annealing, in particular, is effective in increasing ductility while maintaining a balance with hardness [49]. Aging treatments can inadvertently reduce ductility in Ti-6Al-4V ELI alloy if the precipitation of hard phases becomes excessive. When aging treatments are applied, hard phases such as α' martensite or α_2 (Ti3Al) precipitate out of the matrix, leading to an increase in hardness. However, if these hard phases precipitate excessively, they can form a brittle network that compromises the alloy's ductility. Anneal heat treatments, which is not readily achievable with standard Ti-6Al-4V or other titanium alloys, such as Ti-6242, thereby solidifying its position as a premier alloy for high-performance applications, making it suitable for damage-tolerant components on aircraft like the F-22 fighter and critical fittings on the Boeing 777 [50]. Annealing and solution treatments provide more controlled hardness levels by adjusting the balance between the α and β phases, allowing for tailored properties to meet specific application requirements [51].

Aging: Aging and β-phase stabilization processes generally increase hardness by precipitating strengthening phases or retaining a higher fraction of the β phase. This enhances the alloy’s ability to withstand mechanical loads but may reduce its ductility [3]. This Surface treatment effectively improve corrosion resistance and reduce ion release rates [52].

Anodization, a widely used electrochemical process, thickens the natural oxide layer on the alloy, offering superior protection against pitting and crevice corrosion, particularly in chloride-rich environments like seawater [53]. This surface treatment restricts the infiltration process by growing a thin oxide layer on the Ti-6Al-4V ELI alloy surface [54]. This enhanced oxide layer also contributes to the alloy's improved wear resistance, which is critical for biomedical implants exposed to physiological fluids.

Sol-gel coatings, a newer technology, offer excellent protection in both acidic and alkaline environments by forming thin, dense films on the alloy's surface. These coatings can also include functional additives for specific applications, such as inhibitors for medical implants [55].

Laser surface treatment, includes laser cladding and laser nitriding, modify the surface microstructure and composition of Ti-6Al-4V ELI, resulting in a refined, hardened surface that enhances both wear and corrosion resistance [56]. These various surface treatments and coatings collectively extend the alloy's durability and effectiveness in challenging conditions, from marine and aerospace environments to biomedical applications, where long-term performance and reliability are essential.

Nitriding, process for Ti-6Al-4V alloy involves exposing the material to nitrogen at elevated temperatures to enhance its wear resistance. While traditional gas nitriding (GN) at 1000 °C can compromise mechanical strength, alternative methods like plasma nitriding and low-temperature gas nitriding at 540 °C offer improved outcomes. Notably, combining LT-GN with slide burnishing can refine surface grains, accelerate nitrogen diffusion, and enhance wear resistance while maintaining core material strength [57]. This is significant because it enables the production of Ti-6Al-4V alloy components with improved surface properties,

For aerospace and biomedical applications, the choice of treatment depends on the specific requirements for properties of alloy. Solution treatment combined with aging is commonly used to achieve high strength while retaining adequate ductility for structural components and implants [58], [59].

Table 4: Summary of Surface Treatment Methods for Enhancing Ti-6Al-4V ELI Alloy Performance

Treatment	Process Overview	Key Effects	Applications	References
Solution Treatment	Heating to 980-1020°C to stabilize the β phase and dissolve α + β phases. Heat treatment above β transus	Homogenizes microstructure, relieves internal stresses, and improves ductility	Structural aerospace components, high-performance implants, damage-tolerant	[7], [51][48]

	temperature, followed by rapid cooling.		components like F-22 fighter	
Annealing	Controlled heating and cooling for stress relief and phase balance	Increases ductility, maintains hardness balance, reduces brittleness	Aircraft fittings (e.g., Boeing 777), biomedical implants	[3], [49], [52]
Aging	Heat treatment to precipitate strengthening phases	Increases hardness, enhances load-bearing capacity, may reduce ductility	High-strength aerospace parts, medical implants requiring load resistance	[3], [52]
Anodization	Electrochemical oxide layer thickening	Enhances corrosion and wear resistance in chloride-rich environments, improves biocompatibility	Biomedical implants, marine applications	[53], [54]
Nitride Coatings	Exposure to nitrogen at elevated temperatures. Physical/Chemical Vapor Deposition (PVD/CVD) for TiN/TiAlN coatings	Provides a hard, inert surface, enhances wear and corrosion resistance. Improves wear resistance, refines surface grains with LT-GN, accelerates nitrogen diffusion	Cutting tools, high-temperature aerospace parts	[61]
Sol-Gel Coatings	Thin, dense films applied via chemical processing	Enhances corrosion protection in acidic/alkaline environments, customizable for applications	Medical implants, industrial corrosion protection	[62] [63] [55]
Laser Surface Treatment	Surface microstructure modification using lasers	Enhances wear and corrosion resistance through surface refinement	Aerospace components, wear-critical surfaces	[56]
Cryogenic Applications	Operation at temperatures near or below liquid nitrogen levels	Enhances fracture toughness, maintains ductility, resists brittle failure	Cryogenic storage tanks, superconducting magnet systems, space applications	[3], [8], [64], [65] [21] [66]

In industrial applications where hardness is a critical factor, such as in tooling, wear-resistant components, or high-wear machinery parts, a combined approach of β-phase stabilization and aging may be employed to enhance the hardness and performance of Ti-6Al-4V ELI alloy under high-stress conditions. This combined approach enables the alloy to withstand the harsh conditions often encountered in industrial environments, including high loads, impact, and abrasive wear, making it an ideal material for demanding applications[67]. Surface treatment technologies for Ti-6Al-4V ELI alloy and other titanium alloys have undergone substantial advancements in recent years, significantly enhancing their performance in various applications, including aerospace, biomedical, and industrial sectors. These advancements have led to improved corrosion resistance, enhanced wear and fatigue properties, and optimized biocompatibility, thereby expanding the range of potential applications for titanium alloys. Furthermore, ongoing research and development in surface treatment technologies, such as anodizing, electroplating, and laser surface modification, are crucial for further improving the properties and expanding the applications of Ti-6Al-4V ELI alloy, enabling the development of new and innovative products that leverage the unique combination of strength, lightweight, and corrosion resistance offered by titanium alloys.

Figure 7: AM–EBM fabricated Ti-6Al-4V complex objects with a Software models[68]

3.2. Additive Manufacturing

The Ti-alloy has emerged as a leading material in additive manufacturing (AM) research and development, with notable advancements in recent years. AM, also known as 3D printing, has transformed the production of complex titanium alloy components by offering enhanced geometric flexibility, reduced material waste, and improved mechanical properties [69], [70]. Ti-6Al-4V ELI alloy has become a prominent material in AM research. AM offers enhanced geometric flexibility, reduced material waste, and improved mechanical properties. The alloy's superior mechanical properties, corrosion resistance, and biocompatibility make it widely used in AM. Other titanium alloys, such as Ti-5Al-2.5Fe and Ti-6Al-7Nb, have also been explored for AM applications. Research has focused on optimizing AM process parameters for Ti-6Al-4V ELI alloy to achieve improved mechanical properties and reduced porosity [27], [31]. The alloy has been explored for biomedical applications, such as implants and surgical instruments. Additively manufactured Ti-6Al-4V ELI alloy implants exhibit superior osseointegration and biocompatibility. The alloy has also been investigated for aerospace and industrial applications [71]. However, challenges such as residual stresses and distortion necessitate careful process optimization. The high cost of Ti-6Al-4V ELI powder and the need for precise control over AM process parameters can increase production costs [38], [72]. The (Fig 7) shows AM–EBM fabricated Ti-6Al-4V complex objects with a Software models Ensuring consistent quality and reproducibility remains a critical challenge, requiring ongoing research to optimize AM techniques.

4. CONCLUSION

Ti-6Al-4V ELI alloy's exceptional mechanical properties make it suitable for demanding applications in aerospace and biomedical fields. Its high tensile strength, fatigue resistance, and fracture toughness are critical for withstanding extreme conditions. The alloy's reduced interstitial content enhances its performance under cyclic loading. It also demonstrates excellent corrosion resistance, making it suitable for harsh environments. Advancements in additive manufacturing and surface treatments extend the alloy's applications and improve its performance. Its versatility and robustness make it valuable across various high-tech and critical sectors. Ti-6Al-4V ELI alloy's superior performance and versatility influence its application across industries. Its mechanical properties make it valuable in aerospace for producing lightweight yet durable components. In the biomedical field, its biocompatibility and corrosion resistance enhance the reliability of implants and prosthetics. Additive manufacturing and surface treatments broaden its utility. To address gaps in research, further investigation is needed in several areas. Standardization of testing methods, long-term performance data, and optimization of manufacturing processes are crucial. Detailed studies on biocompatibility and sustainable production practices are essential. Exploring the environmental impact of the alloy's lifecycle could contribute to eco-friendly and economically viable applications.

Compliance with ethical standards

Conflict of interest:

The author declare that he has no conflict of interest.

Ethical approval

This article does not contain any studies with human participants or animals performed by the author.

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