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Titanium: abundance, properties, recovery from red mud, and applications of a strategic engineering material

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ABSTRACT

Titanium, although abundant in the Earth's crust, holds strategic value due to its exceptional strength-to-weight ratio, corrosion resistance, biocompatibility, and high-temperature performance. This paper reviews the geological distribution, historical discovery, and evolution of titanium's commercial production through the Hunter and Kroll processes. Titanium's allotropic nature enables the development of alpha, beta, and alpha-beta alloys tailored for diverse engineering applications. Key mechanical and chemical properties are analyzed, highlighting titanium's utility in aerospace, biomedical, marine, and chemical industries. Emerging applications and technologies such as additive manufacturing and powder metallurgy are explored for their potential to reduce production costs and enable advanced designs. Furthermore, innovative approaches to titanium recovery from secondary raw materials such as red mud are discussed to address production costs and improve sustainability. Finally, the paper addresses challenges in processing, cost, and sustainability that must be overcome to expand titanium's role in next-generation technologies. Unlike previous reviews that focus on isolated aspects such as alloy development or specific applications, this work uniquely integrates titanium's abundance paradox with the technological and economic barriers in primary production, explores emerging secondary recovery routes from industrial waste streams, and connects these processing challenges to current and future applications. This integrated framework provides a comprehensive perspective on how to advance titanium from an abundant but underutilized element to a more accessible engineering material.

Keywords: titanium, titanium alloys, production, properties, present and future applications.

1. Introduction

According to Figure 1, titanium (Ti) stands as the fourth most abundant structural metal in the Earth's crust, yet it remains one of the most strategically important materials in modern engineering applications (Beus, 1974). Despite its relative abundance, titanium's unique combination of properties has positioned it as a critical material for advanced technological applications. The metal exhibits an exceptional strength-to-weight ratio that surpasses that of most conventional materials, outstanding corrosion resistance that enables its use in severe environments, and remarkable biocompatibility that makes it invaluable for medical applications (Leyens et al., 2003; Ahmedet al., 2014; Fuji et al., 2003)[4].

Previous reviews on titanium have provided valuable insights into specific aspects of this material; however, they predominantly focus on narrow domains either alloy metallurgy and mechanical properties, specific processing technologies, or dedicated application sectors such as aerospace or biomedical engineering (Beus, 1974; Leyens et al., 2003; Ahmedet al., 2014; Fuji et al., 2003; Subasinghe et al., 2022; Khalloufi et al., 2021). Critically, these reviews rarely integrate the economic and energetic challenges of primary production with emerging sustainability solutions, nor do they connect the fundamental abundance-accessibility paradox to strategic material considerations and circular economic approaches. This fragmented landscape leaves a gap in understanding how titanium's extraction challenges, secondary resource recovery, and evolving applications interconnect to shape its future viability as an engineering material. The strategic importance of titanium extends beyond its physical properties to encompass its role in national security, advanced manufacturing, and emerging technologies. As industries continue to demand materials that can perform under increasingly challenging conditions while maintaining structural integrity and durability, titanium has emerged as an indispensable solution for applications ranging from supersonic aircraft to life-saving

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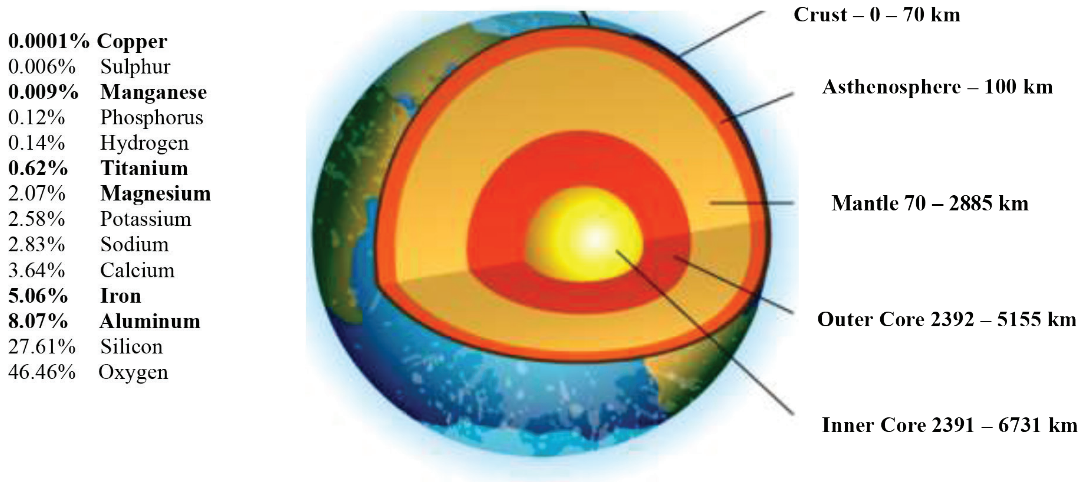

Fig. 1. Distribution of alloying elements in the Earth's crust

medical implants (Leyens et al., 2003; Ahmedet al., 2014; Fuji et al., 2003). However, despite extensive literature on titanium, most reviews address titanium alloys, processing methods, or specific applications in isolation (Leyens et al., 2003; Ahmedet al., 2014; Fuji et al., 2003; Subasinghe et al., 2022; Khalloufi et al., 2021). This review distinctively integrates four critical dimensions: (1) the abundance-accessibility paradox that makes titanium simultaneously common and costly, (2) the evolution and limitations of conventional production technologies, (3) innovative recovery approaches from secondary sources such as red mud that address both sustainability and cost reduction, and (4) the expanding application landscape driven by emerging technologies. By connecting these typically separated topics into a unified narrative, this review provides researchers and engineers with a holistic framework for understanding both current limitations and future opportunities in titanium science and technology.

1.1. Distribution in Earth's Crust

Titanium constitutes approximately 0.57% of the Earth's crust by weight, making it the ninth most abundant element overall and significantly more abundant than many other structural metals, including copper, zinc, and tin. This abundance places titanium in a unique position among high-performance materials, as its absence is not due to natural occurrence but rather to the challenges associated with its extraction and processing (Subasinghe et al., 2022).

The element is primarily found in mineral deposits, such as ilmenite ($FeTiO_3$), which accounts for approximately 92% of titanium ore consumption, as well as rutile (TiO_2) and anatase (TiO_2). Ilmenite typically contains 45–65% titanium dioxide, while rutile contains 95–99% titanium dioxide, making it the preferred source for high-grade titanium production. The largest titanium ore reserves are strategically distributed across several continents, with Australia holding the largest reserves, followed by South Africa, Canada, India, and Norway. China, despite having smaller reserves, has become the world's largest producer of titanium dioxide, primarily for pigment applications (Subasinghe et al., 2022; Khalloufi et al., 2021).

The geographic distribution of titanium resources has major implications for global supply chains and geopolitical issues. The concentration of high-grade rutile deposits in a small number of countries creates potential supply risks, especially for aerospace and defense uses that demand the highest-quality titanium. Although this mineral is abundant in the Earth's crust, titanium's strong affinity for oxygen forms a stable oxide layer, making extraction and purification very difficult and energy-consuming. This significantly increases its cost compared to other structural metals, such as steel and aluminum.

1.2. Major Properties and Applicability

Titanium is a remarkable, silver-colored metal recognized for its exceptional combination of properties that make it indispensable in high-performance applications. With a density of 4.5 g/cm^3, approximately half that of steel, it offers an outstanding strength-to-weight ratio that beats most conventional metals (Beus, 1974; Leyens et al., 2003). This unique balance of low weight and high strength makes titanium an ideal material for applications where structural integrity and weight reduction are critical (Beus, 1974; Leyens et al., 2003; Ahmedet al., 2014). Beyond its superior mechanical properties, titanium exhibits excellent biocompatibility, making it widely used in medical implants, prosthetics, and surgical instruments without adverse reactions in the human body (Beus, 1974; Leyens et al., 2003; Ahmedet al., 2014; Fuji et al., 2003). It is also chemically inert and non-toxic, which, combined with its exceptional corrosion resistance, makes it suitable for applications in aggressive environments and medical applications[4]. Another key advantage of titanium is its remarkable corrosion resistance, even in severe chemical environments including seawater and chlorine-containing solutions. It maintains its integrity in conditions where other metals would rapidly deteriorate (Ahmedet al., 2014; Fuji et al., 2003). With a high melting temperature of 1668 °C, significantly higher than aluminum›s 660 °C, titanium can withstand extreme temperatures while maintaining its structural properties (Beus, 1974; Leyens et al., 2003; Ahmedet al., 2014; Fuji et al., 2003). Furthermore, titanium exhibits outstanding fatigue resistance and can endure repeated stress cycles without failure, making it ideal for aerospace and automotive applications (Leyens et al., 2003; Ahmedet al., 2014; Fuji et al., 2003; Subasinghe et al., 2022; Khalloufi et al., 2021). Its excellent formability allows it to be machined, welded, and shaped into complex geometries, though it requires specialized processing techniques due to its reactive nature at elevated temperatures. These characteristics have established titanium's critical role in industries ranging from aerospace and medical to marine and chemical processing, where performance and reliability are paramount.

In Figure 2, diverse applications of titanium and its alloys across multiple high-performance industries, highlighting their exceptional properties and significance in advanced technology applications[7]: (A) exhaust system (B) engine parts and (C) fasteners & biomedical: (D) complex implants (E) dental implant (F) knee implant (G) hip implant & marine: (H) propeller, (I) heat exchanger & aerospace: (J) exhaust nozzle (K) fan disk (L) fan blades (M) main landing gear.

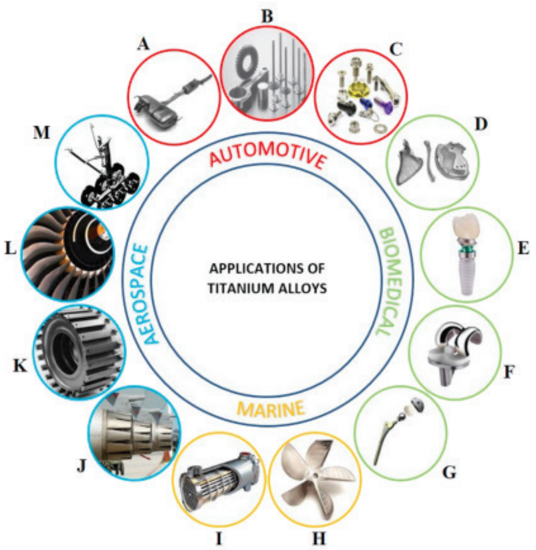

Fig. 2. Diverse applications of titanium and its alloys

Titanium's unique properties stem from its crystal structure and chemical characteristics, which combine to create a material with an extraordinary range of capabilities (Leyens et al., 2003; Ahmedet al., 2014). The exceptional strength-to-weight ratio of titanium alloys represents one of their most significant advantages, with high-strength titanium alloys achieving tensile strengths comparable to those of high-strength steels while maintaining a density approximately 45% lower (Leyens et al., 2003; Ahmedet al., 2014; Fuji et al., 2003). This property makes titanium particularly valuable in applications where weight reduction is critical, such as aerospace structures, automotive performance components, and portable medical devices.

The excellent corrosion resistance of titanium comes from its ability to form a stable, protective oxide layer that forms naturally when exposed to oxygen or moisture (Abakay et al., 2024). This passive oxide film, primarily composed of titanium dioxide, is extremely thin (typically 27 nanometers) but highly effective in shielding the metal beneath from corrosion (David et al., 2016). The oxide layer is self-healing, meaning that if it is damaged, it quickly reforms in the presence of oxygen or water, thereby maintaining the metal's corrosion resistance throughout its entire service life.

Biocompatibility represents another crucial property that sets titanium apart from other structural metals (Leyens et al., 2003). The material is non-toxic and demonstrates excellent compatibility with human tissue, making it the material of choice for orthopedic implants, dental fixtures, and cardiovascular devices (Niinomi, 2008). This biocompatibility is attributed to the stable oxide layer that prevents the release of metal ions into surrounding tissues, combined with the material's low elastic modulus, which more closely matches that of human bone compared to other metallic materials (Yasmin at al., 2013).

Temperature resistance is another significant advantage of titanium alloys, with many maintaining their mechanical properties at elevated temperatures up to 600 °C (Leyens et al., 2003). This high-temperature capability makes titanium essential for aerospace applications, particularly in jet engine components where materials must withstand extreme thermal conditions while maintaining structural integrity. The material's low thermal expansion coefficient, approximately half that of aluminum, provides dimensional stability in applications subject to thermal cycling (Yintong, 2025).

The non-magnetic properties of titanium make it valuable in applications requiring magnetic neutrality, such as medical imaging equipment, marine applications where magnetic signature must be minimized, and electronic devices where magnetic interference must be avoided (Leyens et al., 2003). Additionally, titanium's low thermal conductivity, which is sometimes considered a disadvantage in heat transfer applications, provides benefits in situations where thermal insulation is desired (Celestino, 2012).

These combined properties make titanium indispensable across numerous industries. In aerospace applications, titanium's strength-to-weight ratio and temperature resistance enable the construction of lighter, more fuel-efficient aircraft while maintaining safety and performance standards. Biomedical applications utilize titanium's biocompatibility and corrosion resistance for implants that must function reliably within the human body for extended periods. Chemical processing industries utilize titanium's corrosion resistance for equipment handling aggressive chemicals, while marine applications benefit from its resistance to seawater corrosion.

2. History of Titanium Discovery, Identification, and Production

2.1. Discovery and Early Identification

The discovery of titanium represents a fascinating chapter in the history of chemistry and materials science, involving multiple scientists and covering several decades of research and development. Titanium was first discovered in 1791 by British amateur mineralogist William Gregor in Cornwall, England (Leyens et al., 2003). Gregor, who combined his religious duties with a passion for mineralogy and chemistry, was investigating the magnetic properties of sand from the Menaccan valley when he identified an unknown black metallic oxide in the mineral ilmenite (Ahmedet al., 2014). Gregor's discovery was initially met with skepticism from the scientific community, as the identification of new elements was a relatively new concept in chemistry at the time. He discovered that this unknown oxide was magnetic and could be dissolved in sulfuric acid, producing a yellow solution that turned purple upon treatment with tin. Initially, Gregor named his discovery "menaccanite" after the local parish of Menaccan where he made the discovery, not realizing that he had identified a new element (Leyens et al., 2003). Four years later, in 1795, German chemist Martin Heinrich Klaproth independently discovered the same element while analyzing rutile ore from Boinik, Hungary (Leyens et al., 2003). Klaproth, already famous for his previous discoveries of uranium and zirconium, recognized that he had discovered a new element and named it "titanium" after the Titans of Greek mythology. The name was chosen to reflect the element's strength and the difficulty encountered in isolating it from its compounds, much like the mythological Titans, who were known for their enormous strength and their struggle against the gods. Klaproth's analysis was more thorough than Gregor's initial work, and he was able to demonstrate that the substances found by both researchers were identical. This confirmation established titanium as a legitimate new element, though it would be many decades before pure metallic titanium could be produced in meaningful quantities. The early identification of titanium was complicated by the element's strong affinity for oxygen and other elements, making it extremely difficult to isolate in pure metallic form. Various attempts were made throughout the 19th century to produce pure titanium; however, these efforts were largely unsuccessful due to the limitations of available reduction techniques and the element's inherent reactivity.

2.2. Commercial Production Development

The journey from the discovery to the commercial production of titanium spanned more than a century, involving numerous technological breakthroughs and innovations. Pure metallic titanium was not successfully isolated until 1910 when American chemist Matthew A. Hunter developed what became known as the Hunter process (Leyens et al., 2003). This process involved reducing titanium tetrachloride ($TiCl_4$) with sodium metal in a steel pressure vessel at elevated temperatures, typically around 700–800 °C. The Hunter process represented a significant breakthrough in titanium metallurgy,

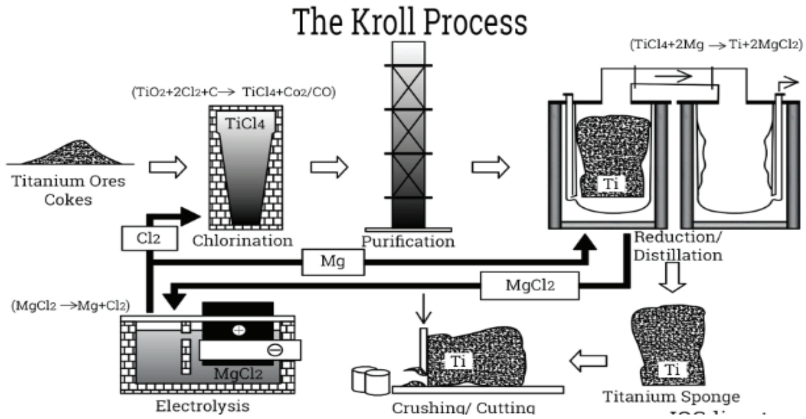

Fig. 3. Review of Kroll process (IQS Directory, 2025)

as it was the first method capable of producing pure metallic titanium, although in very small quantities and with relatively high levels of impurities. The process was batch-based and extremely energy-intensive, requiring careful control of temperature and atmosphere to prevent contamination. Despite these limitations, the Hunter process proved that metallic titanium could be produced and demonstrated many of the unique properties that would later make titanium so valuable. However, the Hunter process was not suitable for commercial production due to its high cost, low yield, and the difficulty of scaling up the process to industrial levels. The sodium reduction process also produced titanium with relatively high levels of impurities, particularly sodium and chlorine, which affected the material's properties and limited its potential applications.

The breakthrough that enabled commercial titanium production came in 1940 when Luxembourg-born American metallurgist William Justin Kroll developed what became known as the Kroll process (Leyens et al., 2003). Working at the U.S. Bureau of Mines, Kroll developed a method for reducing titanium tetrachloride with magnesium instead of sodium, producing what became known as titanium sponge due to its porous, sponge-like appearance (Figure 3).

The Kroll process involves several steps, beginning with the conversion of titanium ore (typically ilmenite or rutile) to titanium tetrachloride through chlorination at high temperatures. The titanium tetrachloride is then purified through distillation to remove impurities before being reduced with magnesium metal in a steel reactor under an inert atmosphere, typically argon or helium. The reaction occurs at approximately 850–950 °C and produces titanium sponge along with magnesium chloride as a byproduct. The Kroll process offered several advantages over the Hunter process, including higher purity titanium, better yield, and the potential for scaling up to industrial production levels. The magnesium chloride byproduct could be electrolyzed to recover magnesium for reuse in the process, making the overall process more economical. Despite these improvements, the Kroll process remained batch-based and energy-intensive, contributing to the high cost of titanium metal.

Commercial titanium production began seriously during the 1950s driven primarily by military and aerospace applications during the Cold War era (Leyens et al., 2003). The development of jet engines and the space race created an unprecedented demand for high-performance materials that could withstand extreme conditions while maintaining low weight. Titanium's unique combination of properties made it ideal for these applications, justifying the high production costs.

The development of vacuum arc remelting (VAR) technology in the 1950s further enhanced titanium quality by enabling the production of high-purity ingots with controlled microstructures (Leyens et al., 2003). VAR involves melting titanium electrodes in a vacuum chamber using an electric arc, which prevents contamination from atmospheric gases and produces extremely pure titanium suitable for critical aerospace applications. Electron beam melting (EBM) technology, developed in the 1960s, provides an alternative method for producing high-quality titanium ingots (Leyens et al., 2003). EBM uses a focused electron beam to melt titanium in a vacuum chamber, offering improved control over the melting process and allowing the production of titanium with very low impurity levels.

3. 3. Properties of Titanium and Titanium Alloys

3.1. Allotropic Properties

Titanium exhibits remarkable allotropic behavior, meaning it can exist in different crystal structures depending on temperature and pressure conditions. This allotropic transformation is fundamental to understanding titanium's properties and forms the basis for developing various titanium alloys with tailored characteristics. The allotropic behavior of titanium is a key factor that makes it a versatile engineering material (Celestino, 2012). As Figure 4 illustrates, the alpha (α) phase of titanium features a hexagonal close-packed (HCP) crystal structure and is stable at room temperature up to 882 °C (Leyens et al., 2003). This phase is characterized by excellent formability and weldability, making it suitable for applications requiring complex shapes or extensive fabrication. The HCP structure provides good ductility and toughness, though it limits the ultimate strength that can be achieved. The alpha phase also exhibits superior corrosion resistance compared to the beta phase, making it preferred for applications in corrosive environments (Ahmedet al., 2014).

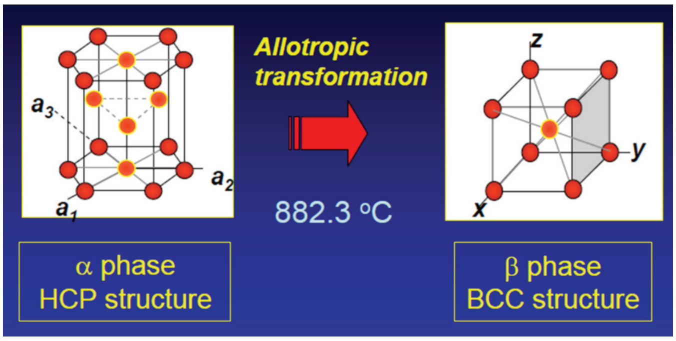

Fig. 4. Allotropic transformation of pure Titanium

The close-packed nature of the HCP structure in the alpha phase results in limited slip systems, which contributes to its good formability but also means that strengthening mechanisms are somewhat limited compared to other crystal structures (Celestino, 2012). However, the alpha phase can be strengthened through solid solution strengthening with elements such as aluminum and tin, as well as through precipitation hardening mechanisms[2]. The beta (β) phase of titanium exhibits a body-centered cubic (BCC) crystal structure and is stable above 882 °C. This phase offers significantly higher strength potential and better machinability compared to the alpha phase, making it attractive for applications requiring high mechanical properties. The BCC structure offers more slip systems than the HCP structure, allowing for improved plastic deformation and work hardening characteristics (Ahmedet al., 2014). However, the beta phase typically exhibits reduced corrosion resistance compared to the alpha phase, and it is generally less stable at room temperature unless stabilized by the addition of appropriate alloying elements. The beta phase can be retained at room temperature by adding beta-stabilizing elements, creating opportunities for developing high-strength titanium alloys (Leyens et al., 2003; Ahmedet al., 2014). The critical temperature of 882 °C, where the alpha-to-beta transformation occurs, is known as the beta transformation temperature. This temperature is crucial in titanium alloy processing, as it determines the heat treatment temperatures and cooling rates needed to achieve desired microstructures and properties (Leyens et al., 2003). The beta transformation temperature can be modified through alloying, with alpha-stabilizing elements raising the temperature and beta-stabilizing elements lowering it (Ahmedet al., 2014 ; Celestino, 2012). The ability to manipulate these phases through careful alloying and heat treatment provides metallurgists with powerful tools for developing titanium alloys with specific property combinations. By controlling the relative amounts of alpha and beta phases, along with their distribution and morphology, it is possible to optimize strength, ductility, toughness, and other properties for specific applications.

3.2. Major Groups of Titanium Alloys

Titanium alloys are classified based on their predominant phase structure at room temperature, determined by the types and amounts of alloying elements present.

3.2.1. Alpha Alloys

Alpha alloys contain alpha-stabilizing elements such as aluminum, oxygen, nitrogen, and carbon, which extend the alpha phase stability and raise the beta transformation temperature. These alloys are characterized by excellent corrosion resistance and thermal stability, making them ideal for use in aggressive environments or at elevated temperatures. The superior corrosion resistance results from the inherent stability of the alpha phase and the beneficial effects of aluminum additions. Alpha alloys exhibit good weldability due to their single-phase structure but have limited strength compared to other titanium alloy classes. Examples include Ti-5Al-2.5Sn for moderate temperature applications and Ti-8Al-1Mo-1V for chemical processing and marine applications.

3.2.2. Beta Alloys

Beta alloys contain sufficient beta-stabilizing elements, such as vanadium, molybdenum, niobium, tantalum, chromium, and iron, to retain the beta phase at room temperature. These elements lower the beta transformation temperature and create unique property combinations. The most attractive characteristic is their high strength potential, with some achieving ultimate tensile strengths exceeding 1400 MPa through heat treatment. Beta alloys exhibit excellent formability due to their BCC crystal structure and superior machinability compared to other classes. However, they have a higher density due to the presence of heavy beta-stabilizing elements and generally exhibit lower corrosion resistance. Examples include Ti-10V-2Fe-3Al and Ti-15V-3Cr-3Sn-3Al, used in aerospace fasteners, springs, and structural components.

3.2.3. Alpha-Beta Alloys

Alpha-beta alloys represent the most commercially important class, containing both alpha- and beta-stabilizing elements that create a two-phase microstructure at room temperature. This balanced approach combines the beneficial characteristics of both phases, offering excellent property combinations suitable for a wide range of applications. The alpha phase contributes corrosion resistance, weldability, and thermal stability, while the beta phase provides strength, toughness, and formability. These alloys can be heat-treated to achieve various properties through microstructural modifications. Ti-6Al-4V is the most widely used titanium alloy, exemplifying the balanced properties that can be achieved with alpha-beta alloys. It combines good strength (900–1000 MPa), excellent corrosion resistance, formability, and weldability, making it suitable for a wide range of applications, from aerospace structures to biomedical implants. Other important examples include Ti-6Al-2Sn-4Zr-2Mo for elevated temperature applications and Ti-6Al-2Sn-4Zr-6Mo for higher strength requirements while maintaining good ductility.

3.3. Mechanical and Physical Properties

The mechanical properties of titanium alloys extend a remarkably wide range, making them suitable for applications from lightly loaded components to highly stressed critical parts in aerospace and defense. Tensile strength ranges from approximately 240 MPa for commercially pure titanium to over 1400 MPa for high-strength beta alloys in peak-aged conditions (Leyens et al., 2003; Celestino, 2012; Lampman, 1990). This wide range allows engineers to select materials with properties closely matched to application requirements. Yield strength values typically range from 170 MPa for annealed commercially pure titanium to over 1200 MPa for high-strength alloys. The high yield-to-tensile strength ratio of titanium alloys, typically 0.8–0.9, indicates excellent resistance to plastic deformation and provides good structural efficiency (Yintong, 2025; Celestino, 2012; Lampman, 1990). The elastic modulus of titanium alloys ranges from 100 to 120 GPa, approximately half that of steel. In structural applications, the lower modulus means titanium components will deflect more under identical loading conditions. However, in biomedical applications, particularly orthopedic implants, the lower modulus is advantageous as it more closely matches the modulus of human bone (approximately 15–30 GPa), reducing stress shielding effects (Leyens et al., 2003; Lampman, 1990). The density of titanium alloys, approximately 4.5 g/cm^3, represents one of their most significant advantages in weight-critical applications (Yintong, 2025; Lampman, 1990). At 45% lighter than steel and 60 % heavier than aluminum, titanium alloys occupy a unique position in the strength-to-weight spectrum, particularly valuable in aerospace applications (Leyens et al., 2003; Yintong, 2025; Celestino, 2012; Lampman, 1990). Fracture toughness values typically range from 30–100 MPa√m, depending on alloy composition and heat treatment conditions. Titanium alloys exhibit excellent fatigue resistance, particularly in corrosive environments. The fatigue limit is typically 50–60% of the ultimate tensile strength, comparable to or better than most structural materials (Leyens et al., 2003; Lampman, 1990). However, notch sensitivity requires careful consideration in component design, as stress concentrators can significantly reduce fatigue life.

3.4. Chemical Properties

The exceptional corrosion resistance of titanium results from the formation of a stable, adherent oxide film composed primarily of titanium dioxide (TiO_2). This oxide film forms spontaneously when exposed to oxygen or moisture, providing remarkable protection against various corrosive environments. The film is typically 2–7 nanometers thick in ambient conditions (David et al., 2016; Lampman, 1990). The self-healing nature of the oxide film is one of titanium's most valuable characteristics. When damaged by mechanical abrasion or chemical attack, it rapidly reforms in the presence of trace amounts of oxygen or water, ensuring corrosion protection throughout the service life. Titanium exhibits excellent resistance to seawater and marine environments, making it invaluable for use in offshore platforms, ship components, and desalination plants. Unlike many metals that suffer from chloride-induced stress corrosion cracking, titanium maintains its integrity even after decades of exposure to seawater (Lampman, 1990). Titanium exhibits excellent resistance to most acids, particularly oxidizing acids such as nitric acid and chromic acid, as well as wet chlorine environments. It also resists many organic acids and performs well in mixed acid environments. However, titanium is susceptible to attack by hydrofluoric acid and fluoride-containing solutions, which can dissolve the protective oxide film. Reducing acids, particularly hydrochloric and sulfuric acid, at elevated temperatures can also cause problems under certain conditions. Despite excellent general corrosion resistance, titanium can be susceptible to specific forms of localized corrosion (David et al., 2016). Hydrogen embrittlement can occur in environments that generate hydrogen, reducing ductility and fracture toughness. Stress corrosion cracking, although rare, can occur in hot salt solutions or when exposed to certain chemicals. Galvanic corrosion can be a concern when titanium is coupled with other metals, as titanium is generally noble in the galvanic series and can accelerate corrosion of other metals in contact with it.

4. Recovery of Titanium from Red Mud

Red Mud (RM), a byproduct of alumina production, derives its name from its distinctive red color, which is attributed to its high iron (III) oxide content (approximately 50%). It also resembles soil in appearance. The production of red mud varies depending on the processes and the quality of the bauxite; it typically ranges from 0.5 to 2.0 tons of red mud per ton of alumina. As of 2020, the accumulation of red mud had surpassed 5 billion tons, with China leading, accounting for 800 million tons (Kostić, 2025).

Fig. 5. Red Mud (Bauxite residue)

As shown at Figure 5, red mud (bauxite residue) was obtained after dissolution of bauxite with sodium hydroxide in an autoclave, and a subsequent drying of the obtained suspension. The chemical composition of red mud is very complex and varies depending on the mining area and production method. However, some properties are common to all regardless of their origin, such as small particle size, complex mineral composition, and high alkalinity. For example, research by Stopic et al. has shown that over 40 % of particles in red mud have sizes less than 10 µm, which contributes significantly to dust generation when red mud is in its dry form (Yasmin at al., 2013). Red mud composition is CaO, SiO_2, undissolved Al_2O_3, Fe_2O_3, TiO_2, Na_2O, and K_2O, and various minerals. Red mud contains both soluble (resulting from sodium hydroxide in the Bayer process) and insoluble alkalis (present in bauxite), with a total alkali content ranging from 2–6 %, and sometimes higher than 10 %, depending on the plant. Alkaline presence is the main contributor to the high alkalinity of red mud (pH ranging from 9.0 to 13.2), with an average around 11.3±1.0 (Stopic et al., 2025). The average chemical composition of red mud after drying is shown in Table 1. The presence of iron (III) oxide is dominant (About 42.3 %), but this value is depending from the bauxite source and origin. The content of TiO_2 amounts about 4.2 %, what is an excellent starting point for a recovery of titanium using different methods.

Table 1. Average chemical composition of the red mud

Composition	weight percentage. (%)
Fe_2O_3	42.34
Al_2O_3	16.26
CaO	11.64
SiO_2	6.97
TiO_2	4.27
Na_2O	3.83
Others	1.85
Ignition loss	12.66

The soluble alkali can pose a significant threat to the environment because it can leach out and cause pollution of groundwater and soil. Additionally, high alkalinity of red mud can cause corrosion to materials, and it is poisonous to living organisms. Also, due to an insufficient leaching process, aluminum compounds can react with silicon minerals, reducing the efficiency of the alumina production process (Liu et al., 2014).

A general strategy for the titanium recovery is proposed by Piga et al, 1993. Titanium dioxide production is the first aim of his study. Red mud contains 3–15 % TiO_2, which is a considerable amount compared to the available alternatives. Recovery methods have focused on beneficiation techniques (reduction roasting), magnetic separation, and then acid leaching, with efficiency going up to 73 % using this method, as shown in Figure 6. Thermal decomposition of titanium oxy sulfate from the non-magnetic fraction leads to the formation of titanium oxide. At the same time, the formation of aluminum oxide is possible through the wet mixing of red mud, coal, calcium hydroxide, and sodium carbonate, followed by reduction, calcination, and water leaching. During one

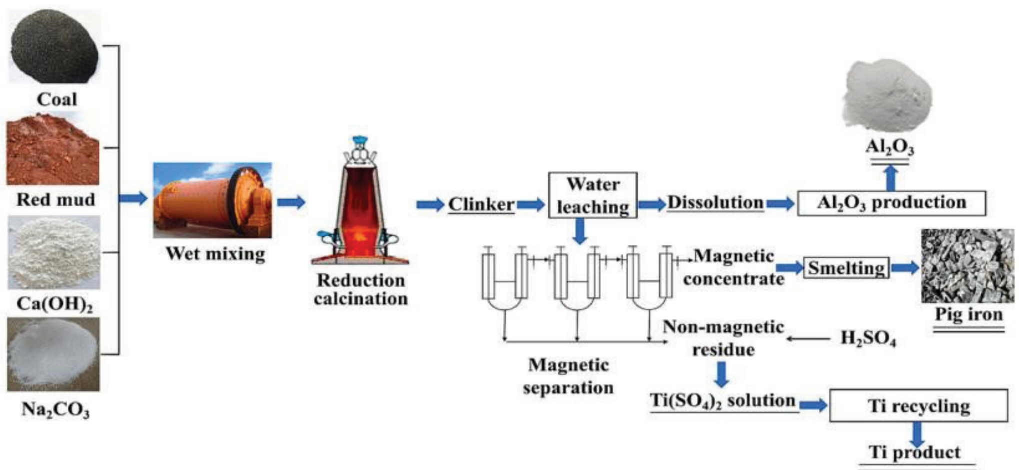

Fig. 6. General strategy for titanium recovery from red mud

aluminothermic reduction of titanium oxide powder, it is possible to prepare TiAl6V4 alloys. Molten salt electrolysis is needed for the formation of metallic titanium from titanium oxide or titanium fluoride powders. This method enables the formation of pig iron after reductive smelting.

For a comparison of different chosen methods for a treatment of red mud Table 2 is additionally included, that systematically compares major titanium recovery routes from red mud. For instance, the table could list reduction roasting–magnetic separation, acid leaching, molten salt electrolysis, and combined pyro–hydrometallurgical routes, alongside parameters such as target product (TiO_2 vs. metallic Ti), titanium recovery efficiency, co-products (iron, alumina), energy intensity, and technology readiness level. By condensing dispersed literature into a single comparative framework, this Table 2 is a reference element that is likely to be reused and improved by researchers working on red mud valorization and critical raw materials.

5. Future Applications of Titanium and Its Alloys

Market projections indicate significant shifts in titanium demand across sectors through 2030 (Grand View Research, 2024). While aerospace currently dominates with 45 % market share, this is projected to stabilize at 40 %, as biomedical applications are expected to grow from 20% to 25 % and automotive applications from 8–15 %, both showing strongly increasing trends. Global titanium production is forecast to exceed 250,000 tons annually by 2030, up from approximately 190,000 tons currently, with aerospace and biomedical sectors as primary drivers (Grand View Research, 2024). However, realizing this growth requires addressing critical cost barriers titanium remains 10–30 times more expensive than steel necessitating breakthrough technologies such as the Fray-Farthing-Chen (FFC or Cambridge) process, which offers potential 30% cost reduction through direct TiO_2 reduction, and intensified recycling initiatives. Additive manufacturing techniques, such as Selective Laser Melting (SLM) and Electron Beam Melting (EBM) provide additional pathways to cost competitiveness through material savings up to 90 % for complex geometries (Chen, et al., 2000). The aerospace industry continues to drive titanium demand, with next-generation aircraft requiring materials that can withstand extreme thermal and mechanical loads. Advanced jet engines require titanium alloys with enhanced creep resistance and thermal stability to operate at higher temperatures. Space exploration vehicles benefit from titanium's strength, corrosion resistance, and thermal stability for spacecraft structures, landing systems, and life support equipment. The growing commercial space industry creates opportunities for reusable launch vehicles, which require materials that can withstand repeated thermal cycling and mechanical stress. Additive manufacturing enables complex geometries with integrated functionality, producing lightweight, optimized structures with hollow, lattice-structured components achieving significant weight savings (Piga et al., 1993). The biomedical field represents one of the fastest-growing markets for titanium, driven by aging populations and advancing medical technologies. Next-generation orthopedic implants incorporate surface treatments promoting bone growth and improved fixation, including porous structures allowing bone ingrowth and bioactive coatings promoting osseointegration. Spinal implants, dental implants, and cardiovascular devices continue evolving with improved designs and enhanced biocompatibility. Three-dimensional printing enables patient-specific implants perfectly matched to individual anatomy, particularly valuable for complex reconstructive procedures. Smart implants with integrated sensors provide real-time monitoring of healing progress and implant stability (Mutombo, 2018). The automotive industry's transformation toward electric vehicles creates new titanium opportunities in high-performance and luxury vehicles. Engine components for high-performance vehicles benefit from titanium's strength-to-weight ratio and temperature resistance. Exhaust systems, suspension components, and electric vehicle battery enclosures leverage titanium's weight savings and performance characteristics. Hydrogen fuel cell components represent an emerging application where titanium's corrosion resistance and hydrogen compatibility provide significant advantages in fuel cell stacks and storage systems (Fuji et al., 2003). Marine applications demonstrate significant growth potential in offshore oil platforms, submarine hulls, and desalination plants, owing to titanium's exceptional resistance to seawater corrosion. The energy sector presents opportunities in geothermal power systems, nuclear reactor components, and wind turbine structures, where severe environmental performance is critical. Consumer electronics, sports equipment, and architectural applications are increasingly utilizing titanium for its strength-to-weight ratio, durability, and aesthetic appeal in mobile devices, sporting goods, and decorative elements (Kostić, 2025). The future of titanium processing involves additive manufacturing techniques, such as Direct Metal Laser Sintering and Electron Beam Melting, enabling complex geometries previously impossible to achieve (Mutombo, 2018). Powder metallurgy contributes to sustainable production through near-net-shape manufacturing, reducing material waste. Advanced forming techniques and surface modification technologies expand fabrication possibilities and enhance surface properties (Leyens et al., 2003). Environmental concerns drive research into sustainable titanium production methods, including alternative extraction processes to replace the energy-intensive Kroll process. Recycling technologies focus on efficiently processing titanium scrap and end-of-life products, while developing titanium powder from recycled materials promotes circular economy approaches (Mutombo, 2018; Kacsó et al., 2025). Despite numerous advantages, titanium faces significant challenges that must be addressed for broader adoption. The high cost associated with titanium extraction and processing remains a primary barrier, driving research into more efficient production processes, alternative extraction methods, and improved recycling technologies to achieve economies of scale (Leyens et al., 2003). Processing improvements are essential due to titanium's high reactivity, requiring advancements in melting, casting, machining, and welding techniques, along with enhanced quality control methods. Market expansion strategies focus on developing lower-cost alloys for non-critical applications, strengthening supply chain management, building comprehensive databases of material properties, and establishing more effective design guidelines and standards. Successfully addressing these cost, processing, and market challenges will be critical for realizing titanium's full potential across emerging applications.

Table 2. Comparative analysis of different chosen methods for treatment of red mud

Method	Main Target Product	Ti Recovery (%)	Co-products	Energy Intensity	TRL
Reduction roasting + magnetic separation	TiO	~70	Pig iron	High	Pilot
Acid leaching	$TiOSO_4$ / TiO_2	50–80	Al_2O_3	Medium–High	Lab
Molten salt electrolysis	Metallic Ti	98	Fe	Very high	Lab
Combined pyro–hydro	Multi-element	99	Fe, Al	Medium	Concep

6. Conclusion

Titanium has evolved from a relatively obscure element into a material of strategic importance across a wide range of high-performance applications. Its unique combination of high strength-to-weight ratio, outstanding corrosion resistance, biocompatibility, and thermal stability makes it indispensable in critical industries such as aerospace, biomedical, marine, and chemical processing. Although titanium is abundantly available in the Earth's crust, its widespread adoption is limited by the energy-intensive and costly nature of its extraction and processing.

Advancements in alloy development, particularly through manipulation of allotropic phases and alloying strategies, have significantly expanded titanium's performance envelope. Market projections indicate substantial growth in biomedical (20–25 % by 2030) and automotive (8–15 % by 2030) sectors, with global production expected to exceed 250,000 tons annually. The emergence of additive manufacturing, powder metallurgy, and sustainable processing technologies, including potential 30% cost reduction through the FFC process and up to 90% material savings via SLM/EBM techniques, offers new opportunities to reduce costs, enable complex geometries, and enhance material efficiency. Furthermore, innovative recovery approaches from secondary sources such as red mud present promising pathways for both sustainability improvements and cost reduction, addressing the dual challenges of resource efficiency and environmental responsibility.

However, realizing titanium's full potential will require overcoming persistent challenges, including high production costs (10–30× more expensive than steel), complex fabrication requirements, and limited recyclability. Continued research into alternative extraction methods, improved processing techniques, and circular economic approaches will be essential.

To accelerate titanium's transition toward broader accessibility and sustainability, the following research priorities are recommended: development of integrated processes for simultaneous extraction of titanium, iron, and aluminum from red mud and other industrial residues; advancement of energy-efficient electrochemical reduction methods as viable alternatives to the energy-intensive Kroll process; establishment of quality standards for titanium powder production from end-of-life components; development of titanium alloy compositions optimized for recyclability with reduction of difficult-to-separate alloying elements; research into lower-cost titanium alloys specifically targeting automotive and energy applications where current costs prohibit widespread adoption despite clear technical advantages; and comprehensive life cycle assessment studies comparing primary versus secondary titanium production routes, including carbon footprint analysis and resource efficiency metrics.

With strategic focus on these research directions and continued technological advancements, titanium is poised to play a pivotal role in shaping the future of advanced engineering and sustainable technology, bridging the gap between its crustal abundance and practical accessibility.

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