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ADVANCED TITANIUM ALLOYS FOR MEDICAL AND INDUSTRIAL USE

BY

ANDREI PRUTEANU[1], MĂDĂLINA SIMONA BĂLȚATU[1,*], ANDREI VICTOR SANDU[1,2] and PETRICĂ VIZUREANU[1,2]

[1]"Gheorghe Asachi" Technical University of Iași, Faculty of Materials Science and Engineering, Iași, Romania
[2]Academy of Romanian Scientists, 54 Splaiul Independenței St., Sect. 5, 050094 Bucharest, Romania

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Abstract. This article aims to discuss ways of improving the properties of titanium alloys, exploring various strategies to enhance strength of the material, the corrosion resistance and most importantly the biocompatibility, meaning a particular focus on mechanical performance, structural integrity, and biocompatibility, suited for orthopaedic and dental implants. It examines the effects of different alloying elements and the impact titanium's phases have on these properties. Additionally, the paper discusses production methods ranging from extraction to surface treatments and includes structural characterization techniques, such as mechanical testing, corrosion resistance evaluation, and microstructure analysis. Titanium and its alloys are highly valued for their strength-to-weight ratio, exceptional corrosion resistance, flexibility, and biocompatibility, making them suitable for a diverse array of applications, which will be detailed further in this work. Future directions emphasize the use of 3D engineering for the development of customized implants, surface modifications to enhance biocompatibility, and the exploration of biodegradable alloys.

Keywords: Titanium Alloys, Biomaterials, Medical Devices, Alloy Characterization, Biocompatibility, Mechanical Testing, Alloying Elements.

[*]Corresponding author; *e-mail*: madalina-simona.baltatu@academic.tuiasi.ro

1. Introduction

Biomaterials are synthetic materials whose function is to replace a living part or a system and also interact and diagnose possible problems with living tissues. Not every artificial material that comes into contact with the skin is part of the biomaterials category, only the materials that replace human organs, parts of them, or systems that lost their function to improve the functions and speed up the recovery process (Detsch *et al*., 2018).

The scientific branch of biomaterials grew larger thanks to the continuous development and research in medicine, providing an alternative method for accelerating the recovery process or assisting the healing of human health problems (Vallet-Regi, 2022).

Biomaterials are a class of special materials used in contact with biological tissues, whose purpose is treating, modifying, or replacing an organ or the functions of the organism, altogether making it possible to observe them.

Biomaterials have specific needs based on their function. However, the main ones are compatibility, which means being able to work with living tissue and not wearing down easily; mechanical properties, like having a certain elastic modulus, being flexible, and not breaking down easily under stress; and corrosion resistance (Najafizadeh *et al*., 2024).

Biomaterials have different purposes, based on the needs of the organism alongside which they function or to replace; examples are contact lenses, dental implants and teeth braces, catheters, finger and knee joint implants, knee and hip replacement, bone cement and plates, synthetic ligaments and tendons, synthetic skin and skin repair devices, heart valves, and hearing aids (Eliaz, 2019).

This paper focuses on biomaterials obtained from processed metals (Fig. 1), such as titanium and its alloys. To further emphasize, the great properties of titanium and the enhanced properties of its alloys, such as mechanical strength, durability, biocompatibility, corrosion resistance, and osseointegration, make it more than suited for biomedical applications (Niinomi and Boehlert, 2015).

The main raw materials used in the creation of biomaterials are metals, polymers, ceramics, and composite materials.

Metals are incredibly hard materials with high density and a good elastic modulus; the problems occur in time, since metallic materials can corrode. Another common problem is the high density, which not only increases the weight of the material, but could also create problems during the removal process (Wang *et al*., 2021).

Tissue engineering, drug delivery systems, and wound care primarily utilize polymers due to their elastic modulus and ease of manufacture. The polymers can be biodegradable and non-biodegradable, in which case the fact that substances are not durable could be an advantage or a disadvantage depending on their use; they can also deform under stress, creating problems.

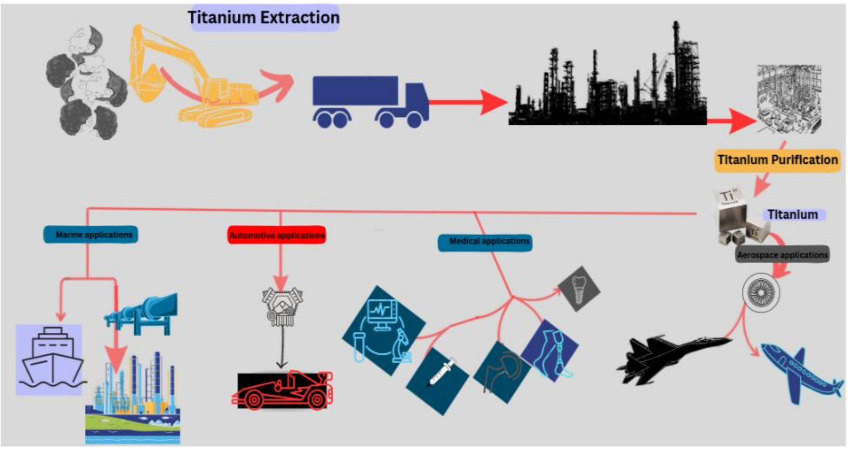

Fig. 1 – Graphical abstract.

Ceramics have a range of applications, especially in orthopedics and dentistry; however, they have certain limitations. Although they have excellent biocompatibility–osteoconductive and low toxicity–and are inert, ceramics are also fragile; they can crumble, are quite difficult to obtain, and are limited in use due to the fact they have no elastic modulus (Shanmugam and Sahadevan, 2018).

Composite materials are a combination of materials whose properties can both be employed together, such as the strength of metals and biocompatibility of ceramics. Based on the materials combined, they usually have enhanced mechanical properties like strength and toughness, improved biocompatibility, wear resistance, customization, and improved processability.

Although composite materials are made with targeted properties, they have Biomaterials are a special class of materials whose purpose is the direct interaction with biological systems with the intention of repairing damaged tissues, replacing certain body parts, or aiding in their recovery (Egbo, 2021). Table 1 presents a brief classification of biomaterials and their respective uses (Baltatu *et al*., 2019b; Raut e*t al*., 2020).

Table 1

Classification of biomaterials and uses

Material type	Biomedical applications
METALS: Titanium alloys, Stainless steel, Co-Cr Alloys, Gold (Au)	Prostheses, bone plates and screws, dental implants, hip and knee joints
POLYMERS: Nylon, Silicone, Teflon, Dacron	Surgical sutures, blood vessels, joints, synthetic skin, soft tissues
CERAMICS: Aluminium Oxide, Carbon Hydroxyapatite, Zirconia (ZrO_2), Ceramic Glass	Dental alveoli, hip joints
COMPOSITES: Carbon-Carbon	Joints and heart valves

Biomaterials are defined by certain characteristics, such as their mechanical properties, microstructural properties, chemical properties, and biocompatibility (Kiran *et al*., 2021).

Biocompatibility is a property that allows biomaterials to interact with human tissues, organs, or cells without creating any risk or adverse reactions–a key factor that ensures that no toxic reactions can occur and promotes healing or integration in the organism or living system.

The mechanical properties are strength, elasticity, hardness, and fatigue resistance–these are variable properties since biomaterials serve different purposes, while overall it is important to have a resistant material that can withstand all; some biomaterials are especially designed to degrade, e.g., polymers, hydroxyapatite.

The purpose of the chemical properties, chemical stability and corrosion resistance, is to prevent degradation due to errosion or unwanted chemical reactions.

Surface properties present in biomaterials are hydrophilicity or hydrophobicity, as well as roughness and porosity.

Although biomaterials come in various forms and from various materials, metals have always been the go-to in this field, thanks to their durability, strength, long-term performance, strength-to-weight ratio, wear, and stress resistance.

In the biomedical field, metals are excellent picks when it comes to orthopedic implants, dental implants, and cardiovascular implants.

Alongside the benefits the mechanical properties bring, the chemical properties of metals are also important, such as the corrosion resistance, prolonging the life of the material and reducing the risk factor.

When it comes to metals, one of the most commonly used is titanium, due to its unique set of characteristics and uses, such as orthopedic prostheses, dental implants, stents, bone plates, screws, and joint replacement.

Important characteristics of titanium are biocompatibility and corrosion resistance; titanium is highly biocompatible, and its surface builds a layer of titanium oxide (TiO_2), furthering its resistance to corrosion.

Titanium also exhibits low thermal conductivity, making it a perfect choice for medical implants that are near or in contact with sensitive tissues and organs, preventing heat transfer, and minimizing the risk of tissue damage.

The importance of titanium is also given by the wear resistance and, more importantly, the ability to encourage osseointegration, which is useful for bone screws and plates and dental implants (Marin and Lanzutti, 2023).

One other benefit titanium has is the ease of manufacture; although at a high price, titanium can be molded and shaped precisely for the device or prosthesis required, coupled with possible surface treatments such as coatings, it can create more durable or porous surfaces to fit the needs.

2. Classification of Titanium Alloys

As previously stated, biomaterials are synthetic materials designed to interact with biological systems to treat, repair, or replace damaged tissues and organs. Among various biomaterials, titanium and especially titanium alloys stand out thanks to their properties. Titanium alloys are widely used in medical applications, such as orthopedics, dentistry, and cardiovascular devices (Wang *et al*., 2021).

Titanium is highly suited for the body; the most important properties for its use in medical applications are:

• **Biocompatibility:** this trait means that titanium does not cause adverse reactions when in contact with human tissues and organs. Titanium also bonds with the bone tissue, further favoring its usage for implants. One other key factor of titanium when it comes to biocompatibility is the oxide layer that it naturally forms when exposed to oxygen, making it more stable and preventing the immune system of the body from attacking the implants (Gobbi *et al*., 2019).

• **Corrosion resistance:** a property evident even in aggressive environments, such as body fluids. The resistance is given thanks to the stable oxide layer on its surface, making titanium particularly suited for biomedical applications, where resistance to moisture, salts, and other elements is a must (Eliaz, 2019).

• **Strength-to-weight ratio:** titanium, being stronger than other metals yet lighter than stainless steel, makes it an ideal material for load-bearing implants, such as joint replacements, a property employed in many more cases and always beneficial.

• **Non-toxic and inert:** titanium is, by nature, a non-toxic material for the human body, a property that is critical in medical applications.

• **Osseointegration**: a process through which titanium integrates with bones, forming a strong bond and ensuring the stability and longevity of implants.

• **Flexibility and ductility:** although a strong material, titanium can easily be bent into the shapes and geometries required for specific applications, creating tailor-made structures for medical devices and biomedical implants.

Titanium and its alloys are fundamental in the development of biomedical devices and implants. Their combination of strength, lightweight, biocompatibility, and corrosion resistance ensures their success in critical applications such as orthopedic and dental implants, cardiovascular devices, and prosthetics (Marin and Lanzutti, 2023; Baltatu *et al.*, 2019a). With ongoing research and development, titanium alloys continue to be optimized for better performance and enhanced patient outcomes in the biomedical field.

Given its properties, titanium is a great material, and when alloyed with other elements, it can be optimized for industrial and biomedical uses. Titanium alloys typically consist of pure titanium combined with other elements, such as

Al, V, Nb, Mo, and Zr, with the main goal being the improvement of targeted properties, strength, toughness, or biocompatibility (Kong *et al.*, 2021).

In normal conditions, such as room temperature and with no outside influencing factors, pure titanium has a hexagonal close-packed structure, mainly known as α-titanium. A stable structure for as long as the temperature of the material is not over 880ºC, reaching that certain temperature makes changes in the structure of the pure titanium, transforming the hexagonal closed-packed in a body-centered cubic structure. A change that can also occur when certain materials are added to the pure titanium, lowering the temperature needed for the transformation, these materials are called β-stabilisers, and some examples include Mo, Nb, Ta, V, Cr, Fe, and Co.

The β-stabilisers are a main class of materials that include the two categories of elements: β-isomorphous elements and β-eutectoid elements, whose roles differ from one another. While β-isomorphous lower the temperature needed for the transition to β-titanium, the β-eutectoid elements, on the other hand, are a composition that stabilizes the β-phase.

While titanium alloys have three main categories, the α-phase, β-phase, and α+β-phase, certain subcategories exist, these being the quasi-α, which contain small traces of the β-phase; the quasi-β, being a phase almost near the β-phase; and the metastable-β phase, an unstable phase stabilized through the addition of stabilizing elements, such as vanadium, molybdenum, and iron (Nada *et al*., 2024; Ahmad and Hussain, 2020).

Titanium alloy phases are presented in Fig. 2.

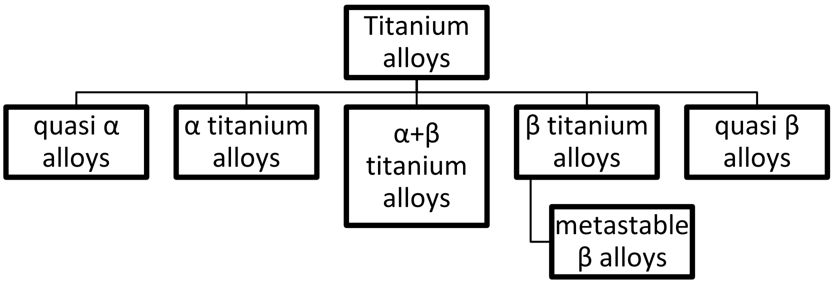

Fig. 2 – The phases of titanium alloys.

2.1. Alpha titanium alloys

Alpha titanium alloys (α-Ti) are titanium alloys whose structure is hexagonal closed-packed (HCP for short). The alpha phase is stable below the transus temperature of ~882ºC; it is strong and ductile with limited formability, provides significant hardness and fatigue resistance at lower temperatures, and also has excellent corrosion resistance. It is a material mainly used in aerospace structures and medical implants and can also be used in chemical industries and marine applications. Table 2 presents examples of these alloys.

Table 2
Examples and uses for alpha and near alpha titanium alloys

Alloy composition	Key properties	Primary applications
Commercially Pure Ti	Weldability and formability, high strength and corrosion resistance	Aerospace and aircraft components, biomedical implants
Ti-5Al-2.5Sn	Good weldability and formability, high strength and corrosion resistance	Aerospace and aircraft components, marine, chemical industries
Ti-8Al-1Mo-1V	High strength, fracture resistance, corrosion resistance and weldability	Aerospace components, marine and chemical industries
IMI-834	Increased tensile strength and creep resistance	Aerospace components

2.2. Beta titanium alloys

Beta titanium alloys (β-Ti) are titanium alloys with a body-centered cubic crystal structure that mostly form at higher temperatures. They are very flexible, easy to shape, and can go through big plastic deformations. It's a stable phase when the temperature is above the α to β transus temperature or can be stabilized using the β-stabilizing elements. The β phase is easier to deform compared to the α phase but at the same time has great toughness, fracture resistance, and high tensile strength at elevated temperatures. Its usage includes aerospace and automotive applications and components. Table 3 provides examples and applications for this type of alloy.

Table 3
Examples and uses for beta titanium alloy

Alloy composition	Key properties	Primary applications
Ti-5Al-5V-5Mo-3Cr	High strength, toughness, and corrosion resistance	High-temperature applications such as aircraft and aerospace components and turbines
Ti-3Al-8V-6Cr-4Mo-4Zr	High-strength, lightweight, and corrosion-resistant	Aircraft springs, tubes, and casing in chemical processing, racing equipment
Ti-4.5Sn-6Zr-11.5Mo	High strength, excellent stress resistance, cold formability, and hardness	Aircraft equipment and sheet metal parts
Ti-8Mo-8V-2Fe-3Al	Enhanced corrosion resistance, ductility, durability, and tensile strength	Aerospace structures, chemical processing equipment

2.3. Alpha+beta titanium alloys

Alpha+beta titanium alloys (α+β-Ti) are a mixture of alpha and beta phases in titanium alloys, providing a balanced combination of strength, toughness, and ductility, perfect for various applications and components in industries. The phase contains both hexagonal closed-packed and body-centered cubic crystal structures. The mixture offers both high strength and excellent formability. The properties can be further enhanced through various surface treatments, such as solution heat treatment or aging. The aerospace, medical, marine, and chemical industries can use this alloy class due to its combination of good properties. Examples of alloys and their uses are presented in Table 4.

Table 4
Examples and uses for alpha+beta titanium alloys

Alloy composition	Key properties	Primary applications
Ti-6Al-4V	High strength, good fatigue resistance, excellent corrosion resistance	Aerospace components, biomedical implants, military applications
Ti-3Al-2.5V	Lower strength when compared to others, excellent corrosion resistance and weldability	Aerospace components, marine, chemical industries
Ti-6Al-2Sn-4Zr-6Mo	Good creep resistance, high strength at high temperatures	Turbines, exhaust, engines, and chemical processing equipment

The transition between the phases is strongly affected by temperature and alloying elements. The transus temperature is approximately 882ºC when these elements are not present, but they can change the temperature to favor one of the phases or a mix of the two.

The purpose of alpha-stabilizing elements is to increase the stability of the alpha phase by lowering the temperature at which the transus to the β-phase occurs. One of the significant stabilizing elements is Al, significantly lowering the transus temperature. Not only this, but aluminum increases creep resistance and corrosion resistance, a fact emphasized by its presence in beta and alpha+beta alloys. Following the importance of aluminum, another beneficial stabilizer is O, and although it increases strength, it can reduce ductility, and in high concentration, can make the material brittle and unusable, meaning that the concentration of oxygen in the material needs a tough control. *C* is another good stabilizing element, alongside *N;* both can increase strength, toughness, and wear resistance (Chen *et al*., 2024). Similar to the excess of oxygen, a high concentration of carbon or nitrogen can also lead to brittleness.

The alpha stabilizers are used for the enhanced thermal stability of the material, the strength-granting properties at the cost of ductility, but their concentration needs to be closely followed to not damage the material.

The beta-stabilizing elements enhance the stability of the beta-phase, the material maintaining its body-centered cubic crystal structure at lower temperatures, or in some cases at room temperature. The importance of having beta alloys at lower temperatures is given in cases where formability is of vast importance. Furthermore, having a material stable both at low temperatures, such as room temperature, and high temperatures, the usual ones for the beta phase, is of importance in various aircraft, chemical, and automotive industries.

As a result of adding V, the alloyed material has lower corrosion resistance (Çömez, 2023), but it also raises the transus temperature and keeps the beta phase stable at lower temperatures. V also improves resistance to creep and high temperatures. In addition to raising the transus temperature, Mo makes alloys stronger at high temperatures and better at resisting creep and corrosion. However, it makes the alloys less flexible. Similar to Mo, Cr also enhances corrosion resistance, but at high concentrations, it diminishes both ductility and toughness. Another notable stabilizing element is Nb, which significantly impacts the transus temperature of alloys, enabling the beta alloy to exist even at room temperature. In addition, Nb enhances strength, creep resistance, and corrosion resistance, at the cost of reduced elasticity (Cardoso *et al*., 2023).

Alongside alpha and beta-stabilizing elements, we have neutral elements–elements that contribute to the overall performance of the alloy without influencing either phase. Elements such as Sn and Zr are usually used to improve the properties of alloys, for example, improving corrosion resistance, enhancing weldability, and improving toughness and ductility (Norihiko *et al*., 2024; Kong *et al*., 2021).

Applications dictate the choice of alloying elements, which significantly influence the properties and performance of alloys. With a wide range of properties and applications, titanium alloys can be tailor-made for specific parts or given a wide array of options, all this thanks to alloying elements, allowing for the selection of alpha, beta, and alpha+beta titanium alloys, whilst ensuring an optimal combination of strength, ductility, corrosion resistance, malleability, or high-temperature stability. The key to the optimization of titanium alloys for targeted applications stands in the understanding of alloying elements and their impact.

3. Extraction and Production of Titanium

Titanium is an important material in several industries due to its properties; however, the extraction and production of high-quality performing alloys is an advanced operation. Starting from the extraction, followed by the

Kroll or Hunter method, and in the end, the incorporation of alloys for better properties, titanium follows a strict journey with many steps.

Titanite is primarily found in ores such as anatase, brookite, ilmenite, rutile, and titanite. Mining these ores is a important step in determining the overall cost-effectiveness and efficiency of the titanium production process. For the mining process, the employed techniques are dry mining, underground shafts, and open-pit mining. The steps following the mining processes usually include the grinding and crushing of the ores and the purification; titanium is then shaped and treated for applications. The sheet flow of titanium fabrication is presented in Figure 3.

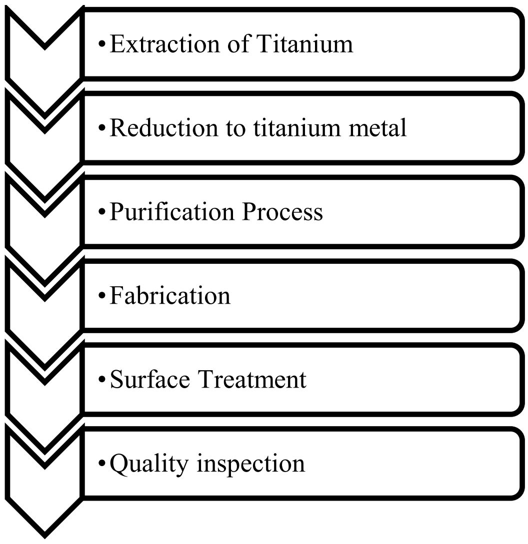

Fig. 3 – Sheet Flow for the Fabrication of Titanium.

The reduction to titanium metal is a step that can occur only after the chlorination of titanium dioxide and obtaining titanium tetrachloride. When the Kroll Method or the Hunter Method is used, titanium tetrachloride is broken down into titanium and magnesium dichloride. When the Hunter Method is used, titanium and sodium chloride are formed (Maldybayev *et al*., 2024; Okabe and Takeda, 2020).

For the purification of the titanium collected, the methods used are vacuum distillation or arc melting. The finishing touches refer to surface treatments and include anodizing or coatings. The final inspections encompass a range of tests, including dimensional inspection, mechanical property testing, and chemical testing.

As an alternative to the Kroll process, the electrolytic reduction of titanium and the hydride-dihydride process are also ways to get titanium. These methods are still being studied in order to make the process cheaper and better for the environment.

Obtaining titanium from its ores is an important first step that dictates the direction in which production is headed, the cost, the impact on the environment, and how fast the material is obtained, reasons for which the study of new methods is always a great idea.

4. The Characterization of Titanium Alloys

The properties of the titanium alloys are well suited for several applications, but there is always room for improvement where alloys have specific targets and the need to be tailor-made. Understanding the mechanical, thermal, and chemical properties is what allows for their optimization.

The chemical and physical properties of titanium are presented in Table 5.

Table 5
Chemical and physical properties of Titanium

Information		Chemical Properties		Physical Properties	
Name	Titan (Ti)	Atomic Mass	47.867	Natural State	Solid
Chemical Class	Transition Metal	Atomic Radius	140 pm	Melting Point	1941 K
Density	4.506 kg/m^3	Oxide	Amphoteric	Boiling Point	2560 K
Colour	White-Silver	Crystalline Structure	hexagon	Molar Volume	$10.64 \cdot 10^{-6}$ $m^3/Kmol$

This chapter will discuss the various methods used in the characterization of titanium alloys, going from microstructure analysis to methods used to inspect corrosion resistance, mechanical behavior, and phase transformation. The information is based on Rusu *et al.* (2012).

4.1. Microstructural characterization

The alloying elements, processing techniques, and heat treatments influence the microstructure, which is crucial for understanding the properties and behavior of titanium alloys. The go-to methods for microstructural analysis are optical microscopy, SEM (scanning electron microscopy), and TEM (transmission electron microscopy).

Optical microscopy allows for the observation of grain size, phase distribution, and the detection of defects (Myslyvchenko *et al.*, 2021).

When you combine energy dispersive x-ray spectroscopy with SEM, you can get high-resolution pictures of the surface microstructure. This can help you figure out what chemicals are in different parts of the titanium alloys (Lypchanskyi *et al.*, 2024; Mello *et al.*, 2020).

Transmission electron microscopy, similarly to SEM, provides high-resolution images, but unlike SEM, TEM shows a 2D image projection of the sample.

4.2. Mechanical characterization

The mechanical characterization includes a series of tests for the alloys; these are as follows (Nazarov, 2022):

- Tensile strength: by applying a uniaxial tensile load to a sample, one can determine the yield strength, tensile strength, and elongation.
- Hardness–measures a material's resistance to plastic deformation, and the wear resistance it provides correlates to its strength. The most common methods include the Vickers, Rockwell, and Brinell hardness tests.
- Fatigue–testing that includes repeated loading of the material, either compression-compression, tension-tension, or the combination of the two.

4.3. Corrosion resistance

The oxide layer that forms on the surface of titanium alloys makes them resistant to corrosion. This is a great standard property, but if titanium alloys are left in harsh environments for a long time, they may not last as long as expected, which is why testing is important. The methods utilized to test the corrosion resistance of the material are electrochemical techniques and salt spray testing.

Salt spraying is the exposure to a salt solution in a special chamber by the same name as the test, the duration of which varies; the shortest period is usually one day.

The electrochemical techniques are *potentiodynamic polarization testing, which implies the immersion of a sample in an electrolyte while applying voltage; Immersion testing*, as the name suggests, is the immersion of a sample in a corrosive medium for 30 to 90 days; *cycling corrosion testing* is a cycle of exposure to salt spraying, drying, and humidity.

4.4. Phase analysis

The phase composition of titanium alloys affects their applications, so it's important to analyze which phase is used. The methods for the test are X-ray diffraction and differential scanning calorimetry.

Characterization in titanium alloys is one of the most important steps for its role in industrial applications. Multiple tests are needed to occur for the study of the material, but this knowledge is also critical for further designs of titanium alloys and, more importantly, enhancing properties for targeted applications.

5. Applications of Titanium Alloys

The properties of titanium, whether alone or alloyed, contribute to its great reputation and are evident in many applications. This chapter will highlight the most significant modern applications of titanium alloys, including aerospace, medical, marine, automotive, and industrial applications.

5.1. Aerospace applications of titanium alloys

Titanium alloys are integral in the aerospace industry thanks to their high strength-to-weight ratio, high corrosion resistance, and high-temperature resistance, used for engine parts, airframes, and landing gear.

The alloys are widely used in engine components like turbine blades, compressors, and casings thanks to the lightweight properties they offer, while alloys like Ti-6Al-4V and Ti-5Al-2.5Sn are favored in high-temperature sections of the engine. At the same time, the corrosion resistance plays a crucial role in the longevity and performance of aircraft; as such, titanium alloys are employed for the construction of wings and fuselages. This information is based on studies conducted by Gialanella *et al.* (2020) and Zhao *et al.* (2022).

5.2. Medical applications

Titanium is the preferred material in the medical field for implants, prostheses, and equipment due to its biocompatibility, corrosion resistance, and ability to integrate into the bone structure.

Orthopedic implants, such as hip replacements and knee implants, have certain strength and corrosion resistance requirements, together with the need to promote osseointegration, alloys like Ti-6Al-4V (Baltatu *et al.*, 2019a).

In the same field, titanium alloys play an important role in dental implants and other medical devices. Medical implants and devices benefit from both the corrosion resistance and non-reactive nature of titanium alloys, according to Marin and Lanzutti (2015) and Khorasani *et al.* (2015).

5.3. Automotive industry

Likewise for the aircraft industry, the need in the automotive one is that of a material that can withstand the high temperatures of the engine while also creating a durable but lightweight automobile with a protective casing. Exhaust systems, engine turbines, suspensions, valves, and certain body kits utilize titanium alloys. Due to the difficulties of shaping titanium, race cars primarily benefit from its properties (Furuta, 2019).

5.4. Marine industry

The marine industry found more uses for titanium alloys due to their exceptional resistance to seawater corrosion. The primary applications for these alloys include marine structures such as ship hulls, propellers, and underwater pipelines, as well as desalination plants, heat exchangers, pumps, and piping systems (Oryshchenko *et al.*, 2015).

Like most metals, titanium allows for recycling and sustainability; its longevity and many uses actually show the demand for these actions. Current studies indicate that recycling titanium is not as easy and forward as it may seem. Given the iron and oxygen impurities found in the scraps, titanium is quite difficult to recycle, or better said, has a high price. For these reasons, the production cost of titanium needs to be lowered, titanium needs to be used more commonly, and further studies need to be developed (Takeda *et al.*, 2020).

Titanium is already a very important element in the industry; further study will only elevate this material, challenging further than the automotive, medical, and aerospace industries.

6. Conclusions and Future Directions

Titanium alloys are used in many applications, including biomedical ones, thanks to their properties; however, like other materials, titanium alloys come with both advantages and disadvantages in certain applications. We went over the various advantages titanium alloys have; as for the disadvantages, these include high production cost, limited wear resistance, difficulty in making, lower modulus of elasticity, the need for surface modification, limited strength in some cases, and critical attention to its purity and alloying elements. While these are not disadvantages, the design of biomaterials presents additional challenges, including material biocompatibility, degradation, and long-term safety.

When considering a biomaterial, the requirements it has include biocompatibility, sterilizability, mechanical compatibility, high corrosion resistance, high wear resistance, and osseointegration.

Biocompatibility is one, if not the most important, property of biomaterials, including titanium alloys, and is usually defined as the ability to interact with the human tissues without causing adverse reactions (Baltatu *et al.*, 2019b). It is clear that the biocompatibility also refers to the chemical reactivity of the material, reactions that need not influence the tissues it comes in contact with, but allowing these reactions to benefit the material, one such example is the oxidation of titanium alloys, whereby it creates an outside oxide layer, making the material more durable at no cost for the living system that is found in contact with. Another example of a beneficial process of biomaterials is osseointegration. The migration of bone cells to the surface of the biomaterial forms a bond between the selected material and the bone. The macro/micro-design of the implant and its chemical and physical characteristics influence osseointegration (Hudecki *et al*., 2019).

When it comes to properties like being able to be sterilized, being mechanically compatible, having high corrosion resistance, and high wear resistance, the alloying elements and processing methods used have a big impact.

The future for the use of titanium alloys in biomedical applications looks promising. Some of the key aspects of innovation are customized implants; with the advancements in 3D engineering, the materials can be made to more easily suit the patients, allowing for the design and production of custom-made implants, resulting in improved outcomes for bone-engineered implants (Ringer and Qian, 2023).

Another aspect is related to the biocompatibility and osseointegration. Thanks to ongoing research on surface treatments and its focus on enhancing the surface properties of titanium alloys, we could see treated materials with faster and more effective osseointegration. Surface treatments, bulk modifications, biologic incorporations, coatings, and alloy modifications aim to make titanium more suited for human tissue interactions and accelerated healing time (Bandyopadhyay *et al.*, 2023).

Yang and Hong (2024) did a study that suggests using nanostructured calcium-incorporated surface treatment to improve bioactivity and bone cell and apatite formation. This makes the material more biocompatible and helps it fuse with bone. Other methods of improving these properties are through chemical methods: surface coatings, electrochemical anodizing, chemical depositions, and etching (Sarraf *et al*., 2022). Efforts are being made to enhance mechanical properties such as fatigue resistance, elasticity, and wear resistance, with the goal of achieving long-term use in high-stress applications.

Although the easiest solution is the usage of alloying elements such as Al and V, the benefit to its properties comes at the cost of implant biocompatibility; as a result, cpTi needs a rework and further study for the improvement of its properties through surface modifications (Pesode and Barve, 2023).

Functionalizing surfaces with bioactive molecules and antimicrobial agents could better sterilize alloy surfaces, thus improving implant success rates. Further refinements can be considered, examples being surface texturing to improve cellular adhesion (Yang and Hong, 2024).

Biodegradable titanium alloys can gradually dissolve and be absorbed in the human body, eliminating the need for removal surgeries and benefiting applications like temporary implants. Magnesium is degradable and gets absorbed in the body; as for the titanium, thanks to its biocompatibility and osseointegration, there exists the possibility of full integration in the bone. While a metallic biomaterial, biodegradable titanium alloys actually refer to magnesium-based alloys with titanium being one of the alloying elements. Due to its biocompatibility and biodegradation, magnesium is a beneficial material for medical applications; however, its rapid degradation rate and low corrosion resistance present challenges. Researchers are studying and proposing Mg-Ti alloys to mitigate issues, such as enhancing corrosion resistance while maintaining biocompatibility (Sharma *et al*., 2024). Titanium plays a significant role in many industries; the focus right now is to further improve its workability, from new alloy designs to improving its properties through surface modifications, and more importantly, to study ways to reduce the risk taken when choosing titanium for biomedical applications.

Recent studies have demonstrated methods for enhancing fatigue resistance, enhancing biocompatibility, and enhancing longevity, but these are not the only advancements. Other important factors to look forward to are reducing production costs and improving recycling. In conclusion, reducing production costs and improving recycling are important factors to look forward to.

The properties titanium alloys offer are essential for industrial applications; the problems that arise are cost-related and accessibility-related. Through the studies for an easier development cycle, titanium could make its way into more applications, in turn raising the interest towards the material and empowering its study, a cyclical process that starts with making titanium and titanium alloys more accessible, promoting its study, and repeating. Through continuous research and innovation, the use of titanium and its alloys can only go up.

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ALIAJE AVANSATE DE TITAN PENTRU UTILIZĂRI MEDICALE ȘI INDUSTRIALE

(Rezumat)

Scopul acestui articol este de a discuta metode de îmbunătățire a proprietăților aliajelor de titan, investigând diferite strategii de intensificare a durității materialului, rezistenței la coroziune, și cel mai important biocompatibilității, cu accent pe performanță mecanică, integritate structurală și biocompatibilitate, potrivite implanturilor ortopedice și dentare. Lucrarea examinează efectele diferitelor elemente de aliere și impactul pe care îl au fazele titanului asupra proprietăților sale. În plus, articolul discută și despre metodele de producție, plecând de la extragere până la tratamente de suprafață, și include metode de caracterizare structurală, testare mecanică, evaluarea rezistenței la coroziune. Titanul și aliajele sale sunt apreciate pentru raportul duritate-greutate, buna rezistență la coroziune, flexibilitate și biocompatibilitate, făcându-le potrivite pentru o gamă variată de aplicații, ce vor fi detaliate în această lucrare. Propunerile viitoare pun accent pe proiectarea cu imprimante 3D, pentru dezvoltarea implanturilor personalizate, modificări de suprafață pentru îmbunătățirea biocompatibilității, și explorarea opțiunilor de aliaje biodegradabile.