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PROSPECTS ON TITANIUM BIOMATERIALS

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Abstract

Biomaterials are substances that have been engineered to interact with biological systems for a medical purpose, either a therapeutic or diagnostic one. Biomaterials have a rich history of evolution, as they have continuously transformed from simple inert substances to complex, interactive materials, designed to communicate with biological systems and promote tissue regeneration and healing. Titanium, due to its excellent biocompatibility, corrosion resistance, and mechanical properties, has established its place as one of the most used biomaterials, particularly in orthopedics and dental applications. This article provides an overview of titanium as a biomaterial, highlighting its properties, applications, and recent advancements.

Keywords: *Biomaterials, Titanium-based alloys, low young modulus, β-type alloys*

Introduction

The introduction of titanium and its alloys into the biomedical field has revolutionized the way medical professionals approach the design and manufacturing of various medical devices and implants. Known for their exceptional mechanical properties, biocompatibility, and resistance to corrosion, titanium and its alloys have become the materials of choice for a wide range of applications, including orthopaedic implants, dental implants, and cardiovascular devices. As the demand for more advanced and customized biomedical devices grows, so does the need for a comprehensive understanding of the fabrication techniques and characteristics of titanium and its alloys. This article aims to provide a state-of-the-art review of the various methods used to fabricate titanium and its alloys, as well as an in-depth analysis of their properties and performance in biomedical applications. Ultimately, this article will serve as a valuable resource for researchers, engineers, and medical professionals seeking to harness the full potential of titanium and its alloys in the development of next-generation biomedical devices [1-3].

In a world where the demand for artificial tissues and implants is steadily rising, the need for safe, durable, and biocompatible materials has never been more crucial. The surge in procedures like arthroplasty, dental implants, and surgical instrumental applications necessitates the development of materials that not only mimic the mechanical properties of natural tissues but also do not elicit adverse reactions in the body. Traditionally, materials like 316L stainless steels and Co–Cr-based alloys have been employed, but recent studies have raised concerns about their long-term safety and effectiveness. Stress corrosion cracking in 316L stainless steel and the release of potentially toxic ions such as Cr and Co from Co–Cr-based alloys have cast doubt on

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their suitability as implant materials [4-6]. This has shifted the focus towards alternative materials, with titanium and its alloys emerging as promising candidates. Known for their exceptional fatigue life, corrosion resistance, and biocompatibility, titanium alloys seem to address many of the shortcomings of their predecessors. However, despite their advantages, there is a need for further development and modification to optimize their performance in clinical applications. This article aims to provide a comprehensive review of the development of titanium and its alloys for various biomedical applications, carefully examining their functional properties, surface modifications, and advanced manufacturing technologies. Additionally, it will delve into the potential of titanium in nanomedicine and discuss future directions for research in this rapidly evolving field [6-8].

The Necessity of Discovery

The discovery of biomaterials is essential for enhancing human life quality and treating a variety of ailments and diseases. Biomaterials are employed in several medical applications, including implants, prosthetics, medical devices, and biomedical research [2].

There is a growing need for innovative and efficient biomaterials for several reasons:

Demographic Growth: The global population is increasing, which brings with it a heightened demand for medical treatments such as implants and prosthetics.

Increasing Life Expectancy: Life expectancy is rising, meaning people are living longer and require long-term medical treatments.

Technological Advancement: Ongoing technological advancements allow for the development of new biomaterials and the improvement of existing ones, enabling the creation of more efficient and safer medical devices.

Increasing Disease Incidence: The incidence of conditions such as cancer, cardiovascular diseases, and osteoarthritis is rising, indicating a heightened demand for efficient and innovative medical solutions.

The evolution of biomaterials science and technology continues to advance (Fig. 1), with ongoing research focusing on improving biocompatibility, enhancing material properties, and developing innovative solutions for various medical and healthcare challenges. This interdisciplinary field plays a crucial role in improving patient outcomes, extending human lifespans, and enhancing the quality of life.

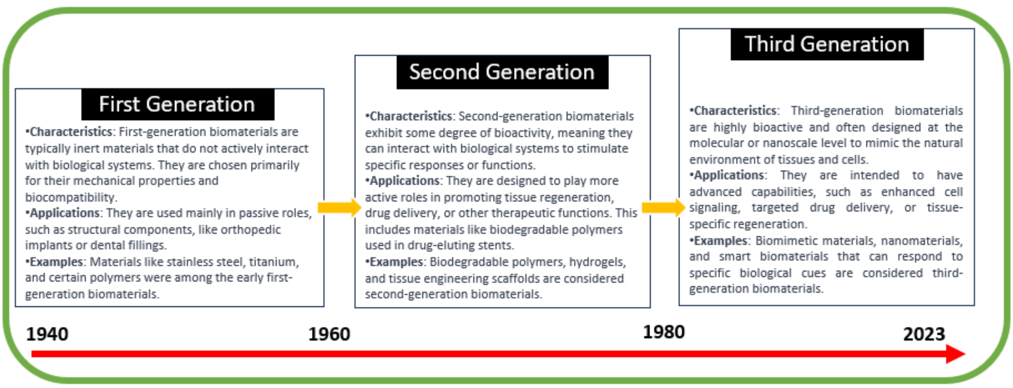

Fig. 1. The evolution of biomaterials science and technology.

Overall, the discovery of biomaterials is crucial for improving health and human life quality. This field continues to evolve and bring innovations to medicine, which could lead to better and more efficient treatments for a wide range of ailments and diseases [11,12].

Classification of biomaterials

Biomaterials are materials used in medical applications to replace or repair tissues and organs. They are often used in implants, medical devices, and drug delivery systems. Biomaterials can be classified in several different ways, depending on various criteria. Here are some common ways to classify biomaterials [13-15]:

By Origin

• *Natural.* These are materials that originate from nature, such as collagen, cellulose, gelatine, and others.

• *Synthetic.* These are materials manufactured in the laboratory, such as synthetic polymers (polyethylene, poly lactic-co-glycolic acid), metals (titanium, stainless steel), and ceramics (hydroxyapatite).

By Type of Material

• *Polymers.* These are materials composed of long chains of molecules. Examples include polylactic acid (PLA), polyglycolic acid (PGA), and polyethylene (PE).

• *Metals.* These are metallic materials, such as titanium, stainless steel, and cobalt-chromium alloys.

• *Ceramics.* These are inorganic materials that are typically very hard and brittle. Examples include hydroxyapatite, alumina, and zirconia.

• *Composite Materials*. These are materials composed of two or more different types of materials. For example, a composite of polymer and ceramic materials.

By Biological Response

• *Bioinert*. These are materials that do not interact with the biological environment and are not resorbed by the body. Examples include titanium and alumina.

• *Bioactive.* These are materials that interact with the biological environment and form a bond with the surrounding tissue. Examples include hydroxyapatite and bioactive glasses.

• *Resorbable.* These are materials that are eventually resorbed by the body and replaced by natural tissue. Examples include PLA and PGA.

By Application

• *Orthopaedic*. These are materials used in the replacement or repair of bones and joints. Examples include titanium alloys, stainless steel, and hydroxyapatite.

• *Dental*. These are materials used in dental applications. Examples include dental amalgams, resin composites, and ceramics.

• *Cardiovascular*. These are materials used in the repair or replacement of cardiovascular tissues. Examples include stainless steel, nitinol, and polyurethane.

• *Drug Delivery.* These are materials used to deliver drugs to specific locations in the body. Examples include PLA-PEG (polylactic acid-polyethylene glycol) copolymers and liposomes.

This is just a basic classification and there are many other ways to classify biomaterials. Additionally, the development of new materials and technologies is constantly expanding the range of biomaterials available [16, 17].

History of titanium

The history of titanium alloys dates back to the early 20th century. Titanium itself was first discovered in 1791 by the British clergyman and mineralogist William Gregor, but it was not until the 1930s that it was first commercially produced. During the 1950s and 1960s, the development of titanium alloys started to gain momentum, primarily driven by the aerospace industry's demands for lightweight and high-strength materials that could withstand extreme temperatures [18].

The first titanium alloy, Ti-6Al-4V, was developed in the 1950s and is still the most commonly used titanium alloy today. It consists of 90% titanium, 6% aluminium, and 4% vanadium, which gives it a good balance of strength, weight, and corrosion resistance [19].

Over the years, various other titanium alloys have been developed to meet specific needs. For example, Ti-6Al-7Nb and Ti-5Al-2.5Fe were developed for biomedical applications due to their excellent biocompatibility and mechanical properties. Ti-3Al-2.5V was developed for aerospace applications requiring higher strength and lower weight [20].

The development of titanium alloys has been influenced by several key factors, including the need for better mechanical properties, improved corrosion resistance, and enhanced biocompatibility for biomedical applications. Advances in manufacturing processes, such as powder metallurgy and additive manufacturing, have also played a crucial role in the development of titanium alloys, allowing for more complex designs and better control over the material's microstructure [21].

Today, titanium alloys are used in a wide range of applications, from aerospace components to medical implants, due to their unique combination of properties. The ongoing research and development in this field promise to bring even more advanced titanium alloys with improved properties and functionalities in the future [22].

Titanium biomaterials have a rich history and have been pivotal in the advancement of medical science. In the Fig. 2 is presented a brief history of titanium biomaterials:

Fig. 2. A brief history of titanium alloys.

Since 2000, several new titanium alloys have been developed for biomedical applications, including Ti-13Zr-13Ta for implants, Ti-15Mo for biomedical applications, Ti-15Mo-2.8Nb-

0.2Si-0.28O for orthopaedics, Ti-15Zr-4Nb-4Ta for implants, Ti-35.3Nb-5.1Ta-7.1Zr for biomedical applications, Ti-29Nb-13Ta-4.6Zr for biomedical applications, Ti-15Zr-4Nb-4Ta-0.2Pd for medical implants, and Ti-5Al-1.5B for biomedical applications [23-25].

Today, titanium and its alloys are widely used in various medical applications including orthopaedic implants (hip and knee replacements), dental implants, pacemaker cases, surgical instruments, and more. The development and refinement of titanium biomaterials have greatly contributed to the success of many medical procedures and improved the quality of life for millions of people.

Properties of Titanium

Titanium is a chemical element with the symbol Ti and atomic number 22. It is a transition metal known for its excellent strength-to-weight ratio, corrosion resistance, and biocompatibility. In Fig. 3 is presented some of the key physical properties of titanium element [17].

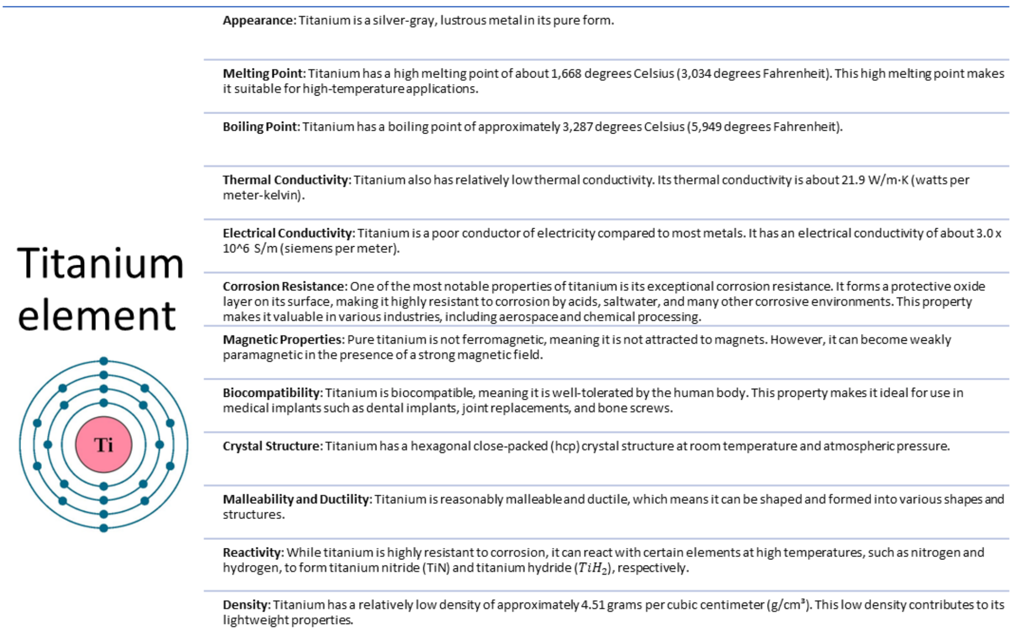

Fig. 3. Some properties of Titanium element.

Titanium alloys (Fig. 4) boast a unique combination of properties that make them the material of choice for a wide array of applications. Their high strength-to-weight ratio makes them perfect for applications requiring strength without the added weight, such as aerospace and medical implants. The alloys are also highly resistant to corrosion from oxygen, water, and various chemicals, a crucial property for materials exposed to corrosive environments like the human body or seawater. Moreover, their biocompatibility ensures they are non-toxic and well-tolerated by the human body, making them suitable for medical applications like implants and prosthetics. Additionally, their low thermal conductivity, good fatigue resistance, ability to withstand high temperatures, and non-magnetic nature further expand their application range to include areas where thermal insulation, repeated loading and unloading, high-temperature resistance, and non-interference with medical imaging are necessary [26]. Lastly, some titanium alloys, such as nickel-titanium (NiTi), exhibit shape memory and superelasticity properties, enabling them to return to their original shape after deformation when heated or undergo large deformations without permanent deformation. It is important to note, however, that the properties of titanium alloys can vary significantly based on the specific alloy, its processing, and the addition of different alloying elements.

Titanium alloys

- **Good fatigue resistance**
- **Ability to withstand high temperatures**
- **Non-magnetic**
- **Shape memory and super elasticity**
- **Biocompatibility**
- **Corrosion resistance**
- **High strength-to-weight ratio**
- **Low thermal conductivity**

Fig. 4. The main properties of titanium biomaterials.

This variability allows for the customization of the alloy's mechanical properties, corrosion resistance, and biocompatibility to suit specific applications. Heat treatment, surface treatment, and other processing techniques can further modify the properties to meet specific requirements [27].

Applications

Titanium biomaterials have revolutionized the field of medical science, finding diverse applications in various healthcare domains. These remarkable materials, known for their exceptional biocompatibility and mechanical properties, have opened new doors for medical advancements. Some of the key applications of titanium biomaterials that are shaping the future of healthcare are [2, 28, 29]:

Orthopedic Implants

Titanium's strength and biocompatibility make it a top choice for orthopedic implants such as hip and knee replacements. These implants provide durability and longevity, allowing patients to regain mobility and enjoy an improved quality of life.

Dental Implants

Dental practitioners widely use titanium for dental implants. These small but essential devices provide a stable foundation for crowns, bridges, and dentures, mimicking the natural tooth root's strength and stability.

Cardiac Devices

Titanium is also utilized in cardiac devices like pacemakers and implantable defibrillators. Its corrosion resistance and lightweight properties make it ideal for these critical applications, ensuring long-term reliability within the body.

Spinal Implants

Titanium spinal implants offer stability and support in spinal surgeries, treating conditions such as herniated discs and spinal deformities. These implants promote spinal fusion while withstanding the stresses of daily life.

Ophthalmic Instruments

In ophthalmology, titanium is used in instruments like intraocular lenses (IOLs) and surgical tools. Its biocompatibility and resistance to bodily fluids make it a safe and effective choice for procedures like cataract surgery.

Craniofacial Reconstruction

Titanium plates and screws are employed in craniofacial surgeries to reconstruct facial bones and repair trauma-related injuries. These implants provide structural integrity while minimizing tissue reaction.

Biomedical Instruments

Titanium's non-magnetic properties have made it invaluable in the manufacture of medical instruments used in MRI and other diagnostic procedures, ensuring patient safety and image clarity.

Dermatological Implants

In dermatology, titanium is used for the production of dermatome blades used in skin grafting procedures, ensuring precision and safety in tissue transplantation.

Drug Delivery Systems

Researchers are exploring the use of titanium-based drug delivery systems. These systems can be implanted to deliver medication directly to target tissues, reducing side effects and improving treatment effectiveness.

Dental and Orthopedic Screws

Titanium screws are widely used in dental and orthopedic surgeries for fixation purposes. Their strength, resistance to corrosion, and biocompatibility play a crucial role in the success of these procedures.

Biological Research

Titanium is utilized in laboratory settings for various applications, including the construction of cell culture dishes and bioreactors due to its ability to foster cell growth without causing contamination.

The most important applications of these titanium biomaterials are illustrated in Fig. 5.

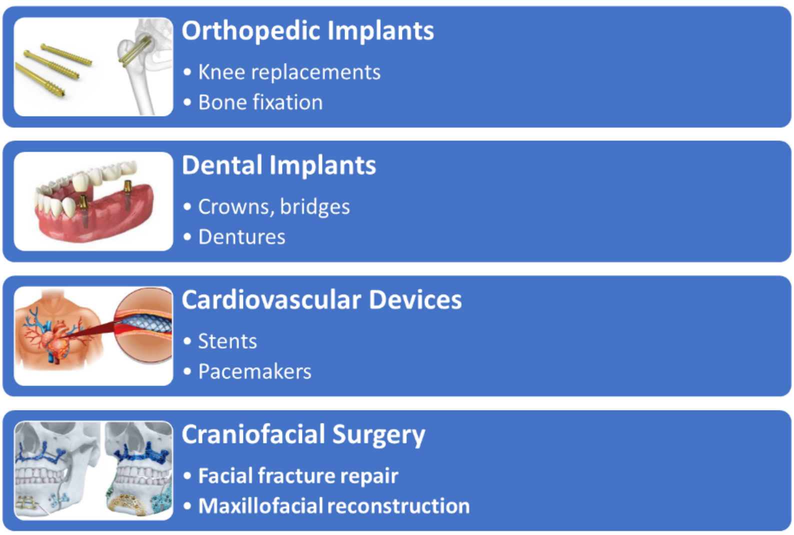

Fig. 5. The main applications of titanium biomaterials.

New generation βeta titanium alloys

In current research on titanium alloys, there are two primary focuses: Firstly, the utilization of non-toxic alloying elements, and secondly, the minimization of Young's modulus within these alloys. Elements like Nb, Ta, Zr, Mo, and Sn, known for their biocompatibility and low toxicity, are being harnessed to pave the way for the development of next-generation β-Ti alloys. Furthermore, alloys incorporating these elements exhibit notably reduced elastic modulus values when compared to other titanium alloys. Consequently, these advanced β-Ti alloys are driving significant advancements in the field of biomaterial manufacturing [6, 30, 31].

Titanium biomaterials must meet specific requirements to ensure they interact effectively and safely within the human body. In the Fig. 6 are some key requirements for titanium biomaterials:

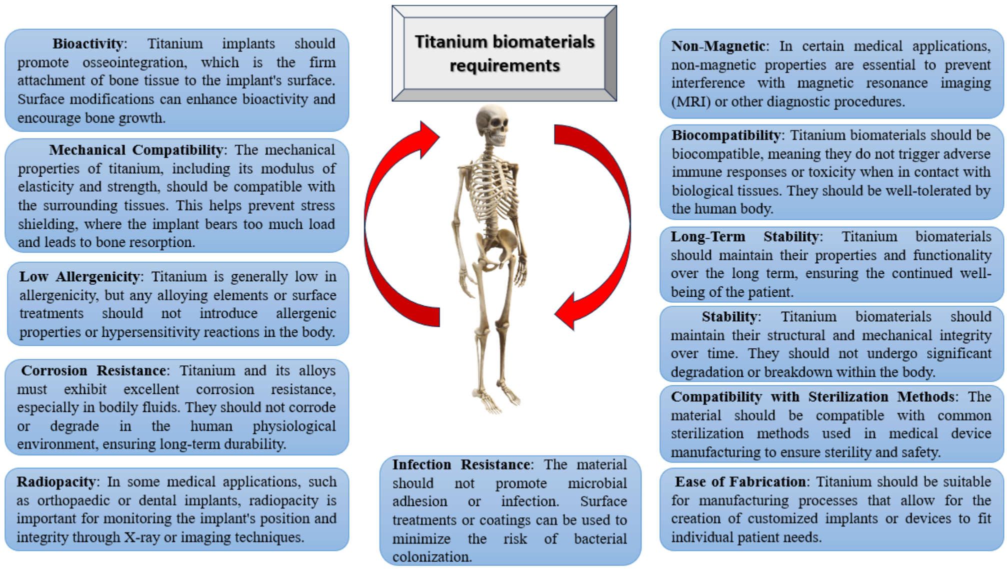

Fig. 6. Requirements for titanium biomaterials.

The elastic modulus of a material, also known as Young's modulus, represents a measure of the stiffness and the ability of materials to return to their original shape after the application of a force. Alloying elements can influence the elastic modulus of a material in various ways (Fig. 7), depending on how they interact with the crystalline structure and atomic bonds of the material. It is important to note that the influence of alloying elements on the elastic modulus can be complex and depends on the exact composition of the alloy, the manufacturing process, and the temperature and pressure conditions. Therefore, in the development and design of alloys, researchers and engineers must consider how alloying elements will affect the mechanical properties, including the elastic modulus, to achieve the desired performance for specific applications [32-34].

Meeting these requirements is essential for the successful integration of titanium biomaterials into the human body, reducing the risk of complications and promoting the overall health and well-being of the patient [17].

Recent Advancements

Recent advancements in titanium alloys and materials are driven by a combination of industry demands, technological opportunities, environmental concerns, and the quest for more efficient solutions to meet the evolving needs of a rapidly changing world. An overview of some promising areas of advancement up to that point [30]:

Additive Manufacturing (3D Printing)

Additive manufacturing techniques, such as selective laser melting (SLM) and electron beam melting (EBM), have enabled the production of complex and lightweight structures using titanium alloys. Researchers have been working on optimizing the microstructures and properties of 3D-printed titanium components for various applications, including aerospace and healthcare.

New Alloy Compositions

Scientists have been developing new titanium alloy compositions to enhance specific properties. For instance, beta titanium alloys, like Ti-10V-2Fe-3Al, have shown improved strength and fatigue resistance, making them attractive for aerospace applications. There's also ongoing research into high-temperature titanium alloys for gas turbine engines.

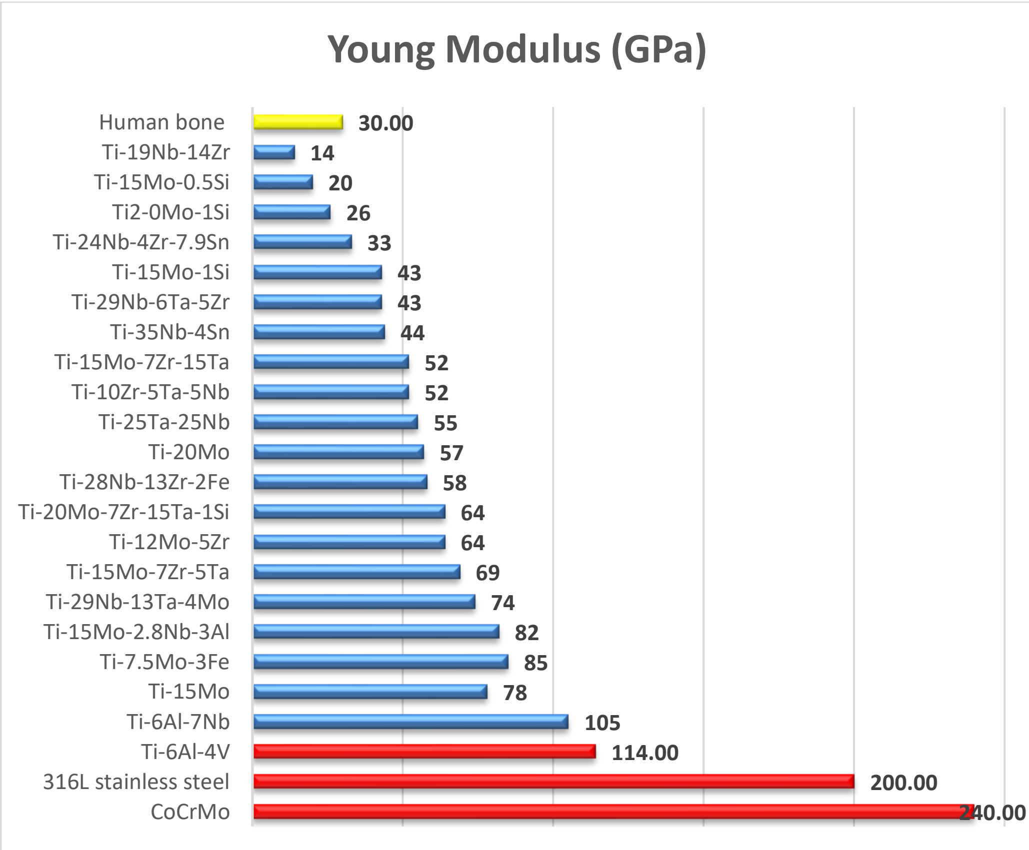

Fig. 7. The influence of alloying elements on the modulus of elasticity of titanium alloys.

Biomedical Applications

Titanium alloys are widely used in medical implants, and research has been focused on improving their biocompatibility and performance. Surface modifications and coatings are being explored to enhance osseointegration (the connection between bone and implant) and reduce the risk of infection.

Corrosion Resistance

Researchers have been working on improving the corrosion resistance of titanium alloys for applications in aggressive environments, such as marine and chemical processing. Surface treatments and coatings are being developed to enhance their performance.

Hydrogen Storage

Titanium-based alloys have been studied for their potential use in hydrogen storage applications. These alloys can absorb and release hydrogen gas reversibly, which is important for clean energy storage and transportation.

Lightweighting in Automotive

Titanium alloys are being considered for lightweighting in the automotive industry to improve fuel efficiency and reduce emissions. Efforts are focused on developing cost-effective processes for incorporating titanium components in vehicle designs.

Aerospace Applications

Titanium alloys continue to play a crucial role in aerospace applications due to their high strength-to-weight ratio. Ongoing research seeks to further optimize these alloys for aerospace use, including improving their resistance to fatigue and damage tolerance.

Improved Manufacturing Techniques

Advances in machining, heat treatment, and forming processes are being developed to reduce production costs and increase the efficiency of manufacturing titanium components.

Recycling and Sustainability

Research has been conducted on recycling titanium alloys to reduce waste and energy consumption. Additionally, efforts are underway to assess the environmental impact of titanium alloy production and identify sustainable practices.

Computational Modelling

Computational modelling and simulation techniques are being used to predict the behaviour of titanium alloys under various conditions, aiding in the design and optimization of materials and structures.

These advancements highlight the ongoing efforts to enhance the properties and expand the applications of titanium alloys. It's likely that research and development in this field have continued to progress, driven by the demand for materials with superior properties in various industries.

Conclusions

Titanium biomaterials have had a remarkable journey over the past few decades, evolving from being a novel material for bone implants to one of the most widely used materials in the field of medicine and dentistry. Initially, the biocompatibility and corrosion resistance of titanium made it a preferable choice over other metallic materials. Over time, advancements in technology have allowed for the development of titanium alloys and surface modifications, which have enhanced the osteointegration, mechanical properties, and overall performance of titanium-based implants. The recent advancements in additive manufacturing and nanotechnology have further revolutionized the use of titanium, enabling the fabrication of patient-specific implants with complex geometries and nanostructured surfaces that promote better cellular interaction and tissue regeneration. Overall, titanium biomaterials have come a long way and will continue to play a pivotal role in the future of regenerative medicine and implantology.

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