Research and progress of mechanical properties of titanium and titanium alloy

Xingping Fan

School of Vanadium and Titanium, Panzhihua University, Panzhihua, 617000, China

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Abstract: With the continuous progress of medical technology, more and more people need to treat various diseases through implants. Titanium and its alloys are one of the first choices for biomedical implant materials because of their excellent biocompatibility, mechanical properties and corrosion resistance. This paper discusses the biomedical titanium and titanium alloy, on this basis, the mechanical properties of biomedical titanium and titanium alloy, and combined with the characteristics of the biomedical implantation of titanium and titanium alloy, further discusses the mechanical properties improvement technology, help to promote the mechanical properties of biomedical titanium and titanium alloy research, and then provide high quality materials for biomedical implantation.

1. Preface

Biomedical implant titanium and titanium alloys is a widely used material in the medical field for making orthopedic and dental implants. With the increasing requirements for biomedical materials, their mechanical properties are increasingly demanding. Mechanical properties are a key index of biomedical implant titanium and titanium alloy, including both static mechanical properties and dynamic mechanical properties. Studying and exploring these mechanical properties can provide a better understanding of the properties of materials and optimize their preparation process and formulation design to improve their application value and safety. Therefore, the study and exploration of the mechanical properties of biomedical implanted titanium and titanium alloy are of great significance to improve their application in the medical field.overview of biomedical titanium and titanium alloys

1.1 Classification and composition

Biomedical titanium and titanium alloys can be divided into pure titanium and titanium alloys according to their composition and application. Pure titanium is divided into four grades according to its impurity content and lattice state, namely TA1, TA2, TA3 and TA4. Titanium alloys can be divided into α, α + β and β alloys, among which the most common is Ti-6Al-4V (α + β) alloy, which consists of 6% aluminum and 4% vanadium, widely used in the biomedical field.

1.2 Biocompatibility

Biomedical titanium and titanium alloys have good biocompatibility and can exist stably in living organisms for long periods without causing rejection reactions. The reason is that the surface of titanium material is easy to form a stable oxide film, preventing the chemical reaction between the material and the components in living organisms. In addition, the elastic modulus of titanium and titanium alloy is similar to that of human bone, which is beneficial to reduce the stress shielding effect between the implant and the bone, thus reducing the risk of fracture and implant loosening.

2. Analysis of the mechanical properties of biomedical titanium and titanium alloys

2.1 Static mechanical properties

(1) The tensile strength

Biomedical titanium and titanium alloys have high tensile strength and can withstand various kinds of tensile forces in living organisms. The tensile strength of pure titanium is usually in

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between 240 and 550 MPa, depending on the preparation process and the material status. Pure titanium materials can reach a high strength level after processing and heat treatment. Titanium alloy Ti-6Al-4V has a higher tensile strength, usually between 900 and 1150 MPa, and also has a high plasticity and toughness. Due to the high strength and good biocompatibility of Ti-6Al-4V alloy, it is widely used in the preparation of medical implant materials. The tensile strength is directly related to the use effect of biomedical titanium and titanium alloy in living organisms. High tensile strength can ensure that the material is not prone to deformation and fatigue damage in the process of long-term use, and can also withstand the influence of external forces to avoid causing tissue damage and inflammatory reaction.

(2) Yield strength

The yield strength of biomedical titanium and titanium alloys refers to the maximum stress that it can withstand before plastic deformation due to external forces. In the case of the application of the implant, the yield strength of the material is very important because if the material cannot withstand the stress, permanent deformation or destruction may occur, resulting in the failure of the implant. Biomedical titanium and titanium alloys have a high yield strength to ensure that the implant does not permanently deform during stress. For example, the yield strength of pure titanium ranges from 170-485 MPa, while the Ti-6Al-4V alloy can yield up to 830-1100 MPa. This high yield strength makes biomedical titanium and titanium alloys ideal for making medical devices such as artificial joints and dental implants. In addition, studies show that the yield strength of biomedical titanium and titanium alloys is related to its grain size, heat treatment status, composition and other factors.

(3) Extension rate

For biomedical implants, a high elongation rate means that it can undergo elastic deformation under complex stress conditions, thus avoiding plastic deformation and fracture of the implant, and ensuring the stability and safety of the implant. Therefore, the elongation rate of biomedical titanium and titanium alloys is also an important parameter in its mechanical properties. In general, pure titanium stretches 10 – 25%, while the Ti-6Al-4V alloy extends 8 – 15%. However, improvements in elongation rates often occur at the expense of a decrease in tensile strength. In the selection of biomedical implants, the balance of tensile strength and elongation rate needs to be comprehensively considered according to the specific use and stress situation of the implants to meet the long-term stability and biocompatibility of the implants in the organism.

2.2 Dynamic mechanical properties

(1) Fatigue strength

Biomedical titanium and titanium alloy have high fatigue strength, which is one of the important guarantees for its long-term use in the human body. When human activities or external forces act, the implant will be loaded repeatedly. If the fatigue strength of the material is insufficient, it may lead to fatigue crack and fracture of the implant, thus affecting the service life and safety of the implant. For pure titanium, its fatigue strength is in the range of 250-400 MPa. The Ti-6Al-4V alloy has a higher fatigue strength, reaching 500-650 MPa. This is because Ti-6Al-4V alloy adds Al and V elements to form a uniformly distributed substable β phase, which makes the material have better fatigue resistance. In addition, the factors affecting the fatigue strength also include the cycle number, cycle load amplitude, cycle load ratio, etc. In practical application, it is necessary to design and select the materials reasonably according to the specific use conditions to ensure the safety and stability of the implant in long-term use.

(2) Impact toughness

The impact toughness of biomedical titanium and titanium alloys is the ability of the material to withstand sudden impact or vibratory loads during implantation. Because within an organism, implants may suffer from sudden impact loads such as exercise or falls. Therefore, the impact toughness of titanium and titanium alloy materials is an important indicator to evaluate the safety of implants. Biomedical titanium and titanium alloys have a relatively high impact toughness, mainly because of their relatively high toughness and ductility. The impact toughness of pure titanium is 4-6 J / cm ^ 2, while that of Ti-6Al-4V alloy is 8-12 J / cm ^ 2. These data show that the impact toughness of the titanium and titanium alloy materials is sufficient to ensure that the implant does not break or deform when subjected to the impact load. In practice, the impact toughness also needs to cooperate with other mechanical properties to ensure the overall safety of the implant. For example, if the strength of the material is too low, the plastic deformation occurs during the large impact loads, leading to the implant failure. Therefore, the mechanical properties of biomedical titanium and titanium alloys need to be fully considered to ensure the long-term safety of the implant.

(3) Wear resistance

The wear resistance of biomedical titanium and titanium alloy is superior to many other metal materials, due to their high hardness and excellent corrosion resistance. Moreover, the surfaces of biomedical titanium and titanium alloys can be modified by a variety of surface treatment techniques to further improve their wear resistance. For example, surface spraying, chemical deposition, electrochemical treatment and other technologies can increase the hardness and wear resistance of the surface of the material, thus improving the wear resistance of the material. In the field of implants, the excellent wear resistance of biomedical titanium and titanium alloy makes it an ideal implant material. For example, in joint replacement surgery, the wear resistance of artificial joints directly affects their service life and patient quality of life. Biomedical titanium and titanium alloys have become commonly used joint replacement implant materials due to their good wear resistance, bringing great benefits to patients. In addition, in the field of bone repair, biomedical titanium and titanium alloy have also been widely used, its excellent wear resistance can ensure the stability and interaction between bone repair materials and surrounding bone tissue, improve the repair effect and the success rate of surgery.

(4) Corrosion resistance

Biomedical titanium and titanium alloys can form dense oxide membranes in living organisms, which is a very thin oxide layer with good stability and corrosion resistance. This oxide film can effectively isolate the direct contact between the corrosion medium and the material surface, thus preventing the corrosion and damage of the material. It have shown that the corrosion rate of pure titanium in saline is about 0.1-0.3 μ m / year, while Ti-6Al-4V alloy in saline is about 0.05-0.2 μ m / year. This shows that biomedical titanium and titanium alloys have good corrosion resistance and can operate stably in living organisms.

3. Improvement of the mechanical properties of biomedical titanium and titanium alloys

3.1 Surface processing technology

Surface treatment technology can effectively improve the mechanical properties, wear resistance and corrosion resistance of biomedical titanium and titanium alloy. The common treatment techniques are as follows:

(1) Surface oxidation

Surface oxidation is a common surface treatment technique whose main purpose is to improve its mechanical properties and corrosion resistance by forming oxide films on the surface of titanium and titanium alloys. The oxide film is usually composed of titanium dioxide (TiO_2) and a small amount of other oxides, with good hardness, wear resistance and corrosion resistance, which can protect the implant surface from erosion and damage from the external environment. Surface oxidation can be achieved by a variety of methods, such as electrochemical, thermal, anodic, etc. Among them, electrochemical oxidation is the most common method. In the process of electrochemical oxidation, the surface of titanium and titanium alloy is placed in the electrolyte as the anode, and the titanium surface is applied to produce oxidation reaction to form an oxide film. Surface oxidation can significantly improve the biocompatibility and mechanical properties of biomedical titanium and titanium alloys. For example, titanium oxide film can increase the friction coefficient and hardness of the implant surface, improve its wear resistance and corrosion resistance, and the oxide film can promote the binding of the implant and the surrounding bone tissue, improve its biocompatibility and long-term stability.

(2) Surface nitrogen infiltration

Surface nitriding is a method of penetrating nitrogen atoms into the surface of titanium and titanium alloy to form a rigid nitride layer. This method can improve the hardness and wear resistance of titanium and titanium alloy surface, thus enhancing their mechanical properties and wear resistance. Surface nitriding technology generally uses nitrogen or ammonia as the nitrogen source, and the nitride layer is formed on the surface of titanium material through the nitriding reaction at high temperature. The advantage of surface nitriding technology is that it does not change the chemical composition of titanium and titanium alloy, and does not have adverse effects on the biocompatibility and bioactivity of the material. In addition, the hardness and wear resistance of the nitrogen infiltration layer are not easily affected by the internal environment. Surface nitriding technology is widely used in the preparation of biomedical titanium and titanium alloys, such as artificial joints, dental implants, etc., which effectively improves the performance and life of implants.

(3) Surface coating

In the biomedical field, the surface coating of titanium and titanium alloys can improve their biocompatibility, bioactivity and antibacterial properties, and improve their application in implants and restorative materials. Surface coatings can be prepared by a variety of methods, including electrochemical deposition, physical vapor deposition, chemical vapor deposition, ion beam deposition, sputtering deposition, etc. Commonly used coating materials include metals, ceramics, polymers, etc.

Metal coatings are mainly titanium alloy and oxides or nitrides of metals such as tungsten, chromium and aluminum. These coatings can increase the hardness, wear resistance and corrosion resistance of titanium and titanium alloy surfaces, but also improve their biocompatibility and bioactivity; ceramic coatings mainly include alumina, zirconia, hydroxyapatite, etc. These coatings promote the binding of titanium and titanium alloy surfaces to bone tissue, increasing the stability of the implant and also improving its wear resistance; the polymer coatings can be prepared by solution deposition, spraying, self-assembly. These coatings can improve the biocompatibility and bioactivity of titanium and titanium alloys, while also achieving functions such as sustained drug release.

3.2 Alloy design and composition adjustment

The mechanical properties, wear resistance and corrosion resistance of titanium alloy are closely related to its composition, so its properties can be improved by alloy design and composition adjustment. The alloy elements added to the titanium alloy include aluminum, vanadium, zirconium, iron, nickel and so on. The addition of these elements can change the crystal structure, grain size and composition ratio of titanium alloy, so as to optimize its mechanical properties and wear resistance. For example, increasing the aluminum content in the Ti-6Al-4V alloy to over 6% can significantly improve its tensile strength and yield strength, while increasing its hardness and wear resistance. In addition, the addition of zirconium elements can improve the corrosion resistance and biocompatibility of titanium alloy, which is suitable for some demanding biomedical applications. At the same time, the addition of elements such as iron and nickel can improve the high-temperature mechanical properties and antioxidant properties of titanium alloy.

3.3 Heat treatment and process optimization

Heat treatment and process optimization is a means to improve the mechanical properties of biomedical titanium and titanium alloys by controlling the processing process and heat treatment parameters of materials. Specifically, process optimization can control the microorganization and morphology of the material by selecting appropriate forging, rolling, and extrusion processing processes. For example, proper cold deformation can introduce higher density dislocations and improve the strength and elongation of the materials. Heat treatment, on the other hand, promotes the grain growth and phase transition in the material by controlling the time and temperature in the heating and cooling process to adjust the mechanical properties and corrosion resistance of the material.

3.4 Research on new biomedical titanium alloy materials

With the development of science and technology, new biomedical titanium alloy materials are constantly emerging. These new materials tend to have better mechanical properties, wear resistance and corrosion resistance to meet the needs of different medical applications. For example, new low elastic modulus titanium alloy, free shape memory titanium alloy and biodegradable titanium alloy, etc.

(1) Low elastic modulus of titanium alloy

Low elastic modulus titanium alloy has an elastic modulus close to the human bone, which can reduce the stress shielding effect between the implant and the bone, and reduce the risk of failure of the bone tissue around the implant. These alloys achieve low elastic modulus characteristics by adding specific elements and adjusting components, such as the addition of molybdenum, zirconium, and tantalum.

(2) Free-shape-memory titanium alloy

Free-shape memory titanium alloy has the ability of free deformation and memory recovery, which can be restored to a preset shape under specific conditions (e. g., temperature, stress). This characteristic makes it widely used in minimally invasive surgery and orthopedic instruments. These alloys usually achieve a memory effect by adding elements such as niobium and hafnium.

(3) Biodegraded titanium alloys

Biodegradable titanium alloy can be absorbed by human tissue within a certain period of time, reducing the long-term impact of implants on human body. These alloys achieve biodegradation properties by adding specific biodegradable elements, such as magnesium, calcium, and zinc. Biodegradable titanium alloy is still in the research stage in the clinical application, but it has great potential and development prospect.

4. Conclusion

In conclusion, great progress has been made in studying the mechanical properties of biomedical titanium and titanium alloys, but further research is still needed. Future research should aim to develop new material design and processing techniques to improve the mechanical properties and biocompatibility of biomedical titanium and titanium alloys to better meet clinical needs.

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