Exploring High-Temperature-Resistant Titanium Alloys: Insights into Multi-Element Alloying for Enhanced Performance

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Abstract. Titanium alloys are essential materials in aerospace engineering, prized for their remarkable strength-to-weight ratio, corrosion resistance, and performance in extreme environments. This essay explores the current state of high-temperature-resistant titanium alloys, focusing on their thermal properties, durability, and mechanical stability under elevated temperatures. Key alloying elements, including aluminum (Al), niobium (Nb), silicon (Si), manganese (Mn), boron (B), and tungsten (W), play a vital role in enhancing the alloy's high-temperature tolerance and mechanical performance. The discussion includes how these elements affect critical factors such as thermal expansion, phase stability, and fatigue resistance while balancing the processing costs associated with their integration. A comparative analysis of different titanium alloys based on their elemental compositions is presented to highlight the strengths and limitations of each variation. In conclusion, the essay provides insights into future developments and the evolving role of titanium alloys in high-performance applications, emphasizing potential improvements in material design and processing techniques to meet the growing demands of aerospace and other industries.

Keywords: Titanium alloy; high-temperature resistance; multi-element alloying.

1. Introduction

Titanium and titanium alloys have the characteristics of lightweight, high specific strength, good corrosion resistance, and excellent high and low-temperature performance. They are high-quality structural materials and have a wide range of applications in aviation, aerospace, marine, power, chemical, metallurgical, light industry, energy, environmental protection and other fields. Titanium is an important strategic metal material that exhibits irreplaceable advantages in many fields due to its outstanding physical and chemical properties, and it is known as the "third metal". The status of titanium is becoming increasingly prominent, and its application scope is constantly expanding, especially in high-end technology fields such as aerospace. The demand for titanium and titanium alloy materials is showing a rapid growth trend, and the requirements for material properties are also increasing accordingly.

Titanium alloy has the characteristics of high specific strength, good medium-temperature mechanical properties, corrosion resistance, non-magnetic properties, and good welding performance. It is an important new type of metal structural material and plays an extremely important role in the development of high-tech weapons and equipment for national defense. Titanium alloy can be widely used in various weapons and equipment, including military aircraft, aviation engines, missiles, various ships, nuclear reactors, light artillery, and armored vehicles. The widespread application of titanium alloys plays an important role in reducing the structural mass factor of military aircraft, improving the thrust-to-weight ratio of aircraft engines, reducing the weight of weapons and equipment, improving armor protection performance, extending service life, enhancing the safety and reliability of nuclear reactors, and improving the search, discovery, and tracking capabilities of ships.

Titanium and its alloys have become critical structural materials in the aerospace industry due to their high specific strength, excellent corrosion resistance, low-temperature performance and high thermal strength [1]. When compared to aluminum and magnesium alloys, titanium and its alloys demonstrate remarkable high-temperature capabilities, particularly in the heat-resistant components of aircraft engines, showcasing significant potential for application. These materials not only exhibit outstanding physical and chemical properties but also excel in withstanding extreme conditions. As a result, they are widely utilized in aviation and are considered essential components. It can be said that titanium and its alloys play an irreplaceable role in the aerospace industry [2].

Most medical devices use titanium alloys for human implants and orthopedic devices. Scientists have been seeking high-performance and abundant sources of biomedical titanium alloy materials. They have developed and prepared a series of titanium alloy biomedical materials with special structures by mimic the composition and structure of natural bone.

2. The Advantages and Design Challenges of Titanium Alloy

2.1. Advantages

Titanium-aluminum alloy is a silvery-white metal that has many excellent properties. With a density of 4.54 g/cm^3, titanium is 43% lighter than steel and slightly heavier than the prestigious light metal magnesium. The mechanical strength is about the same as steel, twice as great as aluminum and five times greater than magnesium.

Titanium is a chemically reactive metal. When heated, it can interact with non-metals such as O_2, N_2, H_2, S and Halogens. However, at room temperature, the surface of titanium is easy to form a very thin and dense oxide protective film, which can resist the action of strong acids, showing strong corrosion resistance. As a result, the general metal becomes porous in the solution of acids, and salts, which cause titanium unharmed.

Titanium is resistant to high temperatures, with a melting point of 1942 K, which is nearly 1000 K higher than gold and nearly 500 K higher than steel.

2.2. Design Challenges

2.2.1 Creep resistance design

High temperature titanium alloy needs to have a low creep rate and high creep fracture life. This is usually achieved by optimizing the alloy composition and microstructure.

2.2.2 High-temperature strength

Retaining strength: titanium alloy needs to maintain sufficient strength so that it will not fail at high temperatures. The strength of conventional titanium alloys may be significantly reduced at this temperature, and specially designed high-temperature titanium alloys are needed. Alloy composition: Adding some elements (such as aluminum, tungsten or molybdenum) can improve the high-temperature strength, but it may also affect other properties of the alloy.

2.2.3 Oxidation resistance

Oxide layer: At a high temperature, an oxide layer may be formed on the surface of titanium alloy. Good oxidation resistance is the key to preventing titanium alloy from oxidation at high temperatures, which leads to strength reduction and material degradation. Stability of oxide layer: In the process of high-temperature oxidation, the oxide layer should be stable and prevent internal oxidation or oxide from falling off.

2.2.4 Thermal expansion

Thermal expansion coefficient: Titanium alloy will have large thermal expansion at high temperatures, so the influence of thermal expansion on the assembly and dimensional stability of parts should be considered.

Design considerations: For applications requiring high dimensional stability, the thermal expansion characteristics of the alloy should be considered in the design, and appropriate compensation measures may be needed.

2.2.5 Material stability

Phase transformation: titanium alloy may undergo phase transformation (such as the transformation from alpha phase to beta phase), which will affect the mechanical properties of the material.

Stability control: it is necessary to select the appropriate alloy composition and heat treatment process to control phase transformation to ensure stable performance at high temperatures.

2.2.6 Fatigue performance

High temperature fatigue: At high temperatures, the fatigue performance of titanium alloy may deteriorate. Alternating loads at high temperatures may accelerate the fatigue failure of materials. Fatigue strength is necessary to evaluate and design the fatigue strength at high temperatures to ensure reliability in long-term use.

2.2.7 Cost and processing

Cost considerations: High-temperature titanium alloys usually cost a lot, so it is necessary to weigh the material performance and cost.

Processing difficulty: Due to the special requirements of high-temperature titanium alloy, the processing technology may be more complicated, and special equipment and technology may be needed.

3. Multiple Elements Mixed in Titanium Alloy

To overcome difficulties and adapt to its application function, scientists usually add multiple elements to the alloy [3-7].

Various elements significantly impact the properties of high-temperature titanium alloys, especially those based on Ti-Al intermetallic compounds. Aluminum (Al), comprising 32-36% of the alloy, is essential for forming TiAl and Ti_3Al phases, which contribute to the alloy's heat resistance. However, an excessive Al content can reduce ductility and oxidation resistance. Niobium (Nb), when combined with silicon (Si), enhances oxidation resistance, particularly above 800 °C, while also increasing strength by forming a solid solution in Ti_3Al. However, too much Nb (over 4%) can negatively affect ductility. Si (0.05-2.00%) improves oxidation resistance, but excessive amounts lead to the formation of silicon compounds that reduce room-temperature ductility. Manganese (Mn) improves room-temperature ductility by forming a solid solution in TiAl, enhancing strength through solid solution strengthening, though exceeding 5% can reduce ductility. Boron (B), at 0.005-0.20%, refines grain size, improving high-temperature ductility and castability, but higher concentrations lead to boride formation, weakening the alloy. These elements collectively contribute to an alloy that balances heat resistance, strength, ductility, and oxidation resistance, making it suitable for high-speed rotating and reciprocating components used in high-temperature environments [3-5].

Alloys 1 and 2 only contain Al and Ti. Compared with formers, alloy 3,4 contains W and Ge, and alloy 5,6 contains W and Si, alloy 7 contains Cr and Ge, alloy 8 contains Ta and Ge, and alloy 9 contains Ta and Si. Therefore, Fig. 1 shows that W, Ge, Si, Cr and Ta can improve the alloy’s HV behavior.

Alloys with Yttrium (Y) and Zr exhibit high-temperature stability with superior yield strength, such as alloy 15 (Ti-49% Y-3% Al), which has a yield strength of 650 MPa at room temperature. Alloys containing boron tend to have enhanced ductility without significantly compromising strength. For instance, alloy 21 (Ti-48% B-0.5% Y) provides an excellent balance between hardness and ductility. The selection of alloys depends on the specific operational conditions, such as temperature and desired mechanical properties (hardness, yield strength, and ductility).

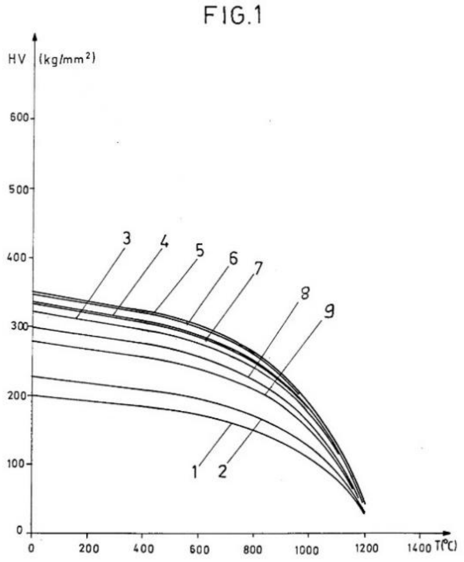

Fig. 1 Different titanium alloys (1-9) HV changes with temperatures [6]

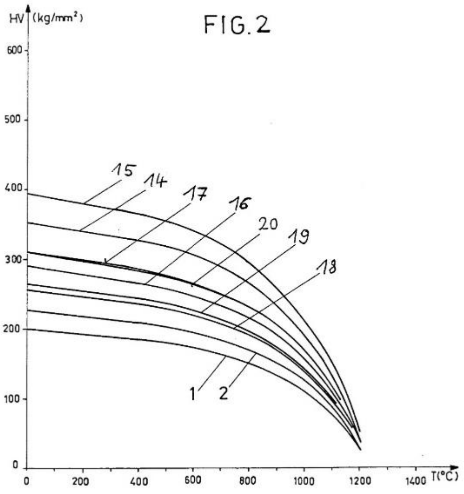

Fig. 2 Different titanium alloys (1,2,14-20) HV changes with temperatures [6]

4. Conclusion

To promote the titanium alloy with more cost-effectiveness, there are multiple ways to achieve this purpose. The first approach is to lower the manufacturing cost, and new preparation technology is ready. For example, according to scientists from USTB, the as-sintered PM titanium instead of as-forged titanium can significantly reduce the cost of titanium products. It reduces deformation during hot working and increases the materials utilization rate.

The second approach is to create a new alloy with a new component combination. For example, use TiAlCrFe alloy instead of TC4 alloy, which will reduce the cost to 80%. Like SP-700 alloy from NKK, as its superplastic feature, it can reduce the difficulty of molding, which significantly reduces its production cost. Furthermore, adding microelements can also refine grain size to lower the cost.

In order to maximize production and work efficiency, it is necessary to choose the right titanium alloy composition to balance the relationship between high temperature and high strength. For different temperatures, different working environments and work needs, select the right composition to finish the best match and the highest price-money ratio. In some potential cases, some properties can be sacrificed to obtain a cheaper alloy if sufficient strength is satisfied.

Another approach is to maximize the material efficiency. The technology for recycling waste materials is becoming more mature, and the cost of raw materials is decreasing. The utilization technology of residual materials not only reduces the cost of raw materials but also improves production efficiency. However, the properties of the alloy after semi-solid processing have decreased, especially the impact toughness, which requires further optimization of the processing technology.

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