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ORIGINAL ARTICLE

Artificial implants of titanium alloys for biomedical applications

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Abstract

The evolving healthcare industry, driven by the growing need for joint replacement surgeries, musculoskeletal repairs, and orthodontic procedures on a global scale, has prompted the creation of innovative technologies. These emerging technologies are designed to adapt to evolving healthcare needs. In the field of biomedicine, there is a history of using metallic orthopedic materials alongside aerospace industry applications. While these materials are only partially effective in the biomedical domain, they are still considered suitable for bone tissue replacements and regenerative therapies because of their exceptional mechanical properties. Tantalum and Molybdenum elements were added to the titanium to improve the corrosion resistance and mechanical properties because Tantalum and Molybdenum are considered β-stabilizer elements. This research focused on synthesizing the Ti-10Mo-20Ta alloy using arc-melting, placing particular importance on its potential medical applications. Furthermore, the investigation scrutinized the consequences of subjecting the alloy to hot annealing at a temperature of 1050 ºC for a duration of 1.5 hours. Subsequently, the alloy was rapidly immersed in water, and its microstructure and mechanical properties were analyzed. The alloy was characterized utilizing methods like X-ray diffraction and optical microscopy, and transmission electron microscopy. The results obtained indicated that the material possessed a metastable β structure with minimal α phase presence, as revealed through structural analysis. Tensile strength testing conducted at room temperature exhibited a significantly higher value of around 1200 MPa in comparison to Ti-6Al-4V and CP-Ti alloys. These alloys were deemed suitable for their intended purpose as orthopaedic implants.

1. Introduction

Compared to other metallic biomaterials, titanium and its alloys offer superior biocompatibility, making them potential replacements for stainless steels and Co-Cr alloys commonly found in commercial implant devices. A key advantage of titanium alloys is their relatively low density of approximately 4.5 g/cc, approximately half the density of stainless steels and Co-Cr alloys [1]. Titanium alloys also exhibit resistance to corrosion, pitting attack, and crevice corrosion when placed in vivo [2]. Additionally, titanium's reduced reactivity within the body allows for relatively unimpeded healing, leading to extended implant lifespans [3, 4]. Furthermore, the affordability of titanium is increasing as its demand expands across various industries like aerospace, sports, and recreation sectors [5, 6]. Two commonly used titanium alloys for implants are the Ti-6Al-4V ELI alloy, known for its (α + β) microstructure in the aerospace industry, and pure titanium.

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However, there are certain challenges associated with these materials. Pure titanium exhibits insufficient strength, while the Ti-6Al-4V ELI alloy contains elements that may have detrimental effects on the human body [7]. Titanium alloys are typically classified into three main types based on their primary constitutional phases: α-type, (α + β), and β-type alloys; α-type alloys consist of single-phase α-microstructures, β-type alloys consist of single-phase β-microstructures, and (α + β)-type alloys have two-phase (α + β) microstructures [8, 9]. In alloys containing 10 to 15% of β stabilizers, the β phase remains metastable at room temperature [8]. The presence of β stabilizers enables control over the amount of β phase in the alloy. When a near-β alloy is heated above the β transus temperature of 882°C, it undergoes increased β grain development and dissolution of the α-phase, resulting in a fully β structure [10]. The phase diagram of titanium alloys is depicted in Figure 1.

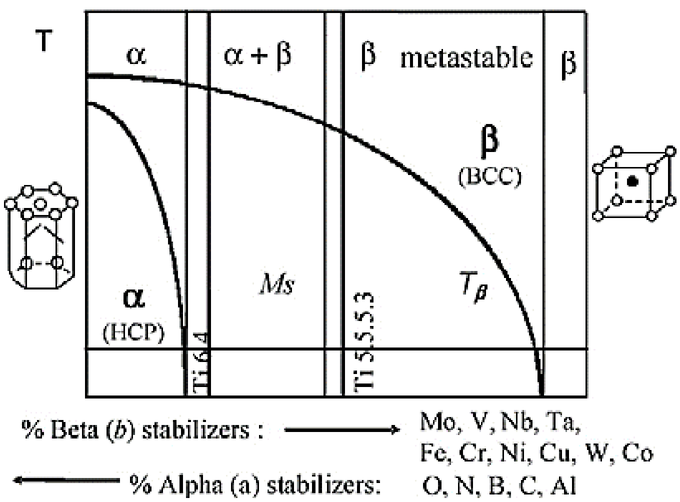

Figure 1: The phase diagram showcasing, the different phases of titanium alloys [11].

Medical implants should possess sufficient strength to withstand and bear the loads exerted by joint and muscle forces. Thus, each biomaterial device must exhibit specific mechanical properties determined by the physiological function of the surrounding bone and tissue in the body [12]. The utilization of titanium and its alloys in dental implants is attributed to their outstanding strength and lower elastic modulus in comparison to alternative alloys such as stainless steel. In achieving clinical success, other factors such as surgical facility, implant design, host bone quality, load-bearing capacity, and surface characteristics must also be considered [13]. Titanium alloys are commonly used in osteosynthesis procedures, such as bone fracture fixation, as they offer excellent biocompatibility and corrosion resistance. When a bone is severely fractured, bone screws and plates are used to align the bone segments before applying a cast. Depending on the healing process and location, screws may or may not be removed after recovery, while bone plates need to be made from strong materials to withstand the typical loads experienced in the bone. Titanium and its alloys are preferred for bone plates as they possess bioactive surfaces that facilitate strong bonding with the bone, reducing relative motions and providing stability [14]. The Replacement of bone by a prosthetic implant requires different mechanical properties to bone fixation. Here, matching the elastic modulus of natural bone is a significant requirement. A significant mismatch in elastic moduli can cause a change in the stress distribution in the adjoining bone during physical activity, which can result in bone loss in a phenomenon known as stress shielding [15]. A standard hip prosthesis comprises three primary components, namely the acetabular cup, the femoral component, and the articular interface, as depicted in Figure 2. To ensure the suitability of biomaterial, mechanical properties such as elastic modulus, tensile strength, and compressive strength are typically assessed [16].

Figure 2: Some applications of artificial implants made from titanium alloys. [17].

Additionally, bone possesses its distinctive characteristics due to the exceptional blend of strong hardness and high resistance to breaking found in its organic components. This coexistence of two greatly different materials, each with their own unique properties, enables the development of a nanocomposite system where the combined physical properties exceed those of individual components. As a result, bone serves as a bio-nanocomposite system that has evolved over countless years, finely adjusted to demonstrate optimized properties. Remarkably, bone has the ability to remodel and adjust itself in accordance with the mechanical forces it encounters in its surroundings [18]. Based on these findings, titanium-molybdenum (Ti-Mo) and titanium-tantalum (Ti-Ta) based alloys, such as Ti-13Ta-29Nb-4.6Zr [19] and Ti-8Mo-4Nb-5Zr [20], have been specifically developed as optimized titanium alloys for use in removable implants.

2. Material and Methods

The Ti-10Mo-20Ta (wt%) ingots were fabricated through the process of arc-melting, utilizing 99.9% pure titanium pellets, along with 99.9% pure molybdenum and tantalum from the Goodfellow group. The melting chamber was first evacuated and then filled with argon gas. The required quantities of metals were melted in a roller-shaped crucible positioned within a copper hearth, employing an arc generated by a tungsten electrode. To enhance chemical homogeneity, the ingots underwent multiple re-melting cycles. The hot-swaged material was subjected to an annealing process at 1050 ºC for 1.5 hours under high vacuum conditions within a tubular furnace. Afterward, it underwent water quenching at room temperature. An analysis using X-ray diffraction was performed utilizing a Siemens D5000 X-ray diffractometer equipped with a copper target, which emitted CuKα radiation with a wavelength (λ) of 1.541 Å. The instrument was operated with a generator set at 40 kV and 40 mA. Diffraction patterns were obtained through angular steps of 0.02°, with a recording time of 2 seconds per angle. The microstructure of the alloy was evaluated through the utilization of both transmission electron microscopy (TEM) and optical microscopy (OM). To evaluate the mechanical properties, a tensile test was performed by subjecting a prismatic bar-shaped specimen of the material to applied tensile stress, measuring the resulting elongation (ΔL). This test was conducted using a tensile testing machine.

3. Results and Discussion

After subjecting the Ti-10Mo-20Ta alloy to thermal treatment, which included annealing at 1050°C for 1.5 hours followed by water quenching, the resulting X-ray diffraction (XRD) pattern was investigated. The analysis verified the existence of the anticipated β single phase, as illustrated in Figure 3. Nonetheless, unexpectedly, a weak reflection originating from α phase was observed at an angle of 37.3° (2θ). The Ti-10Mo-20Ta alloy underwent a series of treatments, including hot swaging, followed by annealing at 1050 ºC for 1.5 hours and subsequent water quenching. The resulting X-ray diffraction (XRD) pattern confirmed the presence of a microstructure consisting of a single phase, characterized by equiaxial β grains. Additionally, the visual analysis shown in Figure 4, through the optical microscopy (OM) test, further confirmed the presence of this monophase microstructure with equiaxial β grains.

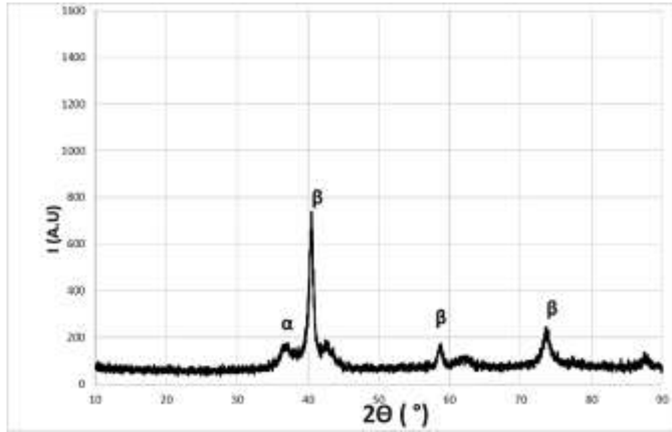

Figure 3: The XRD pattern of Ti-10Mo-20Ta heat treatment, annealed at 1050°C/1.5h and water quenched.

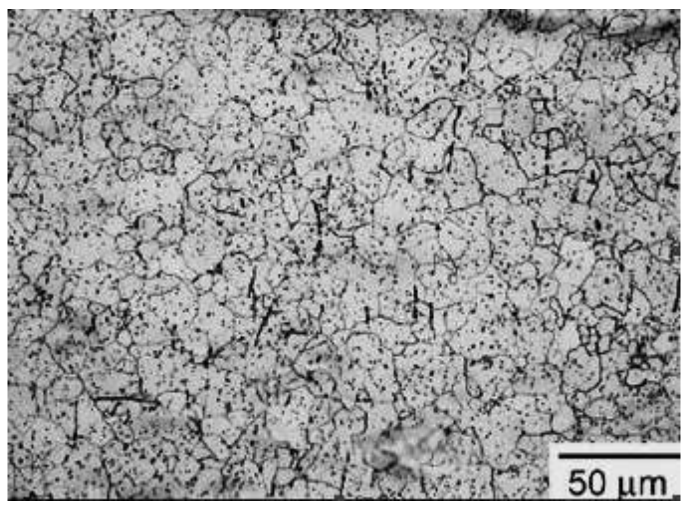

Figure 4: (OM) test of Ti-10Mo-20Ta system underwent heat treatment, specifically annealing at a temperature of 1050°C for a duration of 1.5 hours, after which it was subjected to water quenching.

Moreover, the findings depicted in Figure 5 display the results obtained from the transmission electron microscopy (TEM) analysis of the Ti-10Mo-20Ta alloy. This analysis was conducted after subjecting the alloy to the same procedure of hot swaging, annealing at 1050 ºC for 1.5 hours, and water quenching. These images vividly exhibit the existence of a secondary phase within the β matrix, which aligns with observations made through X-ray diffraction (XRD). This observation confirms the presence of a small quantity of α phase within the alloy. Consequently, following the heat treatment, the Ti-10Mo-20Ta system primarily showcases equiaxial β grains. The swift cooling process from the range of stability for the β phase ensures the presence of a metastable β structure at room temperature, with only a limited amount of the α phase.

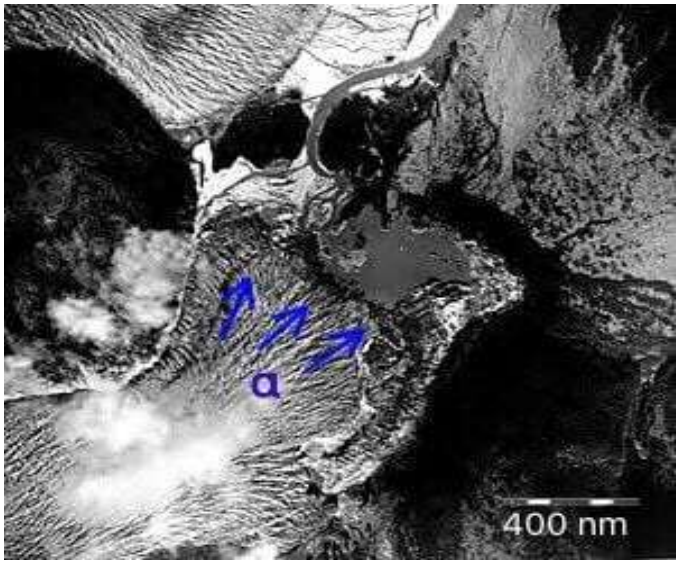

Figure 5: TEM analysis of the Ti-10Mo-20Ta system, after heat treatment and quenching, revealed shining area α -phase precipitation occurring within a β matrix.

The measured mechanical properties, specifically tensile strength, of Ti-10Mo-20Ta alloy are presented in this study. Table 1 also provides a comparative analysis of these mechanical properties with Ti-6Al-4V, CP-Ti, and other biomedical alloys. β-type titanium alloys can enhance their static strength through severe cold-working processes such as severe cold rolling [21] and cold swaging [22]. These processes have the potential to elevate the tensile strength to levels comparable to or greater than that of Ti-6Al-4V, while still maintaining sufficient elongation to failure, the significant work hardening resulting from a high degree of plasticity introduced during such processes. Conversely, the low presence of α phase precipitates in the Ti-10Mo-20Ta alloy does not exert a significant influence on the alloy's properties.

Table 1: Shows the tensile value of Ti-10Mo-20Ta alloy compared with Ti-6Al-4V, CP-Ti, and other biomedical alloys

Systems	UTS (MPa)	YS (MPa)	Elongation %	Reference
Ti-6Al-4V annealed_700°C	930	860	10	[23]
CP-Ti	331	241	30	[24]
Ti-15Mo Annealed_ 800°C	873	544	20	[25]
Ti-13Mo-12Nb Hot swaged_ 500°C	1111	981	6.3	[26]
Ti-10Mo-20Ta	1200	990	5.2	This study

Figure 6 showcases the stress-strain curves acquired at room temperature for the Ti-10Mo-20Ta system, along with the average values of yield strength (YS), ultimate tensile strength (UTS), and elongation at rupture (EL) obtained from these curves. A comparison of these values with the measurements for other alloys listed in Table 1, such as Ti-6Al-4V, Ti-15Mo, and Ti-13Mo-12Nb, highlights that these alloys exhibit relatively high ultimate tensile strengths, exceeding 800 MPa. Remarkably, Ti-10Mo-20Ta demonstrates an exceptionally elevated ultimate tensile strength, surpassing 1200 MPa. In contrast, CP-Ti displays a significantly lower ultimate tensile strength, measuring 331 MPa.

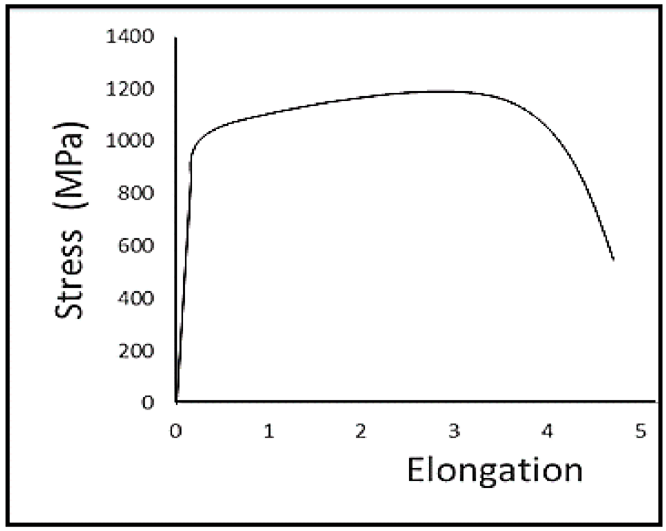

Figure 6: Depicts the stress-strain behavior of the Ti-10Mo-20Ta alloy under room temperature conditions.

Yield strength is similar to ultimate tensile strength, Ti-6Al-4V, Ti-15Mo, and Ti-13Mo-12Nb have relatively high yield strengths, with values exceeding 540 MPa. CP-Ti and Ti-10Mo-20Ta have lower yield strengths. While the elongation of CP-Ti has the highest value at 30%, indicating good ductility and deformability. Ti-15Mo has an elongation of 20%, which is also favorable. However, Ti-6Al-4V, Ti-13Mo-12Nb, and Ti-10Mo-20Ta show relatively low values, with Ti-10Mo-20Ta having the lowest elongation at 5.2%. Overall, the selection of the titanium alloy would depend on the specific application requirements. If high strength and rigidity are crucial, alloys like Ti-6Al-4V, Ti-15Mo, or Ti-13Mo-12Nb might be suitable choices. On the other hand, if ductility and deformability are essential, CP-Ti would be a preferable option due to its higher elongation value. Ti-10Mo-20Ta stands out for its exceptional strength but lower elongation, making it more suitable for applications where high strength is prioritized over ductility and deformability.

4. Conclusions

The Ti-10Mo-20Ta alloy, subjected to hot swaging, annealing at 1050°C for 1.5 hours, and subsequent water quenching, predominantly exhibits a β structure with a minor proportion of α phases. This specific microstructure contributes to the alloy's exceptional mechanical properties, particularly in terms of tensile strength, surpassing those of the alloys listed in Table 1. These findings indicate that the Ti-10Mo-20Ta alloy holds significant promise as an attractive choice to Ti-6Al-4V for biomedicine demands. Moreover, compared to the previously investigated Ti-13Mo-12Nb alloy hot-swaged at 500°C, the Ti-10Mo-20Ta alloy offers a competitive advantage by enabling the production of lighter orthopaedic implants at a reduced cost.

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