Mechanical behavior and corrosion properties of Ti-7Mo-8Nb alloy for biomedical applications

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Abstract

The present study investigates the microstructural, mechanical and corrosion properties of Ti-7Mo-8Nb alloy manufactured through powder metallurgy. The performance of the developed alloy is benchmarked against cast Ti-6Al-4V. Microstructure examination of Ti-7Mo-8Nb revealed a Widmanstätten structure containing equiaxed β grains along with acicular α phase. In regards to the mechanical properties, Ti-7Mo-8Nb possessed higher compressive yield strength, higher hardness but lower elastic modulus than Ti-6Al-4V. The elastic modulus of Ti-7Mo-8Nb was almost 44.9 GPa, approaching the usually desired value of 30 GPa for cortical bone. Wear test revealed also a lower wear rate for Ti-7Mo-8Nb. Potentiodynamic polarization and electrochemical impedance spectroscopy (EIS) experiments were carried out for both Ti-7Mo-8Nb and Ti-6Al-4V immersed in Hank’s solution as a simulated body fluid at a temperature of 37 °C. Both experiments revealed higher corrosion resistance for Ti-7Mo-8Nb manifested by lower corrosion and passivation current densities, higher negative phase angle, higher impedance modulus and larger Nyquist semicircle diameter as compared to Ti-6Al-4V alloy. The superior corrosion properties of Ti-7Mo-8Nb are indicative of the development of a more stable passive layer on the surface. The fitting of EIS data into an equivalent circuit suggested the formation of a double oxide layer consisting of an inner compact base passive film along with an external porous layer. The presented combination of high strength, high corrosion resistance along with low elastic modulus puts forward the Ti-7Mo-8Nb alloy as a good candidate for orthopedic biomedical applications.

1. Introduction

Metallic materials are usually considered as the prime choice for biomedical implants. This is due to their advantageous mechanical properties such as high strength, high fatigue strength, and good toughness. The first used metallic biomaterial was stainless steel. After that, Vitallium, which is a cobalt-based alloy, was used as a metal implant. Titanium was used later in the biological sector since 1950 and since then titanium and its alloys have received much attention as biomaterials [1]. In addition to titanium and its alloys, other classes of biomaterials include various metallic alloys, polymers and ceramics. An alternative approach to classify biomaterials in terms of their functionality, instead of their microstructure, was recently presented in [2].

Ti-6Al-4V alloy (consisting of α-β structure) is the most commonly used Ti-based alloy. However, it was later recognized that this alloy causes health problems due to the release of Al and V ions. Aluminum ions cause Alzheimer’s disease whereas vanadium is toxic both in elemental form and as an oxide [3, 4]. Another concern for Ti-6Al-4V alloy is the significant mismatch in the elastic modulus between Ti-6Al-4V alloy (~115 GPa) and cortical bone (~30 GPa). Such a considerable difference in the elastic modulus results in stress shielding problems after implantation [5].

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In the recent years, numerous studies focused on development of near-$\beta$ and $\beta$-type Ti alloys containing non-toxic and non-allergic elements to be used as implant materials. This was motivated by the excellent mechanical properties and high resistance to corrosion for these alloys [6]. Near-$\beta$ and $\beta$-type Ti alloys, containing non-toxic alloying elements, can be obtained through the substitution of V and Al in Ti-6Al-4V with beta-stabilizer elements such as Nb, Sn, Ta, Zr, and Mo. The combined content of beta-stabilizers in Ti alloys is usually quantified through Molybdenum Equivalent (MoE). Alloys having $5 \leq \text{MoE} < 10$ are classified as near-beta, alloys with $10 \leq \text{MoE} < 30$ are considered as metastable, and alloys having MoE $> 30$ are labeled as stable. It is worth noting that increasing MoE value decreases the alloy $\beta$-transus temperature $T_c$ [6]. Extensive research was carried out over the past years to characterize the behavior of the new $\beta$ and near-$\beta$ Titanium alloys containing non-toxic beta-stabilizing elements [7–19]. These researches focus on investigating the microstructure, mechanical properties, corrosion resistance and biocompatibility of the newly developed $\beta$ and near-$\beta$ Titanium alloys.

Two elements that offer strong $\beta$-stabilizing effects on Ti-based alloys and were proved to significantly alter their properties are Mo and Nb, which are isomorphous type $\beta$ stabilizers. Nazari et al [20] investigated the microstructure and the mechanical properties of Ti-xMo-yNb alloys fabricated through powder metallurgy. It was shown that Ti-alloys having Nb content $\leq 25$ wt% and Mo content $\leq 5$ wt.% developed Widmanstätten structure. Further increase in Nb and Mo additions led to predominantly $\beta$ phase microstructure. In regards to the mechanical properties, increasing Mo and/or Nb content resulted in decreasing yield strength, hardness and elastic modulus. Xu et al [13] investigated porous Ti-Mo alloys and showed that the amount of pores increased as the Mo content increased. This in turn resulted in a significant concurrent decrease in both compressive strength and elastic modulus. The effect of Mo to increase the corrosion resistance of Ti-Mo alloys in Ringer’s solution was investigated by Bolat et al [9]. The results exhibited the formation of two-layer passive oxide film that attains higher resistance as the Mo content increases. The corrosion resistance enhancement of Ti-Mo alloys in phosphate buffered saline due to the increase in Mo content was also reported in [21], which was attributed to the formation of highly resistant single oxide passive film. Niobium, on the other hand, was also shown to boost the corrosion resistance in Ti-Mo-Nb alloys [17]. Investigating the corrosion behavior of various Ti-Mo-Nb alloys with MoE of 12 wt% showed that as the Nb wt% increases (and so Mo wt% decreases), the resistance of the developed compact passive oxide layer increases. Accordingly, when MoE is kept constant, Ti-Mo-Nb alloys were shown to possess higher corrosion resistance than binary Ti-Mo alloys.

Increasing Mo and/or Nb content in Ti-based alloys might not be always advantageous, especially when the alloy’s overall performance is taken into consideration. For example, when considering the optimum combination of strength, ductility and elastic modulus, Ti-10Nb-3Mo was suggested to be a better choice for implant applications than Ti-40Nb-3Mo, although the later possessed the lowest elastic modulus [20]. In addition, when investigating the tribocorrosion behavior of Ti-(8–20)Mo alloys, Ti-16Mo alloy attained the highest hardness value and the lowest wear rate under tribocorrosion conditions [21]. Accordingly, further development of novel near-$\beta$ and $\beta$-type Ti-alloys and the characterization of their overall performance remain to be of a great scientific importance.

In the present study, a comprehensive investigation is carried out for the microstructural, mechanical, tribological and corrosion properties of a novel Ti-7Mo-8Nb alloy manufactured by powder metallurgy technique. The performance of the developed alloy is benchmarked against Ti-6Al-4V alloy. The alloy chemical composition was selected aiming to obtain a near-beta alloy that is expected, based on the results in [20], to retain a high strength value along with a low elastic modulus. In addition, the Mo and Nb content is expected to enhance the corrosion resistance of the developed alloy.

2. Material and experimental procedure

2.1. Material preparation

Ti-7Mo-8Nb (wt%) alloy was manufactured through powder metallurgy. Elemental powders of Ti (99.7% purity and particle size 44 $\mu$m), Mo (99.95% purity and particle size 8 $\mu$m) and Nb (99.8% purity and particle size 45 $\mu$m) with rough geometry were used. The elemental powders were weighed and then mixed using elemental blend technique for better blending between alloying powders. The powders were mixed in Turbula mixer at 150 RPM and then compacted using a universal testing machine using a compaction pressure of 600 MPa in argon atmosphere. The compacted samples were then sintered in Carbolite HVT/15/75/450 vacuum furnace (10–4 mbar) at a temperature of 1300 $^\circ$C. After a dwell time of 3 h, the samples were furnace cooled at 10 $^\circ$C min$^{-1}$. The resulting samples dimensions were $35 \times 10 \times 5$ mm$^3$. Ti-6Al-4V alloy was prepared by casting using vacuum arc melting furnace. Ti-6Al-4V samples were melted 6 times in order to get a homogenous structure. The samples were prepared as discs having a diameter of 80 mm and thickness of 10 mm.
2.2. Material characterization

The chemical composition of the samples was analyzed using a vacuum Oxford Pro spectrometer. The porosity (P) was characterized using Archimedes test according to the procedure listed in (ASTM B962–14) [22]. The porosity is calculated using the formula:

\[
P = 1 - \frac{\rho}{\rho_0}
\]

(1)

The theoretical density of Ti-7Mo-8Nb alloy (\(\rho_0\)) is calculated by the following formula:

\[
\rho_0 = 1\left(\frac{m_{Mo}}{\rho_{Mo}} + \frac{m_{Ti}}{\rho_{Ti}} + \frac{m_{Nb}}{\rho_{Nb}}\right)
\]

(2)

where \(m_{Mo}\), \(m_{Nb}\) and \(m_{Ti}\) are mass fractions of the Mo, Nb and Ti, respectively. \(\rho_{Mo}\), \(\rho_{Nb}\) and \(\rho_{Ti}\) are defined as the densities of Mo, Nb and Ti, respectively. Based on equation (2), the theoretical density of Ti-7Mo-8Nb alloy is 4.886 g cm\(^{-3}\) while that obtained from Archimedes test is 4.813 g cm\(^{-3}\). This implies a porosity percentage of only 1.5%, which can be due to the relatively high temperature during the sintering process [20].

The microstructure of the alloy was examined using both optical and scanning electron microscopes. The sample preparation steps included grinding using silicon carbide papers (up to 2400 grit size) followed by polishing with a 0.25 \(\mu\)m diamond paste and diamond coolant solution for a few minutes to avoid oxidation. After that, the samples were washed with distilled water followed by ethylic alcohol and dried with warm flowing air. The samples were then etched using a reagent of 3% HF, 30% HNO\(_3\) and distilled water. Scanning electron microscope (SEM) with EDAX Genesis Analyzer was used also for both microstructure investigations and phases analysis. The phases were identified using x-ray diffraction using Cu K\(\alpha\) radiation (45 kV and 40 mA).

2.3. Mechanical and wear characterization

Vickers hardness testing was carried out by taking the average value of ten measurements in accordance with ASTM E384–11. The indentation was carried using a diamond indenter having 136° included angle under a load of 30 kg for 15 seconds. Both the strength and the elastic modulus (E) of the investigated samples were characterized through the compression test using a universal testing machine of 300 KN capacity using a crosshead speed of 1 mm min\(^{-1}\). The compression test was carried out for three samples. The elastic modulus of the alloy was also determined using the ultrasonic pulse-echo technique.

Wear test was performed using pin-on-disc tribometer testing machine. A rectangular pin specimen was fixed against rotating martensitic stainless-steel disc having a surface hardness of 63 HRC. The sample weight difference due to wear was measured using 0.1 mg sensitive balance. The wear test was carried out at different load of 10, 20, 30 and 40 N at a sliding speed of 265 rpm for 30 min. Both the fracture surface after compression test and the worn surface after the wear test were investigated using SEM. For the purpose of comparison, both compression and wear tests were also carried out for Ti-6Al-4V cast samples.

2.4. The electrochemical characterization

The electrochemical tests were carried out using a conventional three-electrode system in simulated body fluid (SBF) at a temperature of 37 °C. Hank’s solution (with the chemical composition stated in table 1 and pH 7.4) was used as SBF. The counter electrode was a platinum wire and the reference electrode was an Ag/AgCl electrode. The electrochemical tests were carried out for Ti-7Mo-8Nb samples in addition to cast Ti-6Al-4V samples, as working electrodes, for the sake of comparison. Prior to testing, the working electrodes were ground using SiC abrasive paper of 2000 grit size.

Potentiodynamic polarization tests were carried out when the open circuit potential (OCP) reached a stable value after 1 h of immersion in SBF. The tests were conducted at a scan rate of 0.001 V s\(^{-1}\) in the potential range from −0.8 V to 1.0 V versus OCP. Electrochemical impedance spectroscopy (EIS) measurements were carried out at a frequency range from 100 kHz to 10 mHz using an AC voltage signal of 10 mV amplitude. Nova 1.2.5 software was used in the fitting of the EIS results into equivalent circuits in addition to the simulation of the impedance response of such equivalent circuits.

| Table 1. Chemical composition (g/l) of Hank’s solution (SBF). |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| NaCl            | CaCl\(_2\)      | KCl             | NaHCO\(_3\)     | C\(_6\)H\(_12\)O\(_6\) | NaH\(_2\)PO\(_4\) | MgCl\(_2\)      | Na\(_2\)HPO\(_4\) | MgSO\(_4\)      |
| 8.00            | 0.14            | 0.4             | 0.35            | 1.00             | 1.00             | 0.06            | 0.06            |
3. Results and discussion

3.1. The alloy composition and phase analysis

The resulting chemical composition of the investigated Ti–7Mo–8Nb and Ti-6Al-4V alloys is given in Table 2. For Ti-7Mo-8Nb, the alloy molybdenum equivalent was calculated in which it gave a value of MoE = 9.24. In regards to the β-transus temperature, this alloy registered a β-transus at almost 815 °C [23]. Hence, Ti-7Mo-8Nb alloy is considered to belong to the near-β Titanium alloys category.

More quantitative details regarding the phases existing in the alloy are provided through XRD diffractograms, as shown in Figure 1. The XRD patterns revealed the existence of both α and β phases in the structure of the alloy. The relatively lower peaks intensity for the α phase indicated that most of the alloy microstructure consists of BCC β phase (approximately 86%) while the reminder (approximately 14%) exists as HCP α phase. Existence of β phase at room temperature is of course due to the addition of both Mo and Nb as β stabilizer elements.

3.2. Microstructure examination

Figure 2 shows both optical (a) and SEM (b) micrographs for the investigated Ti-7Mo-8Nb alloy. It shows that the alloy structure consists of equiaxed β grains along with acicular α phase. Such a microstructure is known as the Widmanstätten structure. This is consistent with previous literature results which revealed the formation of Widmanstätten structure in as-sintered Ti-Mo-Nb alloys having Nb ≤ 25 wt.% and Mo ≤ 5 wt.% [20]. Although the current Mo content of 7 wt.% is slightly higher than the aforementioned limit, the significantly lower Nb content of only 8 wt.% results in a lower MoE for the present alloy in comparison to a Ti-5Mo-25Nb alloy. The formation of lamellar α structure usually results from cooling the alloy from a temperature above the β-transus temperature at relatively slow cooling rate [20, 23]. When cooling below the β-transus temperature, the α phase starts its nucleation at the grain boundaries followed by a lamellar fashion growth in orientations specified by the slip systems. Recalling that the β-transus temperature of the alloy is almost 815 °C, the formation of such a microstructure can occur during the furnace cooling of Ti-7Mo-8Nb samples after being sintered at 1300 °C for 3 h. Figure 2(b) shows also very limited porosity existence, which is in agreement with the Archimedes test results that indicated a porosity percentage of 1.5%.

The microstructure of Ti-6Al-4V alloy exhibited an equiaxed structure composed of α + β phases, as shown in Figure 2(c). Because Ti-6Al-4V alloy is produced by casting, it has a large grain size in the range of 500 μm. Due to the rapid solidification after melting in the vacuum furnace, the α-phase has a fine structure. The α-phase appears as the white phase in the microstructure.

Table 2. Chemical composition of the Ti–7Mo–8Nb and Ti-6Al-4V alloys (wt%).

| Alloy     | Ti   | Mo  | Nb  | Al  | V   | Cr  | Si  | Fe  |
|-----------|------|-----|-----|-----|-----|-----|-----|-----|
| Ti7Mo8Nb  | 84.727 | 6.9 | 7.8 | 0.0115 | 0.0513 | 0.0101 | 0.0221 | 0.0639 |
| Ti6Al4V   | 89.73 | 6.12 | 3.98 | 0.02 | 0.11 | 0.03 | 0.01 |

Figure 1. X-ray diffractograms for the Ti-7Mo-8Nb alloy.
3.3. The mechanical properties

The measured hardness values for Ti-7Mo-8Nb and Ti-6Al-4V alloys are 380 HV and 307 HV, respectively. This shows that Ti-7Mo-8Nb hardness is higher than that for the Ti-6Al-4V alloy. This is consistent with literature results [20] showing that some Ti-Mo-Nb alloys do attain higher hardness values than Ti-6Al-4V. Other alloys having significant Nb content (>25wt%) exhibited a decline in the hardness values, which was attributed to the formation of a larger fraction of the BCC $\beta$ phase, at the expense of the $\alpha$ phase. This implies that the existence of considerable acicular $\alpha$ structures within the $\beta$ grains provides a strengthening effect to the Ti-7Mo-8Nb alloy. The observed higher hardness value for Ti-7Mo-8Nb, in comparison to Ti-6Al-4V, can then be interpreted in such context.

Further details regarding the mechanical performance are provided through the compression test results. The compression stress-strain curves for Ti-7Mo-8Nb and Ti-6Al-4V alloys are shown in figure 3. The yield strength was approximately 1260 MPa and 925 MPa for the Ti-7Mo-8Nb and Ti-6Al-4V, respectively. The ultimate compressive strength was approximately 1771 MPa and 1738 MPa for the Ti-7Mo-8Nb and Ti-6Al-4V, respectively. Such results, along with the above hardness measurements, indicated that the mechanical properties of Ti-7Mo-8Nb are superior to Ti-6Al-4V alloy. This again can be attributed to the strengthening effect of the acicular $\alpha$ structures within $\beta$ grains. It is worth noting that the increase in both strength and hardness for Ti-7Mo-8Nb alloy was not accompanied with a significant ductility decrease. The stress-strain curves exhibited only a minor difference in the ductility values for both investigated alloys. The enhanced ductility of near-$\beta$ Ti alloys is usually attributed to the higher plasticity of the BCC $\beta$-phase, in comparison to the HCP $\alpha$-phase [20, 23].

In regards to the elastic modulus, the measured values through the ultrasonic method are 44.9 GPa for Ti-7Mo-8Nb and 115 GPa for Ti-6Al-4V. The measured elastic modulus for Ti-6Al-4V alloy is very close to that reported in [14] using also the ultrasonic technique. On the other hand, the elastic modulus of Ti-7Mo-8Nb is significantly lower than that for Ti-6Al-4V, and is much closer to the cortical bone elastic modulus of 30 GPa. Such a lower elastic modulus for Ti-7Mo-8Nb alloy is highly desirable for the implant applications in order to minimize stress shielding effects. Previous research showed that it is possible to attain even lower elastic modulus for Ti-Mo-Nb alloys; e.g. almost 25 GPa for the Ti-40Nb-3Mo alloy in [20]. However, such a lower elastic modulus was however accompanied with a significant decrease in the alloy strength. On the other hand, the Ti-7Mo-8Nb alloy considered in the current investigation attained both a significantly higher yield strength and a significantly lower elastic modulus in comparison to Ti-6Al-4V. The effect of both Mo and Nb to reduce the...
The elastic modulus of Ti alloys can be attributed to their role in reducing the atomic bonding in Ti lattice \[20, 24\]. It is worth mentioning that the elastic modulus of the Ti-7Mo-8Nb alloy calculated through the compressive stress-strain curve is \(42.5 \pm 2.0\) GPa, which is very close to that determined value through the ultrasonic method.

Figure 4 shows the SEM micrograph for the fractured surface of the Ti-7Mo-8Nb samples after the compression test. The fractured surface exhibits mainly a dimple structure, implying a dominantly ductile fracture mode.

### 3.4. Wear test

Figure 5 shows the wear results for the investigated Ti-7Mo-8Nb and Ti-6Al-4V alloys under various loads. The results exhibited mostly a relatively higher wear resistance for Ti-7Mo-8Nb in comparison to Ti-6Al-4V. The observed superior mechanical properties for Ti-7Mo-8Nb can then be responsible for its lower wear rate, in comparison to Ti-6Al-4V. The difference in the wear rate between the investigated alloys decreases as the load increases. This can be due to the higher strain hardening capability for Ti-6Al-4V, in comparison to Ti-7Mo-8Nb, manifested by the larger difference between the yield and ultimate compressive strengths for Ti-6Al-4V, as was shown in the stress-strain curves in figure 3. The morphology of worn surfaces for Ti-7Mo-8Nb is shown in figure 6. The figure reveals grooves and ridges along the sliding direction along with a discontinuous oxide-like layer that apparently was squashed by the countersurface. At relatively low loads, adhesive wear can be
considered to be dominant, which in turn depends largely on the plastic deformation at the developed tribo-layer [25].

3.5. Electrochemical characterization results
Figure 7 depicts the potentiodynamic polarization curves for the studied Ti-7Mo-8Nb and Ti-6Al-4V. Both alloys exhibit stable passive polarization behavior manifested by the stable current density value as the applied potential increases. This indicates the formation of a passive film on the alloy’s surfaces after immersion in SBF. Table 3 gives the corrosion parameters obtained from the potentiodynamic polarization curves. The corrosion current density ($j_{corr}$) was obtained through Tafel analysis for both anodic and cathodic branches of the PD polarization curve. The results showed lower passivation current density ($j_{pass}$) for Ti-7Mo-8Nb, indicating higher stability for the passive film, in comparison to Ti-6Al-4V. The results also revealed low corrosion current density, and accordingly low corrosion rate for Ti-7Mo-8Nb alloy. This is consistent with previous literature results investigating the effects of Mo and Nb additions on corrosion behavior of various Ti alloys. For example, Chelariu et al [17] reported a decrease in both corrosion and passive current densities for Ti-Mo-Nb alloys immersed in saline solution as the Nb content increases. The corrosion behavior of Ti-Mo alloys immersed in phosphate buffered saline solution was investigated in [21], which showed a monotonic decrease in both $j_{corr}$ and $j_{pass}$ as the Mo content increases. All Ti-Mo alloys considered in the aforementioned study exhibited lower $j_{corr}$ and $j_{pass}$ than CP-Ti and Ti-6Al-4V. The presented results confirmed such role of Mo and Nb to decrease the corrosion rate for Ti-7Mo-8Nb immersed in Hank’s solution. It is worth noting that even the application of relatively larger potential does not show any sign for the breakdown of the formed passive layer.
Further characterization of the corrosion behavior is provided through the electrochemical impedance spectroscopy results. Figure 8 shows Bode and Nyquist plots for both Ti-7Mo-8Nb and Ti-6Al-4V alloys. The phase angle diagram in figure 8(a) reveals a higher phase angle for Ti-7Mo-8Nb that approaches 80°, implying a better near-capacitive behavior for the alloy, in comparison to Ti-6Al-4V. The impedance modulus plots in figure 8(b) also exhibit higher impedance values for Ti-7Mo-8Nb. The high phase angle and impedance modulus for Ti-7Mo-8Nb suggest the formation of a more stable passive film on the surface and accordingly a high corrosion resistance capability for Ti-7Mo-8Nb. The Nyquist curve showing the complex versus real components of the impedance is shown in figure 8(c). The plot exhibits incomplete semicircle curves for both alloys which reflects the capacitive response of the passive film. The semicircle diameter is higher for the Ti-7Mo-8Nb alloy, which corresponds to a higher corrosion resistance due to the formation of a more stable passive film.

Further quantitative characterization of the corrosion behavior can be obtained through the fitting of EIS data into equivalent circuits. Two candidate equivalent circuits were used before to simulate the EIS data for Ti-6Al-4V and Ti-Mo alloys, as shown in figure 9[17, 21, 26]. Figure 9(a) shows the simplified Randles equivalent circuit which simulates the behavior of a compact single passive layer. Figure 9(b) shows another equivalent circuit which is usually employed to simulate the behavior of a double-layer passive film consisting of a compact base layer forming on the metal surface and covered by another external porous passive layer. The suitability of a circuit to simulate a given EIS data is assessed through the chi-squared value. In regards to Ti-6Al-4V, both equivalent circuits shown in figure 9 resulted in similar chi values in the order of 10⁻². This is an indication of the development of a single compact passive layer on the surface of Ti-6Al-4V after immersion in Hank’s solution. On the other hand, EIS data for Ti-7Mo-8Nb could be reasonably fitted only using the equivalent circuit in figure 9(b). This implies the formation of a double-layer passive film on the surface of Ti-7Mo-8Nb. For more consistency in comparing the behavior of the investigated alloys, it is recommended to simulate the corrosion behavior of both alloys using the equivalent circuit in figure 9(b). The complex impedance for this equivalent circuit is expressed as [27]

$$Z = R_s + \frac{R_p}{1 + (j\omega C_p R_p)^n} + \frac{R_b}{1 + (j\omega C_b R_b)^n},$$

where $R_s$ is the solution resistance; $R_b$ and $R_p$ are the resistance of the base compact passive film and the external porous layer, respectively; $C_b$ and $C_p$ are the Constant Phase Elements (CPE) representing the capacitive behavior of the base compact passive film and the external porous layer, respectively; and $\omega = 2\pi f$ is the angular frequency.

| Alloy          | $E_{corr}$ (V$_{Ag/AgCl}$) | $j_{corr}$ (μA cm⁻²) | $j_{pass}$ (μA cm⁻²) | corr. rate (mm year⁻¹) |
|---------------|----------------------------|-----------------------|-----------------------|------------------------|
| Ti-6Al-4V     | −0.5975                    | 0.37468               | 9.235                 | 0.00256310             |
| Ti-7Mo-8Nb    | −0.4167                    | 0.05313               | 7.914                 | 0.00049497             |

Figure 7. Potentiodynamic polarization curves for Ti-7Mo-8Nb and Ti-6Al-4V alloys.
Table 4 gives the values of the fitting parameters for both Ti-7Mo-8Nb and Ti-6Al-4V alloys. Since the EIS data for Ti-6Al-4V could be simulated through the behavior of a single compact passive film, the implemented fitting through a double-layer equivalent circuit produces a redundancy in the fitting parameters. This is evident from Figure 8. The marks represent the measured values while the continuous lines represent the simulated values using the equivalent circuit in Figure 9(b).

![Equivalence circuits](Image)

**Figure 8.** Bode (a) and (b) and Nyquist (c) diagrams for Ti-7Mo-8Nb and Ti-6Al-4V alloys after 1 h in Hank’s solution. The marks represent the measured values while the continuous lines represent the simulated values using the equivalent circuit in figure 9(b).

**Figure 9.** Equivalent circuits used for fitting the experimental data: (a) Simplified Randles circuit representing the behavior of compact passive layer and (b) Equivalent circuit representing the behavior of double-layer passive film.

| Alloy          | \( R_s \) (Ω cm\(^2\)) | \( R_p \) (kΩ cm\(^2\)) | \( C_p \) (Ω\(^{-1}\)s\(^{n-1}\)cm\(^{-2}\)) | \( n_1 \) | \( R_b \) (kΩ cm\(^2\)) | \( C_b \) (Ω\(^{-1}\)s\(^{n-1}\)cm\(^{-2}\)) | \( n_2 \) |
|---------------|--------------------------|--------------------------|-----------------------------|--------|--------------------------|-----------------------------|--------|
| Ti-6Al-4V     | 45.3                     | 12.3                     | 79.7                        | 0.748  | 12.3                     | 79.7                        | 0.748  |
| Ti-7Mo-8Nb    | 26.5                     | 18.7                     | 24.6                        | 0.75   | 66.9                     | 35.3                        | 0.942  |

Table 4 gives the values of the fitting parameters for both Ti-7Mo-8Nb and Ti-6Al-4V alloys. Since the EIS data for Ti-6Al-4V could be simulated through the behavior of a single compact passive film, the implemented fitting through a double-layer equivalent circuit produces a redundancy in the fitting parameters. This is evident from Figure 8.
from the similarity in the values of $R_b$ and $R_p$ and likewise the values of $C_b$ and $C_p$ given in table 4. The identical values for the parameters defining the behavior of the ‘assumed’ double-layer passive film is merely a confirmation that a single compact passive layer formed on the surface of Ti-6Al-4V due to the immersion in Hank’s solution. Again, such an overdetermined fitting for Ti-6Al-4V EIS data was carried out only for the purpose of a more consistent comparison with Ti-7Mo-8Nb.

The fitting parameters for Ti-7Mo-8Nb are also listed in table 4. It is evident that the value of $R_b$ is higher than $R_p$, which supports the suggestion that an external porous layer (having relatively lower resistance) was developed above a base compact passive film (having relatively higher resistance). The high value for $C_b$ in comparison to $C_p$ implies that the compact base layer thickness is slightly lower than the porous layer thickness. When comparing the values for both Ti-7Mo-8Nb and Ti-6Al-4V alloys, the higher $R_b$ and $R_p$ values for Ti-7Mo-8Nb are an indication of the higher resistance for the passive layers developed on Ti-7Mo-8Nb. The lower values of $C_b$ and $C_p$ for Ti-7Mo-8Nb also suggest a larger thickness of the duplex passive film formed on Ti-7Mo-8Nb.

The presented results confirm the effect of Mo and Nb to improve the corrosion resistance for Ti alloys. The role of Mo in enhancing the corrosion resistance of Ti-Mo alloys can be attributed in part to the higher nobility of Mo than Ti. The existence of Mo in the developed passive film can then increase its stability[21]. In regards to the role of Nb to increase the corrosion resistance of Ti-Mo-Nb alloys, scanning electrochemical microscopy measurements revealed that increasing the Nb content up to almost 16% significantly restrains the electron transfer on the metal surface covered by the passive film[17]. The combined effect of both Mo and Nb results in the observed superior corrosion behavior for Ti-7Mo-8Nb in comparison to Ti-6Al-4V.

4. Conclusions

A comprehensive investigation of the key microstructural, mechanical, tribological and corrosion properties was carried out for a novel Ti-7Mo-8Nb alloy and benchmarked against Ti-6Al-4V. The corrosion properties of both Ti-7Mo-8Nb and Ti-6Al-4V immersed in Hank’s solution were investigated at a temperature of 37 °C. The main investigation results can be summarized as follows:

1. Microstructure examination of Ti-7Mo-8Nb revealed equiaxed β grains along with acicular α phase near the β grain boundaries.
2. Compression tests revealed a higher yield strength of 1260 MPa for Ti-7Mo-8Nb in comparison to 925 MPa for Ti-6Al-4V.
3. The Ti-7Mo-8Nb alloy attained a lower elastic modulus of 44.9 GPa, in comparison to 115 GPa for Ti-6Al-4V alloy. The lower elastic modulus is very advantageous in orthopedic biomedical applications in order to minimize the stress shielding effects.
4. Dry wear tests revealed a lower wear rate for Ti-7Mo-8Nb, in comparison to Ti-6Al-4V.
5. Potentiodynamic polarization experiments exhibited a lower corrosion current density and a lower passivation current density for Ti-7Mo-8Nb, in comparison to Ti-6Al-4V.
6. The EIS data fitting into an equivalent circuit suggested that the corrosion behavior of Ti-6Al-4V can be simulated through the response of a single compact passive film, while that for Ti-7Mo-8Nb indicated the formation of a double-layer consisting of a base compact film along with an external porous passive layer.
7. The fitting parameters values exhibited the formation of a thicker passive layer that possesses a higher resistance on the surface of Ti-7Mo-8Nb, in comparison to Ti-6Al-4V.

The presented results demonstrating the overall superior performance of Ti-7Mo-8Nb alloy support its high potential as a candidate alloy for orthopedic biomedical applications.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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