Corrosion resistance and biocompatibility of Ti–Ta alloys for biomedical applications

Ying Long Zhou [a,*], Mitsuo Niinomi [a], Toshikazu Akahori [a],
Hisao Fukui [b], Hiroyuki Toda [a]

[a] *Department of Production Systems Engineering, Toyohashi University of Technology, Toyohashi 441-8580, Japan*
[b] *School of Density, Aichi-Gakuin University, Nagoya 464-8650, Japan*

Abstract

Corrosion resistance, wear resistance and biocompatibility of the studied Ti–Ta alloys with Ta contents of 10, 30 and 70 mass% together with the currently used metallic biomaterials pure titanium (Ti) and Ti–6Al–4V extra low interstitial (ELI) alloy were investigated for biomedical applications. Corrosion resistance was measured by an anodic polarization test using an automatic potentiostat in 5% HCl solution at 310 K. Wear resistance was evaluated using a pin-on-disk type friction wear test system with a load of 4.9 N at 310 K in a simulated body fluid (Ringer's solution), and biocompatibility was judged by evaluating the cyto-toxicity through MTT assay. The passive behaviors are observed for all the studied Ti–Ta alloys, and the TiO_2 passive films strengthened by the more stable Ta_2O_5 passive films result in improved corrosion resistance of the studied Ti–Ta alloys with increasing Ta content. All the studied Ti–Ta alloys are non-cytotoxic like pure Ti. The crystal structure shows little influence on the corrosion resistance and cyto-toxicity of the studied Ti–Ta alloys. The experimental results conform the expected excellent corrosion resistance and biocompatibility of the studied Ti–Ta alloys, which are better than or similar to those of pure Ti or Ti–6Al–4V ELI alloy used as standard biomaterials, suggesting their promising potential for biomedical applications.
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1. Introduction

Metallic biomaterials, including stainless steels, Co–Cr-based alloys, Ti and its alloys are the most widely used biomaterials especially for orthopedic implants even in highly loaded areas such as the stem of artificial joints, and hence are required to possess some special mechanical, physical, chemical or biological properties such as high strength and a Young's modulus close to that of a human bone which are indispensable to bear various biofunctions. Recently, Ti and its alloys have become one of the most attractive biomaterials due to their better corrosion resistance, biocompatibility, greater specific strength and much lower elastic modulus than the other metallic biomaterials [1].

The previous investigations [2,3] indicate that the Ti–Ta alloys are expected to become promising candidates for biomedical applications due to their better mechanical biocompatibility than pure Ti and Ti–6Al–4V alloy used as standard biomaterials, i.e. their lower moduli and higher strength-to-modulus ratios than those of the above currently used implant materials. However, an excellent corrosion resistance preventing any degradation of metallic biomaterials in the body fluids and biocompatibility indicating no toxicity and allergic reactions inside a living creature are crucial prerequisites for biomedical applications. The superior corrosion resistance and biocompatibility of pure Ti and pure Ta have been extensively evaluated and recognized by many researchers [4–10]; however, both the alloys and their components should be individually tested for the above properties for safety in biomedical applications [10]. Although the previous studies show that the corrosion resistance of Ti–40% and 50% Ta alloys in the simulated biological solution sur-

* Corresponding author. Tel.: +81 532 470111 5220; fax: +81 532 446690.
E-mail addresses: ylzhou_2@yahoo.com,
shuu@sp-mac4.tutpse.tut.ac.jp (Y.L. Zhou).

passes that of Ti–6Al–4V ELI alloy [11], and that there is no difference in biocompatibility between Ti–5% Ta alloy and pure Ti [12], to date, the corrosion resistance and biocompatibility of Ti–Ta alloys have not yet been studied systematically.

The aim of this study is to investigate the corrosion resistance and biocompatibility of typical Ti–Ta alloys with Ta contents of 10, 30 and 70 mass% for biomedical applications. For comparative purpose, the same measurements were also performed on pure Ti and Ti–6Al–4V ELI alloy which was annealed at 1023 K for 3.6 ks to remove any residual stress.

2. Experimental procedure

2.1. Material preparation

Three kinds of binary Ti–Ta alloys with Ta contents of 10, 30 and 70 mass% (hereafter, 'mass%' will be referred to as '%') were chosen to investigate their corrosion resistance, wear resistance and biocompatibility. The ingots of the studied alloys were fabricated from high-purity sponge titanium (99.5%) and sheet Ta (99.95%) in the appropriate proportions as detailed in previous study [2]. Owing to the big difference in melting point (Ti: 1953 K, Ta: 3273 K) and density (Ti: 4.51 g/cm^3, Ta: 16.6 g/cm^3) between the two pure metals, and owing to the relatively large two-phase (liquid and solid) field in the binary Ti–Ta phase diagram [13], all the ingots of the designed alloys were melted and inverted more than 10 times in order to promote their chemical homogeneities. They were then homogenized in vacuum at 1273 K for 21.6 ks to eliminate the residual chemical segregation, and then rolled into 3-mm thick plates by a total thickness reduction of 80%. The chemical compositions of the studied Ti–Ta alloys according to the wet chemical and (infrared absorption) gas analysis are shown in Table 1, indicating that the actual chemical composition of each designed alloy is close to its nominal composition.

In order to be consistent with the previous measurements of dynamic Young's modulus and mechanical properties of the Ti–Ta alloys [2,3], all the specimens cut from the cold rolled plates were subject to a solution treatment (ST) at 1223 K, which is above the β transus temperature [13], for 3.6 ks followed by a rapid ice water quenching. Subsequently, the specimens of ST-treated Ti–30% Ta alloy were aged at 773 K for 259.2 ks and immediately quenched into ice water (STA). The solution and aging treatments were introduced in this study in order to investigate the effect of different mi-

crostructures on the corrosion resistance and biocompatibility of the Ti–Ta alloys at the same time. All the heat treatments were performed by a direct drive oil-sealed rotary vacuum pump under a vacuum pressure of about 6.7×10^{-2} N/m^2 (Pa).

2.2. Corrosion test

Anodic polarization tests, which are stipulated by the Japanese Industrial Standards (JIS) T 0302, were carried out by an automatic potentiostat in 5% HCl solution at 310 K to evaluate the corrosion resistance of pure Ti, Ti–6Al–4V ELI and the studied Ti–Ta alloys. The specimens with a square surface area of 1 cm^2, i.e. the working electrode, were embedded with epoxy resin and ultrasonically cleaned in distilled water after being polished with waterproof emery papers up to 1500 grit under running water. The acid solution was agitated and deaerated with high-purity nitrogen gas at a flow rate of about 250 mL/min for 2.4 ks to reduce the oxygen content, and was replaced for each experiment. The cathodic treatment was then carried out at −0.9 V for 600 s to remove any oxide films present on the surface of each specimen. After the natural electrode potential was held for 1.2 ks, the anodic polarization test was performed in the air at a sweep rate of 3.33×10^{-4} V/s (20 mV/min). A saturated calomel electrode was used as a reference electrode and a platinum wire as a counter electrode. The anodic test was repeated three times for each specimen which was polished using waterproof emery papers between two tests.

To characterize the anodic oxide films formed on the surfaces of specimens, the specimens were ultrasonically cleaned in methanol after the corrosion tests and then examined by a scanning electron microscopy (SEM) operated at 20 kV and an X-ray diffraction (XRD) analysis using a Cu Kα irradiation in the regular range $2\theta = 20$–$65°$ with an accelerating voltage of 40 kV and a current of 250 mA at a scanning speed of 1°/min at room temperature.

2.3. Evaluation of cyto-toxicity

Biocompatibility of the studied Ti–Ta alloys and pure Ti was judged by evaluating the cyto-toxicity through MTT assay. Two specimens with a size of Ø 10 mm × 2 mm and Ø 15 mm × 2 mm were prepared for each Ti–Ta alloy and pure Ti, respectively, and then polished using waterproof emery papers up to 1500 grit under running water. Each specimen was put on zirconia balls in a vessel and in the autoclave. The vessel with 10 ml Eagle's culture solution at a temperature of 310 K was rotated with a speed of 240 rpm, and extraction periods were 7 and 14 days. As-extracted solution and filtrated extract solution using 0.22 μm membrane filter were prepared. In the as-extracted solution and filtrated extract solution, the survival rate of L-929 cells derived from mice was evaluated using MTT methods as detailed in [14], which indicates the cyto-toxicity level of the extracts.

Table 1
Chemical compositions of studied Ti–Ta alloys

Alloy code	Ta (%)	O (%)	Ti (%)
Ti–10% Ta	10.0	0.075	Balance
Ti–30% Ta	29.6	0.088	Balance
Ti–70% Ta	69.9	0.034	Balance

2.4. Friction wear test

The friction wear characteristics of the studied Ti–Ta alloys together with Ti–6Al–4V ELI alloy versus a zirconia ball were evaluated using a pin-on-disk type friction wear test system. Specimens with a size of Ø 15 mm × 3 mm were wire-cut from the heat-treated plates, and then polished with waterproof emery papers up to 1500 grit under running water. The friction wear tests were carried out with a load of 4.9 N at 310 K in a simulated body fluid (Ringer's solution) for 100,000 cycles at one cycle per second. The wear test was repeated for three times each specimen which was polished using waterproof emery papers between two tests. The wear characteristics were evaluated by measuring the average weight losses of each specimen.

2.5. Hardness measurement

Vickers hardness measurements were conducted with a load of 98 N for a loading time of 15 s using a hardness tester. The samples for hardness measurements were ground and polished after the heat treatments.

3. Results

3.1. Microstructural characteristics

The microstructures of three different alloys as summarized in Table 2 were presented elsewhere [2,3], but briefly

Table 2
Constitutional phases and their morphologies of studied Ti–Ta alloys

Ta content	Heat treatment	Formed phase	Morphology
10%	ST	α'	Lamellar
30%	ST	α''	Needle-like
30%	STA	α	Lamellar
70%	ST	β	Equiaxed β with unrecrystallized structure

shown in Fig. 1 for clarity and easy understanding. It should be noted that the present microstructures of the studied alloys are slightly different from those shown in the previous studies [2,3] because they were obtained by deep etching treatment in order to display clearly their grain boundaries for an easy explanation.

3.2. Corrosion resistance

The anodic polarization curves for the studied Ti–Ta alloys together with pure Ti and Ti–6Al–4V ELI alloy are shown in Fig. 2. Obviously, like pure Ti and Ti–6Al–4V ELI alloy, all the studied alloys reach their respective stable passive current densities as the potential increases, indicating the existences of their passive behaviors in the 5% HCl solution. The Ti–10% Ta alloy shows the close current density, including the critical current density (I_{cc}) and passive current density (I_{pc}), and primary passivation potential (E_{pp}) similar to those of pure Ti and the Ti–6Al–4V ELI alloy, suggest-

Ti–10% Ta (ST)

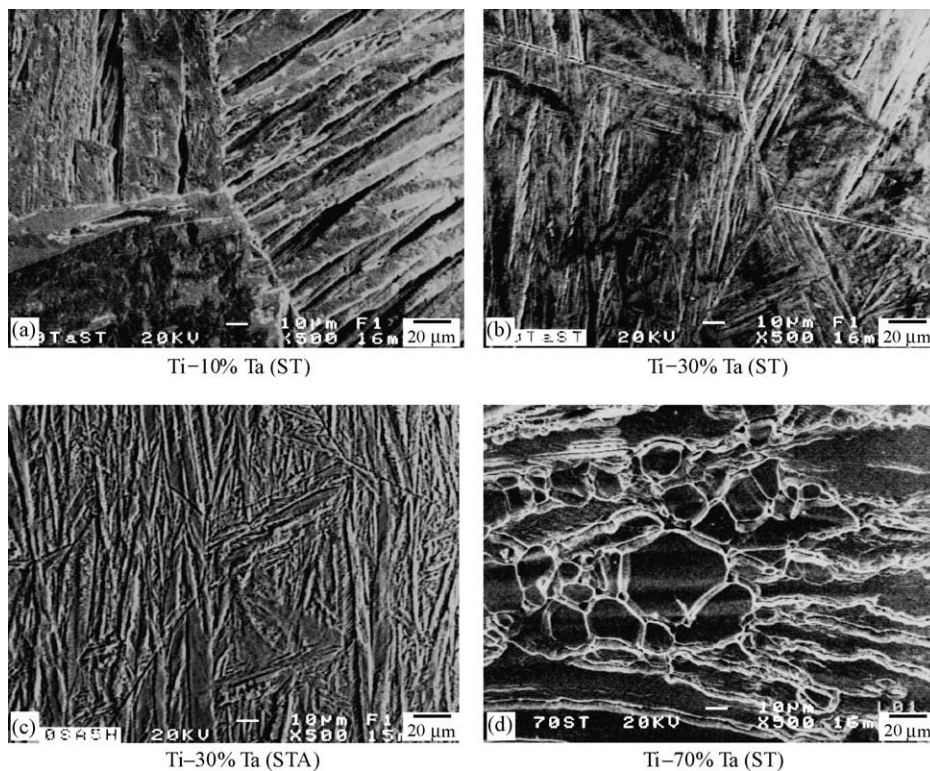Ti–30% Ta (ST)

Ti–30% Ta (STA)

Ti–70% Ta (ST)

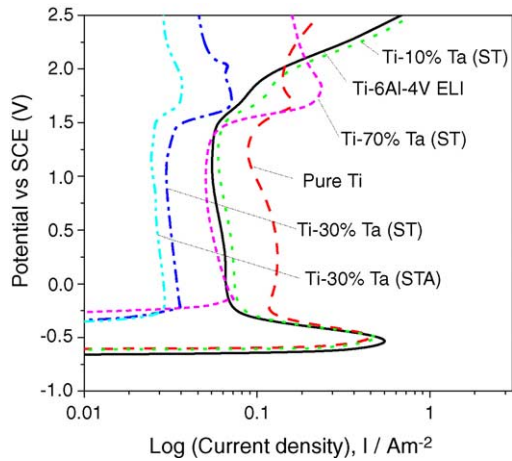Fig. 1. SEM micrographs of studied Ti–Ta alloys.

Fig. 2. Comparison of anodic curves for pure Ti, Ti–6Al–4V ELI and studied Ti–Ta alloys in 5% HCl solution at 310 K.

ing their similar corrosion resistance. In contrast, the current densities (I_{cc} and I_{pc}) of the other studied alloys decrease and the breakdown potentials (E_{br}) increase (the passive regions become wider), which indicates that the Ti–30% and 70% Ta alloys show better corrosion resistance than the other studied materials. There is no marked electrochemical difference between the ST-treated and STA-treated Ti–30% Ta alloys, implying that the corrosion behavior of an alloy is mainly decided by its chemical composition and a crystal structure has little influence on the corrosion resistance of an alloy. It can also be seen that the anodic polarization curve of the Ti–Ta alloy shifts to the noble (positive) direction with increasing Ta content, which is similar to the effect of addition of Pt [15] or Mo [16,17] on the corrosion behavior of Ti alloys.

The SEM micrographs of the passive oxide films formed on the surfaces of specimens are shown in Fig. 3, which are in agreement with the above anodic curves since the morpholo-
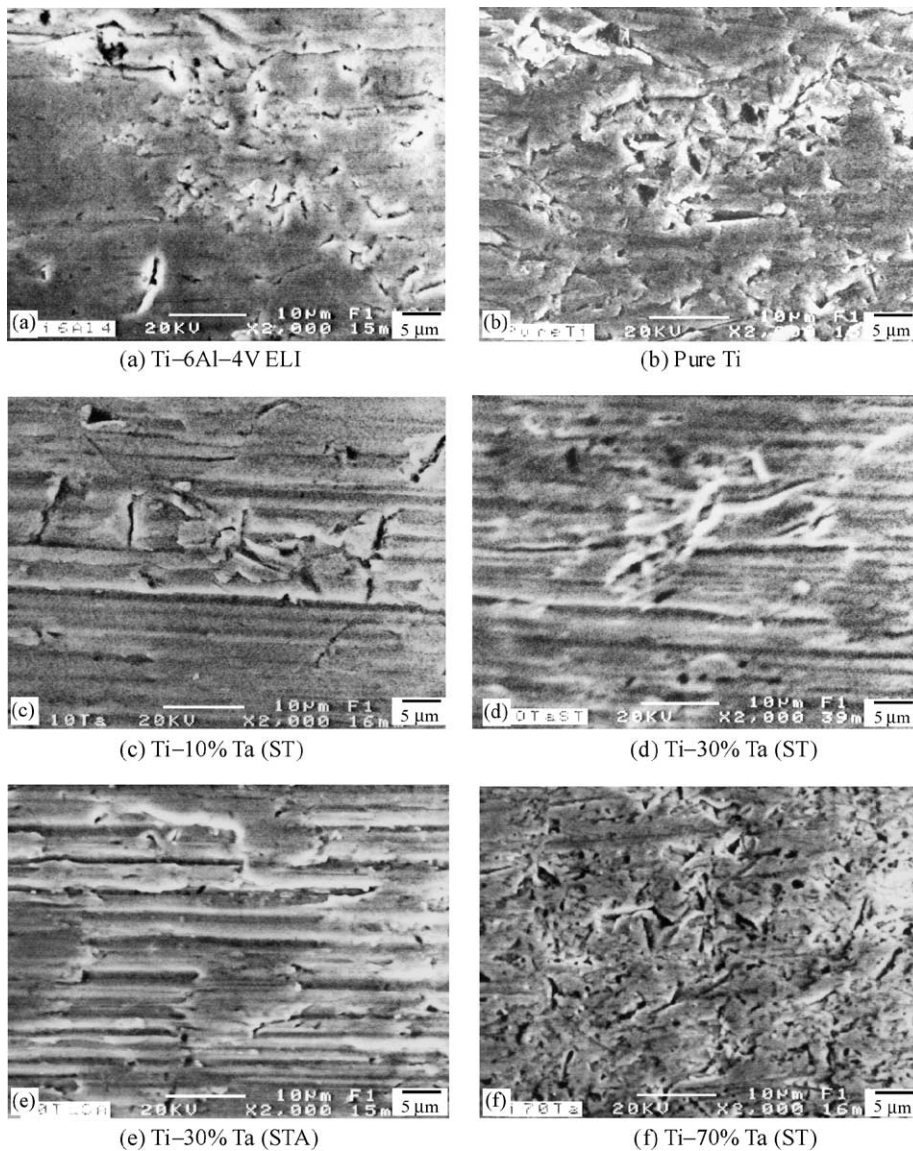

(a) Ti–6Al–4V ELI

(b) Pure Ti

(c) Ti–10% Ta (ST)

(d) Ti–30% Ta (ST)

(e) Ti–30% Ta (STA)

(f) Ti–70% Ta (ST)

Fig. 3. SEM micrographs of oxide films on the surfaces of pure Ti, Ti–6Al–4V ELI and studied Ti–Ta alloys after anodic tests.

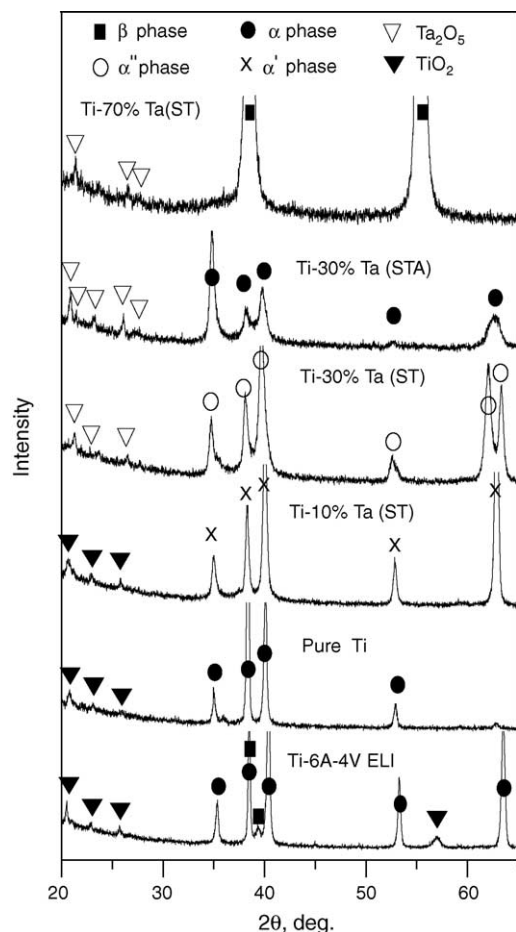Fig. 4. XRD patterns of pure Ti, Ti–6Al–4V ELI and studied Ti–Ta alloys after anodic tests.

Fig. 5. Cell viability of L-929 in (a) non-filtrated and (b) filtrated solutions evaluated by MTT method for studied Ti–Ta alloys and pure Ti.

gies of anodic films critically depend on the oxide growth behaviors. The oxide films formed on the surfaces of Ti–30% Ta alloys (ST and SAT), as shown in Fig. 3(d) and (e), are basically non-porous barriers (compact and uniform), characterized by grooves and ridges, which are related to their smaller current densities and narrow regions of second active–passive transitions as shown in Fig. 2. By contrast, the ones formed on the surfaces of the other materials have substantially different porous structures (the colonies unburied by oxide films) due to the dielectric breakdown.

The XRD analysis results of passive films formed on the surfaces of specimens are plotted in Fig. 4. It can be observed that the orthorhombic TiO_2 films form on the surfaces of pure Ti, Ti–6Al–4V ELI and Ti–10% Ta alloys, and the orthorhombic Ta_2O_5 films are, by contrast, presented on the surfaces of other alloys.

3.3. Cyto-toxicity and wear resistance

Since cyto-toxicity testing is a rapid, standardized, sensitive and inexpensive means to determine whether a material contains significant quantities of biologically harmful extractables, it was used to evaluate the biocompatibility of
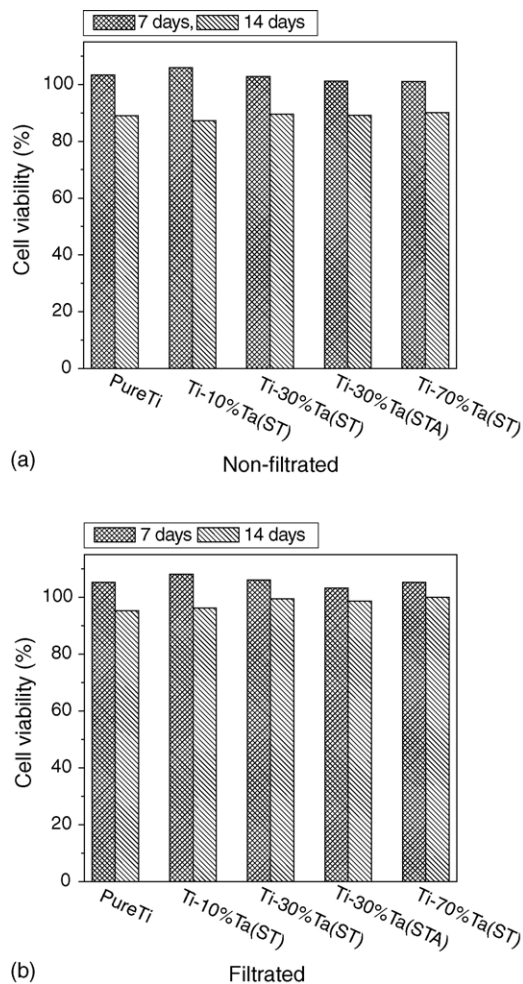
studied Ti–Ta alloys in this study. Fig. 5 shows the comparison of cell viability of filtrated extracts and non-filtrated extracts of the studied Ti–Ta alloys and pure Ti after extracting for 7 and 14 days evaluated through MTT assay. It can be seen that the cell viability of studied Ti–Ta alloys is almost the same as that of pure Ti in both filtrated extracts and non-filtrated extracts, indicating the non-cytotoxicity of studied Ti–Ta alloys like pure Ti. The ST treated Ti–30% Ta alloy exhibits the very close cell viability to the STA treated alloy in the above two extracts, which suggests that a crystal structure has little influence on the cyto-toxicity of an alloy.

The measured average weight losses and Vickers hardness numbers (Hv) of studied Ti–Ta alloys together with the Ti–6Al–4V ELI alloy are plotted in Fig. 6. It can be seen that the measured weight loss of each Ti–Ta alloy is smaller than that of Ti–6Al–4V ELI alloy, indicating their better wear resistances than the Ti–6Al–4V ELI alloy. The change in the trend of average weight loss for all the studied materials is inconsistent with that of their Vickers hardness number because the wear resistance of a Ti alloy is insensitive to its
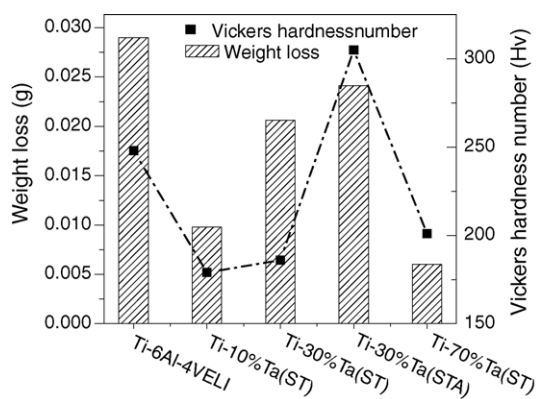
Fig. 6. Weight losses and Vickers hardness numbers of Ti–6Al–4V ELI and studied Ti–Ta alloys.

mechanical properties such as hardness and tensile strength [18].

4. Discussion

The corrosion resistance of a pure metal or an alloy strongly depends on the environment where it is exposed, the chemical composition, temperature, velocity and so forth. The excellent corrosion resistance of pure Ti and its alloys results from the formation of very stable, continuous, highly adherent, self-realed and protective oxide films (mainly TiO_2) on metal surfaces within milliseconds in a wide range of corrosive media with all pH ranges, and the outstanding corrosion capacity of Ta and its alloys are by contrast because of the formation of the protective oxide films (mainly pentoxide Ta_2O_5) [15–17,19–41]. Thus, those TiO_2 and Ta_2O_5 oxide films can definitely result in the expected superior corrosion resistance of Ti–Ta alloys, which is proven by the present study.

Ti–30% and 70% Ta alloys have current densities smaller than those of the other materials as shown in Fig. 2, which indicates that the oxide films (mainly Ta_2O_5 as detected by the XRD analysis) formed on the surfaces of Ti–30% and 70% Ta alloys can more effectively prevent an exchange of electrons and ions than those (mainly TiO_2 as detected by the XRD analysis) formed on the surfaces of the other materials, and thus the Ta_2O_5 oxide film is stronger and more stable than the TiO_2 oxide film. The compositions of the corrosion products formed on the surfaces of studied Ti–Ta alloys in 5% HCl solution change predominately from TiO_2 to Ta_2O_5 with increasing Ta content and the negative free energy of Ta_2O_5 is relatively higher than that of TiO_2 oxide [42], which are related to the noble shift of anodic polarization curves of studied Ti–Ta alloys with increasing Ta content as shown in Fig. 2 according to the relationship between free energy and electrochemical potential [17,27,28].

As mentioned above, the TiO_2 oxides have been extensively observed on the surfaces of Ti and its alloys when exposed in the moist media with the air or moisture. However, they cannot be detected on the surfaces of Ti–30% and 70% Ta alloys by the XRD analysis in this study, which may be due to its relatively smaller volume fraction in the passive layers. The difference in free energy between the products of reactions and reactants is the driving force of corrosion reactions, which controls the formations of various oxides [17,27,28]. However, once corrosion products form, the further behaviors depend on the natures of the film substances such as the electrical, chemical and mechanical properties [17,27,28], resulting in various amounts of oxide films on an anode. For instance, the chloride solutions strongly promote the anodic corrosion of TiO_2/Ti [36–38] while Ta has the chemical properties similar to glass, which is immune to attack by almost all acids except HF [17] and is particularly resistant to chlorine due to the relatively more stable Ta_2O_5 oxide film [20,28]; thus, the TiO_2 oxides are possibly largely dissolved in the HCl solution especially with increasing electrochemical potential. From Fig. 2, it can be seen that pure Ti, Ti–10% Ta and Ti–6Al–4V ELI alloys begin to enter into the transpassive regions in the potential range of 1.6–1.8 V, indicating the starting dissolution of passive TiO_2 oxide films (pitting). By contrast, the more stable Ta_2O_5 oxide films formed on the surfaces of the other alloys can sustain the potential up to 2.5 V without a pitting where the second active–passive transitions are observed due to the dissolution of passive TiO_2 oxide films in the same potential range of 1.6–1.8 V, which strongly support the above inference. In addition, it was reported that the anodic films of Ti–Ta alloys consist of a relatively thin outer layer of TiO_2 and inner layer of units of TiO_2 and Ta_2O_5 due to the faster migration of Ti^{4+} ions in the inner layer relative to that of Ta^{5+} ions [43] and the XRD analysis technique is more suitable for the chemical analysis of surface constituents whose depth is between 10 and 100 μm from the outermost surface of a specimen [17], which is possibly another reason why the TiO_2 oxide cannot be detected on the surfaces of Ti–30% and 70% Ta alloys in this study. The TiO_2 oxide rather than vanadium or aluminium oxides is detected on the surfaces of Ti–6Al–4V ELI alloy maybe due to its relatively larger volume fraction, which agrees with the other observations [17,20,39–41].

The anodic oxides (mainly TiO_2 and Ta_2O_5) of Ti and Ta can exist in an amorphous, or a crystalline structure or a combination of both of them, which are determined by varied factors such as temperature, electrochemical potential, oxygen evolution and current density or stress [32–35,44]. They extensively exist in a glassy state; however, there are contrasting findings since an amorphous anodic oxide film may be crystallized by thermal crystallization [44] or electric field crystallization [32–35]. For example, the crystalline Ta_2O_5 oxides were observed previously during anodization of Ta [32,33], and Marino et al. [35] reported that the crystalline anodic TiO_2 oxides form in phosphoric acid solutions, and Sul et al. [45] found that the crystal structures of Ti oxides are composed of amorphous, anatase (crystalline) and a mixture of anatase and rutile type. In this study, the different peaks of orthorhombic TiO_2 and Ta_2O_5 can be clearly detected, which

also prove the existence of anodic oxide crystallization. Since the direct structural information on the anodic films of the studied materials with the film growth is not easily acquired during the experiments, it is hard to know how these amorphous oxides have been crystallized with increasing electrochemical potential. According to the review of Leach and Pearson [34], the growth of a crystalline oxide is generally favored when an amorphous oxide is under the compressive stress because a crystalline material occupies smaller volume than the same-weight amorphous material. It was also pointed out that the anodic film is crystalline when the internal stresses become compressive at low current density, and it is glassy when the tensile stresses occur at higher current density [34], which could account for the above experimental discrepancies. Unfortunately, the detailed information on stresses in TiO_2 and Ta_2O_5 is not readily available, especially as a function of current density; thus, further discussion in this study is impossible.

Previous studies show that pure Ta exhibits better corrosion resistance than pure Ti in various corrosive solutions [28] and the corrosion resistance of Ti–20, 40, 60 and 80% Ta alloys, which were annealed at 1473 K for 172.8 ks followed by a furnace cooling, increases with Ta content in the H_2SO_4 solution according to the measured open-circuit potentials [19]. However, it is unexpected that the ST-treated Ti–70% Ta alloy shows bigger current density than the Ti–30% Ta alloys (ST, STA) in the HCl solution in this study, which seems to be contradictory with the above finding. Comparing the microstructures of the Ti–Ta alloys in this study with those in the previous one [19], it can be seen that the unrecrystallized and recrystallized structures coexist in the Ti–70% Ta alloy (Fig. 1(d)) after the solution treatment at 1223 K for 3.6 ks, and the grains in the ST treated Ti–70% Ta alloy are much finer than those in the other alloys as shown in Fig. 1, which are quite different from the fully recrystallized structures in the other Ti–Ta alloys [19]. It is well known that a unrecrystallized structure has extra free energy and higher density of dislocations accumulated by a plastic deformation, and that a fine-grained material has higher internal energy than the similar coarse material because of the structural and chemical differences between the grains and grain boundaries, which can result in the acceleration of corrosion [8,17,27,28] and the stress-corrosion cracking caused by the introduced residual stress [17,20]. Those account for that the ST treated Ti–70% Ta alloy has slightly higher current density, wider region of second active–passive transition than those of the Ti–30% alloys (ST and STA) as shown in Fig. 2 and the highest pore density among all the studied materials as shown in Fig. 3. It is expected that the Ti–70% Ta alloy would have smaller current density than the Ti–30% Ta alloy if it is without the presence of the unrecrystallized and much finer-grained structures.

The studied Ti–Ta alloys are non-toxic like pure Ti as proven by this study, and the previous study [14] shows that the cell viability of pure Ti in the above two extracts is greater than that of Ti–6Al–4V alloy used as a standard biomaterial, thus the Ti–Ta alloys are highly expected to have superior

biocompatibility. Additionally, the toxicity of metallic biomaterials may also be caused due to metal debris released into a living body by wear after being implanted [11,18,46,47], and a high wear resistance can minimize the debris generation and thus significantly prevent the resulting inflammation inside the host. The wear performances of the studied alloys are related to the properties of the oxide layers such as TiO_2 and Ta_2O_5 and the deformation behavior of the substance regions. The TiO_2 and Ta_2O_5 oxide layers can form spontaneously within millisecond on the surfaces of pure Ti, Ta and their alloys when exposed in the moist media with the air or moisture. However, they have different mechanical properties due to their different chemical compositions and the volume fraction of those oxide layers formed in a certain medium actually changes with the chemical composition of present alloy as shown in 5% HCl solution of the above anodic tests, which naturally influence the wear performances of the studied alloys. On the other hand, however, those oxide layers are easily damaged or fractured under fretting and sliding wear conditions because they are very thin and have poor mechanical properties [48], which is one of the important reasons responsible for the poor wear resistance of Ti and its alloys. According to the analysis by Long and Rack [49], α-titanium, relatively low shear strength HCP material, exhibits not only higher friction values but also greater material transfer, due to its high reactivity to non-metallic counterfaces, than higher strength materials. Hence, Ti and its alloys are considered to have poor oxidative wear resistance when "tribo-chemical" reactions occur at the contact area. The β-type Ti alloys exhibit some strain hardening and thus offer the enhanced wear resistance [49], which helps to understand why the Ti–70% Ta alloy with β phase shows the best wear performance in this study. The orthorhombic α″ structure is regarded as a transitional product between α and β structures, the wear resistance of Ti alloys with α″ phase are thus expected to be between those of α and β type alloys. Actually, the reasons for the wear performance of the studied Ti–Ta alloys may be complicated, and hence further experiments are necessary.

Although the studied Ti–Ta alloys exhibit better wear performance than Ti–6Al–4V ELI alloy, the wear resistance of studied Ti–Ta alloys should be further improved by surface treatments such as coatings [50] and oxygen diffusion hardening layer [48,51,52] almost without the expense of other important properties since the Ti–6Al–4V ELI alloy implants have shown the presence of black wear debris in the tissues surrounding the implant due to fretting and abrasion with the bone and bone cement [51], and Ti and its alloys have had a reputation for poor tribocharacteristics [49,53].

The biocompatibility is the ability of a material to remain biologically innocuous during its functional period inside a living creature, and for a metallic material it is determined by its corrosion resistance and toxicity of its corrosion products [49,54–56]. As proven by the present results, the Ti–Ta alloys show excellent corrosion resistance because the protective surface films of semi-conductive or non-conductive TiO_2 and Ta_2O_5 oxides are able to prevent to a great extent

an exchange of electrons and ions, and hence the resulting ion releases are expected to be low or negligible due to the isolating effects of the protective layers. The stronger and more stable the passive film formed on the surface of an implant, better is the corrosion resistance and lesser is the release of metal ions from the surface [47]. In fact, it was reported that the addition of Ta remarkably decreases the concentration of metal releases [31,57,58]. In addition, there has been no allergy report associated with the Ti and Ta elements till date [59], and the TiO_2 and Ta_2O_5 oxide films exhibit to be inert in the body fluids [8,10]. These can be the reasons why the Ti–Ta alloys possess excellent biocompatibility.

Recent investigations [60–62] have reported that the biomimetic coatings with bioactivity such as the apatite or hydroxyapatite (HAP) can form on the surfaces of pure metals and Ti alloys as the interface between implant and hard tissues by chemical and heat treatments to overcome the inertness of TiO_2 and Ta_2O_5 oxide films in the body fluids; thus, the excellent biocompatibility of Ti–Ta alloys can be expected to further improve by a biomimetic coating treatment.

5. Conclusions

The corrosion resistance, wear resistance and cyto-toxicity of Ti–10, 30 and 70% Ta alloys with different microstructures were investigated in this study. The following conclusions can be obtained.

(1) The passive behaviors are observed for all the studied Ti–Ta alloys, and the corrosion resistance of studied alloys is improved by alloying Ta element because the more stable Ta_2O_5 passive films strengthen the TiO_2 passive films.
(2) The studied Ti–Ta alloys are non-cytotoxic like pure Ti.
(3) Crystal structure shows little influence on the corrosion resistance and cyto-toxicity of the studied Ti–Ta alloys.
(4) The wear resistance of the studied Ti–Ta alloys is better than that of Ti–6Al–4V ELI alloy.
(5) The experimental results confirm the expected excellent corrosion resistance and biocompatibility of the studied Ti–Ta alloys, which are better than or similar to those of pure Ti or Ti–6Al–4V ELI alloy used as standard biomaterials, suggesting their promising potentials for biomedical applications.

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