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Biocompatibility of new Ti–Nb–Ta base alloys

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ABSTRACT

β-type titanium alloys are promising materials in the field of medical implants. The effect of β-phase stability on the mechanical properties, corrosion resistance and cytotoxicity of a newly designed β-type ($Ti_{77}Nb_{17}Ta_6$) biocompatible alloys are studied. The β-phase stability was controlled by the addition of small quantities of Fe and O. X-ray diffraction and microstructural analysis showed that the addition of O and Fe stabilized the β-phase in the treated solution condition. The strength and hardness have increased with the increase in β-phase stability while ductility and Young's modulus have decreased. The potentio-dynamic polarization tests showed that the corrosion resistance of the new alloys is better than Ti–6Al–4V alloy by at least ten times. Neutral red uptake assay cytotoxicity test showed cell viability of at least 95%. The new alloys are promising candidates for biomedical applications due to their high mechanical properties, corrosion resistance, and reduced cytotoxicity.

1. Introduction

The increase in traffic accidents, especially for young people, has brought an ever-increasing need for implants for long term application in human body [1]. Due to the interaction of such implants and body tissues and fluids, a class of materials called biomaterials has emerged. This class of materials can be distinguished from other classes by their biocompatibility. Such implants have to be biocompatible. The term biocompatibility refers to "*The ability of a material to perform with an appropriate host response in a specific situation*" [2]. Due to the wide range of biomedical applications, that range from sensors [3], artificial vascular tissues [4], orthopedic implants [5], etc..., and to fit aforementioned generalized definition of biocompatibility, we limited our discussion to the parameters that affect the implants for bone replacements.

Due to the requirements of quality of life in modern societies, implants should serve for a lifetime without failure. Researchers are working hard to develop materials for long life implantation in the human body. This is because commercial biomaterials have exhibited tendencies to fail after long-term use due to their high modulus compared to that of bone, and lack of biocompatibility [6]. In that sense, parameters for biocompatibility of orthopedic implant materials include biological biocompatibility, mechanical biocompatibility and corrosion resistance [5]. Biological biocompatibility is a general term expressing the interaction of the implant material effects on the biological process; whether the material is carcinogenic, mutagenic, genotoxic or cytotoxic. Moreover, it includes resistance to the corrosive biological environment. The majority of these implant materials contain; V, Al, Co, Cu, Cr, Mo and Ni, which have biocompatibility issues [5]. On the other hand, Ti, Zr, Nb, Ru, Ta, Au and Sn exhibit the best biological biocompatibility and can be used safely in the human body [5].

Mechanical biocompatibility (i.e., high strength, high-wear resistance and low Young's modulus) is essential for orthopedic long-term implantation. Among these mechanical properties, Young's modulus is of a major importance because of the "stress shielding" effect, which is one of the main reasons for revision surgeries [7,8]. Titanium alloys are excellent biomaterials for long-term implantation compared to stainless steel and Co–Cr alloys due to their relatively low Young's modulus, good fatigue resistance and chemical inertness [9].

Morinaga et al. [10–13] developed an alloy design approach based on electronic structure calculations. The outputs of these calculations are two electronic parameters: B_o, the bond order and M_d, the *d* orbital energy level. By plotting these parameters for titanium alloys in a B_o–M_d diagram, a correlation between alloying elements, phase composition of the alloy and the elastic properties was successfully established [13]. Recently, a new $Ti_{77}Nb_{17}Ta_6$ alloy was designed in the $\beta + \alpha''(+\omega)$ phase zone in the B_o–M_d diagram [14] where it is anticipated to have a Young's modulus in the range of 50–60 GPa [13]. Minor quantities of O and Fe were added to enhance the strength and control the β-phase stability. X-ray diffraction and microstructural studies showed the domination

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Table 1
XRF results and designed composition values of the designed alloys (in mass%).

		Nb	Ta	O	Fe	Ti
TNT	Measured	30.0	17.6	–	0.0701	Balance
	Nominal[a]	24.86	17.08	–	0.0	
TNTO	Measured	30.7	17.5	NA	0.140	
	Nominal[a]	24.99	17.17	0.25	0.0	
TNTFO	Measured	29.9	16.7	NA	1.08	
	Nominal[a]	24.96	17.15	0.25	0.88	

[a] As calculated during alloy preparation.

of the β-phase in the solution treated condition. On the other hand, aging treatments showed considerable precipitations of the α-phase in a β-matrix [15]. In this article, we investigated the mechanical properties of the alloys in the solution treatment condition. Corrosion and cytotoxicity testing were performed to assess the potential use of these alloys for orthopedic implants application.

2. Experimental methods

The alloys were prepared by arc-melting from a mixture of pure metals. The specimens were then solution treated at 900 °C for 0.5 h using a tube furnace under a vacuum of 5 Torr. Samples were then 50% cold rolled to achieve a final thickness of approximately 2 mm.

The chemical composition of the samples was measured semi-quantitatively using Rigaku NEX-CG energy dispersive X-ray fluorescence (XRF) spectrometer. XRD was performed using PANalyticX'Pert PRO diffractometer at a scan rate of 2.4 °/min. For metallographic analysis samples were wet ground with SiC papers up to #4000, polished with colloidal alumina and colloidal silica successively and then etched in a solution of 8% HF (40% conc.) and 8% HNO_3(70% conc.). Optical micrographs were observed using Keyence confocal microscope. The hardness of the samples was measured using Shimadzu HMV2 Micro-Hardness tester.

The corrosion behavior of the designed alloys was assessed in terms of the corrosion current density (j_{corr}), and corrosion potential (E_{corr}) from potentiodynamic polarization tests [16]. The samples were compared to the Ti–6Al–4V alloy that is widely used in orthopedic applications. A typical three-electrode cell configuration was used consisting of the studied specimen, Ag/AgCl electrode as reference electrode and a platinum foil as the counter electrode. Each test run was performed

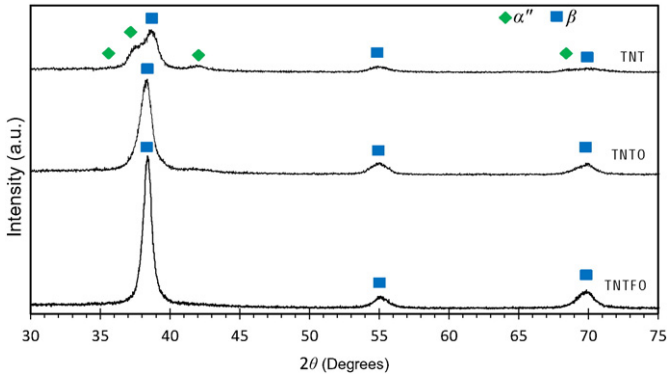

Fig. 2. XRD patterns of the designed alloys in the ST condition.

in a fresh 50 ml of physiological Ringer's solution after 30 min immersion in open-circuit potential condition. Potentiodynamic tests were performed at a potential range of −250 mV to +250 mV with respect to the open circuit potential of each alloy using Gamry G 300/750 potentiostat with a scan rate 1 mV/s [17,18].

Cells from a human cervical cancer cell line (HeLa) were used for neutral red uptake cytotoxicity. The total surface area of each sample was approximately 1 cm^2. Each sample weighted approximately 0.5 g after grinding with #1200 SiC papers. All samples were cleaned ultrasonically in distilled water and 99.5% acetone for 30 min respectively and then sterilized by autoclaving in dry heat at 180 °C for 1 h. The sterilized samples were then kept under UV microbicide lamp radiation for 12 h. Each sample was extracted in Dulbecco's Modified Eagle Medium for 7 days at 37 °C. The cells were seeded to all wells with 4×10^5 cell/well count using hemocytometer. After cells attained almost 50% confluency, 125 μl of each of the previously prepared test extracts were added to each well. Untreated cells, i.e. with no metal extract added, were used as a negative control. Cells were cultured for two successive days at 37 °C in 90% ± 5% humidified air with 5.0% CO_2. Every 24 h, the test wells were examined under a phase contrast microscope to identify systematic cell seeding errors and growth characteristics of the control and treated cells. The cell viability was calculated as the ratio of living cells to the number of viable cells in the negative control. All of the experiments were conducted in triplicates.

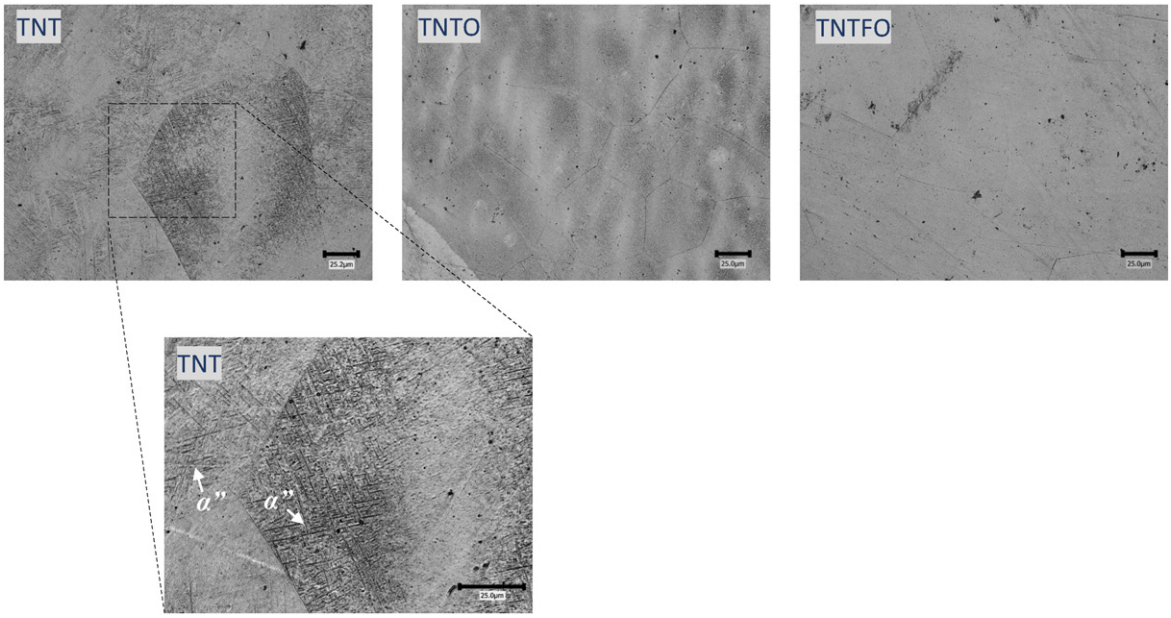

Fig. 1. Optical micrographs of the designed alloys in the ST condition.