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Effect of heat treatment on mechanical properties of Ti–6Al–4V ELI alloy

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ABSTRACT

Ti–6Al–4V alloy of extra low interstitial (ELI) grade has been used in the biomedical applications because of its high strength-to-weight ratio and excellent biocompatibility. However, its relatively poor wear resistance leading to excessive wear and implant loosening requires proper surface hardening. The body implants are also subjected to a variety of loads at varying strain rates. The objective of this study was to evaluate the hardening behavior, strain rate sensitivity and fracture mechanisms with or without hardened surface layer. It was observed that the hardened surface layer had only a small effect on the strength but reduced the ductility. The yield strength (YS) and ultimate tensile strength (UTS) were higher in the water quenching and aging condition while the ductility was lower, when compared to the as-received condition and air cooling and aging condition. As the strain rate increased both YS and UTS increased and ductility decreased. The strain hardening exponent decreased with increasing strain rate. The strain rate sensitivity evaluated via both the common approach and Lindholm approach decreased as the true strain increased. Fractal dimension of fracture surfaces was observed to be associated with the heat treatment condition, ductility, fracture surface characteristics and roughness. The fractal dimension increased with increasing roughness of fracture surfaces.

1. Introduction

The extra low interstitial (ELI) grade of titanium alloy Ti–6Al–4V has been used in the biomedical industry because of its high strength-to-weight ratio, superior mechanical properties over other materials, relatively low elastic modulus, excellent corrosion resistance, and outstanding tissue compatibility [1–4]. Interest in the Ti–6Al–4V ELI alloy for total joint prosthesis grew significantly in the United States toward the late 1970s [4]. Current uses of Ti–6Al–4V alloy include hip and knee joints prosthesis, trauma/fixation devices and dental implants [1].

However, where a contacting motion of counterparts is required, the relatively poor wear resistance of this alloy leads to excessive wear, mechanical and chemical instability, and implant loosening [5]. Various surface treatment methods, such as ion implantation, TiN coating, and thermal oxidation, have thus been proposed to improve the wear resistance by changing the nature of the surface. Thermal oxidation, carried out in normal atmospheric condition containing oxygen and nitrogen, has recently been reported to be a promising approach for producing hard surfaces on Ti alloys [5], where a hardened oxygen diffusion zone (ODZ) formed beneath the TiO_2 layer provided good protection from corrosion and wear [6]. The TiO_2 layer has also found potential applications in photocatalysis, solar cells, gas sensors and waste remediation [7–9].

With regard to basic characteristics of titanium alloy, such as the equilibrium phase diagram, physical and metallurgical properties, heat treatment process and metallographic structure, there is a lot of useful data for reference. A variety of microstructures can be acquired by simple thermo-mechanical treatments on this $\alpha+\beta$ alloy, with a β transus temperature of about 975 °C [10]. Ti–6Al–4V ELI alloys used in the body implants are inevitably subjected to a variety of loads during walking, running and climbing, which necessitates the knowledge of mechanical properties at different strain rates. Naughton and Tiernan [1] have recently conducted experiments for the strain rate sensitivity index *m* for the Ti–6Al–4V ELI grade wire alloy at the temperatures ranging from 750 to 1050 °C to determine superplastic forming capabilities. While there are numerous data on the common Ti–6Al–4V alloy, very limited studies involving the strain rate sensitivity and strain hardening characteristics of the ELI grade alloy have been reported. The primary objective of this investigation is, therefore, to evaluate the strain rate sensitivity and the strain hardening exponent of the Ti–6Al–4V ELI alloy subjected to different heat treatment conditions with and without the thermal oxide layer.

2. Experimental procedure

Ti–6Al–4V alloy of ELI grade in an initially annealed condition with a thickness of 3.125 mm was selected in this study. The chem-

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Table 1
Chemical composition of the as-received Ti–6Al–4V ELI alloy selected in the present investigation (wt%).

N	C	H	Fe	O	Al	V	Ti
0.004	0.010	0.0052	0.18	0.10	5.90	4.06	Balance

ical composition of this alloy is given in Table 1. Subsized tensile specimens of 140 mm long with a gauge length of 25 mm and gauge width of 6 mm according to ASTM E8 were machined in the rolling direction using a CNC machine. Heat treatment was carried out at a temperature of 955 °C for 30 min in an argon environment using a Lindberg atmosphere furnace, which was calibrated with chromel–alumel thermocouples in accordance with AMS2750 standard. Two cooling conditions—water quenching and air cooling were used. The specimens were then subjected to aging treatments at a temperature of 525 °C for 4 h in the argon atmosphere at a flow rate of 15 CFH. The as-received and heat-treated specimens were mounted using the bakelite powder, ground with SiC papers of different grades, polished using the 6μ diamond paste and Master prep solution, and etched with Kroll's reagent (2%HF + 4%HNO_3). The microstructure was observed using a light microscope, and the Knoop hardness values were determined using a computerized Buehler microhardness tester under 200 g.

Post-heat treatment process included cleaning and removing burrs. To reveal the effect of thermal oxide layer on the mechanical properties, some specimens were pickled using HF/HNO_3 solution to remove the oxidized alpha case layer for about 0.2 mm. All samples were hand-ground progressively along the loading direction with 120, 320, and 600 emery papers to achieve a smooth surface. Both pickled and un-pickled specimens oriented in the rolling direction were subjected to tensile tests using a computerized Instron testing system at a strain rate between 0.01 s^{-1} and 0.00001 s^{-1}. Fracture surfaces after tensile testing were examined using scanning electron microscope (SEM) coupled with energy dispersive X-ray spectroscopy (EDS). Fractal dimensions were determined via three-dimensional (3D) measurements of fracture surfaces areas vs. the ruler scale (i.e., the side length of equilateral triangular tiles) using MeX software. The recorded tensile test data were used to evaluate the strain hardening exponent (or index) n and strain rate sensitivity m in two ways: the common approach [11] and the Lindholm approach [12].

3. Results and discussion

Fig. 1 shows the microstructures of Ti–6Al–4V ELI alloy in different conditions. As seen in Fig. 1(a), the microstructure of the as-received material consisted of primary α and α + β phases. Fig. 1(b) shows the microstructure obtained after air cooling from 955 °C and subsequent aging which resulted in a mixture of acicular α and β with primary α, similar to the result obtained by Jovanovic et al. [13] and also described by Donachie [14]. After water quenching from 955 °C and subsequent aging at 525 °C (Fig. 1(c)), the microstructure consisted of primary α and α′ + β. The subsequent aging resulted in precipitation of some fine secondary α phase in the metastable β phase [15]. Semiatin and Bieler [16] confirmed this in their experiments for Ti–6Al–4V alloy and stated that the breakdown operation of microstructure takes place at the two-phase field, below the beta transus temperature at which the β becomes α + β. The formation of martensite transformed from β phase at 955 °C is due to the fast cooling rate during water quenching, as noted by Zhang et al. [17] for Ti–6Al–4V alloy. They explained

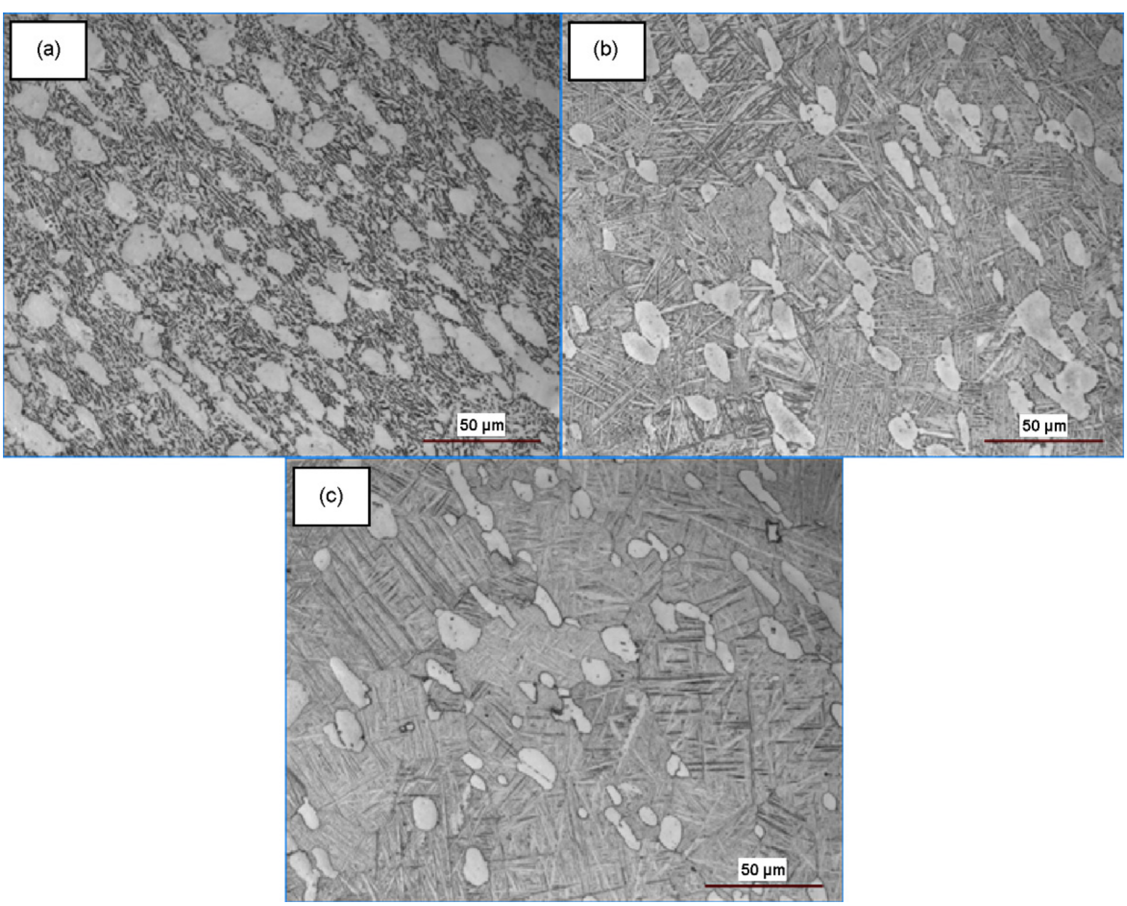

Fig. 1. Microstructures of Ti–6Al–4V ELI alloy in different conditions, (a) as-received, (b) air cooling plus aging (AC + aging), and (c) water quenching plus aging (WQ + aging).