ELSEVIER

Materials Science and Engineering A 486 (2008) 19–26

MATERIALS SCIENCE & ENGINEERING A

www.elsevier.com/locate/msea

Effect of precipitates on damping capacity and mechanical properties of Ti–6Al–4V alloy

Dong-Geun Lee[a,*], Sunghak Lee[b], Yongtai Lee[a]

[a] *Korea Institute of Materials Science, 66 Sangnam-dong, Changwon 641-831, South Korea*
[b] *Department of Materials Science and Engineering, Pohang University of Science and Technology, Pohang 790-784, South Korea*

Received 24 January 2007; received in revised form 17 August 2007; accepted 17 August 2007

Abstract

The present study was concerned with the effects of over-aging on damping property and fracture toughness in Ti–6Al–4V alloy. Damping property and toughness become important factors for titanium implants, which have big modulus difference between bone and implant, and need high damping capacity for bone-implant compatability. Widmanstätten, equiaxed, and bimodal microstructures containing fine α_2 (Ti_3Al) particles were obtained by over-aging a Ti–6Al–4V alloy. Over-aging heat treatment was conducted for 200 h at 545 °C. Fracture toughness, Charpy impact, and bending vibration tests were conducted on the unaged and the over-aged six microstructures, respectively. Charpy absorption energy and apparent fracture toughness decreased as over-aging was done, even if the materials were strengthened by precipitation of very fine and strong α_2-Ti_3Al particles. On the other hand, damping properties were enhanced by over-aging in Widmanstätten and equiaxed microstructures, but was weakened in bimodal microstructure due to the softening of tempered martensite and the decreasing of elastic difference between tempered martensite and α phase contained α_2 particles, *etc*. These data can provide effective information to future work about internal damping and fracture properties of Ti–6Al–4V alloy.

Keywords: Ti–6Al–4V; α_2-Ti_3Al precipitates; Widmanstätten; Equiaxed; Bimodal; Damping capacity; Impulse-frequency response method; Fracture toughness

1. Introduction

Ti–6Al–4V alloy is characterized to be sensitive to microstructural variations such as volume fraction of α and β phases, morphology, and crystallographic arrangement. Its microstructure is largely divided into Widmanstatten, equiaxed, and bimodal according to heat treatment conditions. Major microstructural parameters affecting mechanical properties of these microstructures are prior β grain size, colony size, thickness of boundary α phase, volume fraction of α, β, and tempered martensite. Many researches have been performed to obtain desired mechanical properties by controlling these microstructural factors through heat treatments or thermomechanical treatments [1–10]. When Ti–6Al–4V alloy is over-aged at 500–600 °C, nanometer-sized, fine, ordered α_2 (Ti_3Al) particles can be homogeneously precipitated inside α phases [11–13], and α_2 phases have coherent relationship with α during aging. Al in Ti–6Al–4V alloy works as an α stabilizer, therefore it increases α/β transformation temperature and forms a region coexisting α and α_2 phases in phase diagram [14]. Size and inter-particle spacing of α_2 phases are mainly affected by aging temperature, time, and Al concentration related to α_2 dissolving temperature. On the other hand, prevention of resonance is important in the field of dynamic structures and implant biomaterials, and many alloys do not meet sufficiently this requirement even if it is needed to have high damping properties absorbing vibration and oscillation when materials are used under these conditions. Therefore, it is required to obtain additional information on oscillation absorbing ability of material itself against unnecessary noise and mechanical vibration, *etc.* to use Ti–6Al–4V alloy for implant materials or dynamic parts.

In this study, Widmanstatten, equiaxed, and bimodal microstructures were obtained by different heat treatment, and then α_2 particles were homogeneously precipitated inside α phases by over-aging heat treatment of Ti–6Al–4V alloy. Fracture toughness and impact properties of these three over-aged microstructures were investigated in comparison with those of unaged microstructures. Damping loss factor was

---

[*] Corresponding author. Fax: +82 55 280 3393.
E-mail address: leechodg@kims.re.kr (D.-G. Lee).

0921-5093/$ – see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.msea.2007.08.053

tested and evaluated by using impulse-frequency response method, and effects of over-aging on damping and mechanical properties of titanium alloy were investigated in three microstructures.

2. Experimental

The material used in this study was a Ti–6Al–4V alloy plate (thickness; 50 mm) obtained from Supra Alloys Inc., U.S.A., and its chemical composition was 6.19Al–4.05V–0.19Fe–0.12O–0.02C–0.01N–0.004H–Ti(wt.%). Widmanstätten microstructure was obtained by holding at 1050 °C, above the β transformation temperature, for 1 h followed by furnace cooling, while equiaxed microstructure by holding at 950 °C, the α + β region, for 1 h followed by furnace cooling. Bimodal microstructure was obtained by holding at 950 °C for 1 h followed by water cooling, which was then aged for 24 h at 600 °C and air-cooled. These microstructures were over-aged at 545 °C for 200 h to precipitate very fine α_2 phases.

Specimens were etched using a Kroll solution (H_2O 100 ml, HF 100 ml, HNO_3 100 ml), and their microstructures were observed using an optical microscopy. The size and volume fraction of each phase were measured using an image analyzer. Tensile bars with a gage length of 30 mm and a gage diameter of 6 mm were machined, and tensile tests were conducted at room temperature and at a strain rate of $10^{-3}\,s^{-1}$. Apparent fracture toughness was measured using compact tension specimen with sharp notch. Sharp notch with 30 μm radius, 1.3 mm length was machined in 6 mm thickness CT specimen by EDM machining and fracture test was conducted at loading speed, $1\,MPa\sqrt{m}/s$ in accordance with ASTM-E399 rule by servo-hydraulic Instron (model 8501) [15]. Fractographs of specimens were observed using an SEM after fracture tests. Charpy impact specimen was machined as 7.5 mm × 10 mm × 55 mm, 3/4-subsize Charpy V-notch specimen according to ASTM E23-02 in the longitudinal-transverse direction [16], and was tested at room temperature by 500 J capacity tester (model: FAHC-J-500-01, JT Tohsi, Japan).

Damping test was performed using impulse-frequency response method, which can simply and rapidly measure damping property of material [17–19]. Fig. 1(a) and (b) showed the schematic diagram of testing machine and shape and size of specimen (77 mm × 20 mm × 2 mm). Exciting force detected from hitting hammer is input into FFT (fast Fourier transform) analyzer through power unit and response displacement is input into FFT analyzer through eddy current type sensor of non-contact style. Measuring conditions of FFT analyzer are frequency bandwidth 400 Hz, resolution 1600 line, and overlap 75%. Signals input into FFT are calculated to a frequency response function by Fourier transformation. When this function is plotted by linear curve fitting in first bending mode, resonant frequency (f_n) and half-power bandwidth frequency (Δf) are measured and damping loss factor can be calculated using these data. Δf is half-power bandwidth at 3 dB smaller point from maximum point of frequency response function and damping loss factor can be calculated as a ratio of Δf and f_n.

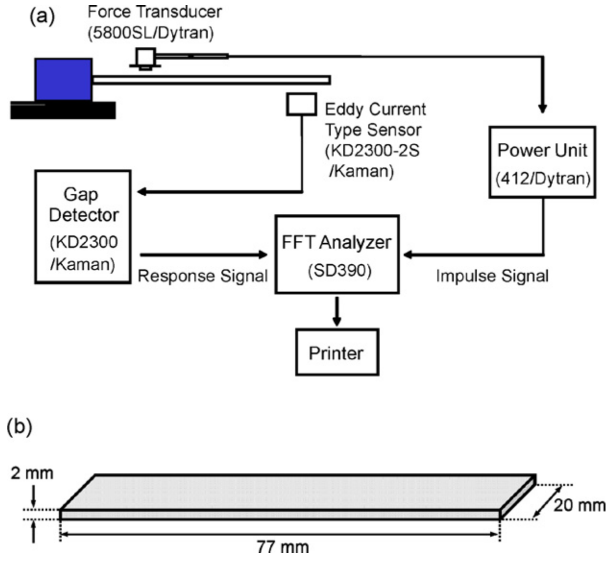

Fig. 1. Schematic diagrams of (a) experimental setup for the vibration test and (b) shape and dimensions of a plate-type specimen.

3. Results and discussion

3.1. Microstructure

Fig. 2(a)–(f) are optical micrograph of the unaged and the over-aged Widmanstätten, equiaxed, and microstructures. In the Widmanstätten microstructure, α phases are formed along prior β grain boundaries, and colonies of lath-type β and α lamellar structure are present inside prior β grains (Fig. 2(a) and (d)). α and β platelet were known to have different Burgers direction [14]. Colony size in prior β grain, thickness of boundary α phase and α platelets were measured to be 120–400 μm, 7–10 μm, and 5–7 μm, respectively (Fig. 2(d)). In the equiaxed microstructure, about 9 vol.% of β is present at triple points of α grains, and grain size of α is about 20 μm (Fig. 2(e)). Bimodal microstructure consists of equiaxed α phase and tempered martensite as shown in Fig. 2(c) and (f). α grain size, volume fraction of α phase and tempered martensite after over-aging were measured to be 19 μm, 39%, and 52%, respectively (Fig. 2(f)).

Table 1 shows the quantitative analysis data of the microstructural factors of unaged and over-aged microstructures. Since these factors are within the error range, the over-aging treatment hardly affects to the change in the optical microstructures. However, there are some differences in the high-magnification SEM micrographs of the Widmanstätten, equiaxed, and bimodal microstructures after over-aging for 200 h, as shown in Fig. 3(a)–(c). Fine α_2 phases of 50–200 nm size are homogeneously distributed inside α phases of the three microstructures. This matches well with the results of Margolin and Welsch [12,13].

3.2. Tensile properties

The tensile results of Widmanstätten, equiaxed, bimodal microstructures of unaged and over-aged for 200 h are shown in