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Statistical fatigue properties and small fatigue crack propagation in bimodal harmonic structured Ti-6Al-4V alloy under four-point bending

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ABSTRACT

Small fatigue crack propagation in bimodal harmonic structured titanium alloy (Ti-6Al-4V) with high strength and ductility was examined under four-point bending at a stress ratio of 0.1 in the ambient laboratory atmosphere. The crack profiles were observed using optical microscopy and scanning electron microscopy, and analyzed using an electron backscattered diffraction to examine the mechanism of small fatigue crack propagation. Fatigue crack paths were not influenced by the bimodal harmonic structure, and the crack growth rates, da/dN, in the harmonic structured Ti-6Al-4V were almost the same as those in a material with coarse acicular microstructure for comparable values of stress intensity range, ΔK. In contrast, the harmonic structured Ti-6Al-4V had a higher resistance of fatigue crack initiation due to the grain refinement induced by mechanical milling, which resulted in an increase of the fatigue life and fatigue limit. Furthermore, the statistical fatigue properties of Ti-6Al-4V alloy were analyzed using the stress dependence of Weibull parameters to quantitatively examine the effects of the bimodal harmonic structure on its fatigue life.

1. Introduction

Titanium alloys have been used in various engineering fields and products, such as aerospace components [1], energy industry applications [2], marine applications [3], biomaterials [4,5], and consumer applications (e.g., watch bands) [6], because titanium alloys exhibit high specific strength, high heat resistance, and excellent corrosion resistance. In recent years, demand has been increasing for improvement in the mechanical properties of titanium alloys, including the Ti-6Al-4V alloy featured in this study, and reduction of the cost of titanium products [7]; therefore, increasing the structural reliability of Ti-6Al-4V alloy has become an important research effort.

The microstructure and mechanical properties of Ti-6Al-4V alloy can be controlled by heat treatment [8,9], the addition of different elements (boron [10,11] and niobium/molybdenum [12]), and grain refinement [13,14]. In particular, grain refinement using severe plastic deformation is an effective approach for strengthening metallic materials based on the Hall-Petch relationship [15,16]. In contrast, to prevent a decrease in ductility of materials [13] due to the formation of homogeneous fine-grained structure, bimodal microstructural designs were proposed [17–19]. Our group also has developed a harmonic structure design using powder metallurgy to sinter mechanically milled Ti-6Al-4V powders [20–22], which improves both their strength and ductility by suppressing necking during tensile deformation [23].

In particular, we have focused on the fatigue properties [22,24] and near-threshold fatigue propagation of long cracks [25–27], which depend on the stress ratio (the ratio of minimum to maximum stress) [8,28] for Ti-based materials with a bimodal microstructure. However, to achieve sufficient performance for the newly developed materials for practical applications, small fatigue crack propagation needs to be examined due to the differences in the threshold stress intensity range, ΔK_{th}, for small and long cracks [29,30]. Previous studies examined small fatigue crack propagation in conventional Ti-6Al-4V alloys [8,31–36]; Nakajima et al. [31] reported that fatigue cracks were initiated in α grains as stage-I cracks in a conventional Ti-6Al-4V alloy and their propagation direction changed at the grain boundary. Another important aspect in the newly developed materials is an evaluation of fatigue life scatter [37,38], which occurs even if highly controlled techniques for material preparation are employed. The authors previously [37] proposed the approach of evaluating the statistical fatigue properties of Zr-based bulk metallic glass using the distribution of the normalized time strength.

The purpose of this study is to examine small fatigue crack propagation in bimodal harmonic structured Ti-6Al-4V alloy with high

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strength and ductility under four-point bending. Furthermore, the statistical fatigue properties of this alloy are analyzed to quantitatively examine the effects of the harmonic structure on its fatigue life.

2. Experimental procedure

2.1. Material and microstructural characterization

This study employed Ti-6Al-4V alloy containing 6.51% Al, 4.26% V, 0.17% Fe, 0.0023% H, 0.003% N, 0.18% O, and 0.01% C (all by mass, with the balance being Ti). This material was made into a powder (186-µm particle diameter) using a plasma rotating electrode process, which can be used to fabricate spherical particles that have negligible contamination by impurities such as oxygen or nitrogen gas [39].

Bimodal microstructural design using mechanical milling (MM) and spark plasma sintering (SPS) was introduced for the formation of the harmonic structured Ti-6Al-4V alloy, as defined in later. MM was performed for 90 ks in an Ar gas atmosphere at room temperature for the Ti-6Al-4V powders using a planetary ball mill (Fritch P-5) with a tungsten carbide vessel and steel ball bearings to form fine grains at the particle surfaces. The rotation speed was 200 rpm, and the ball-to-powder mass ratio was 1.8:1. The powders were subsequently consolidated by SPS at 1123 K for 1.8 ks under vacuum (less than 15 Pa) and applied pressure (50 MPa) using a 25-mm internal diameter graphite die to produce the specimens referred to herein as the "MM series." A second set of specimens was prepared by sintering the as-received powders (referred to herein as the "untreated series") for comparison. The tensile strength for the MM series (956 MPa) was higher than that for the untreated series (864 MPa), but the elongation for the MM series (22.0%) is slightly higher than that for the untreated series (20.9%) [22].

The microstructure of sintered compacts was characterized using electron backscattered diffraction (EBSD) at an accelerating voltage of 20 kV. The inverse pole figure (IPF) map obtained by EBSD analysis for the MM series is shown in Fig. 1. The MM series contained regions of fine equiaxed grains and regions with a coarse acicular microstructure. The regions of fine equiaxed grains formed a continuous connected three-dimensional network structure that surrounded the coarse acicular microstructure. This network structure is referred to as a harmonic structure in this study.

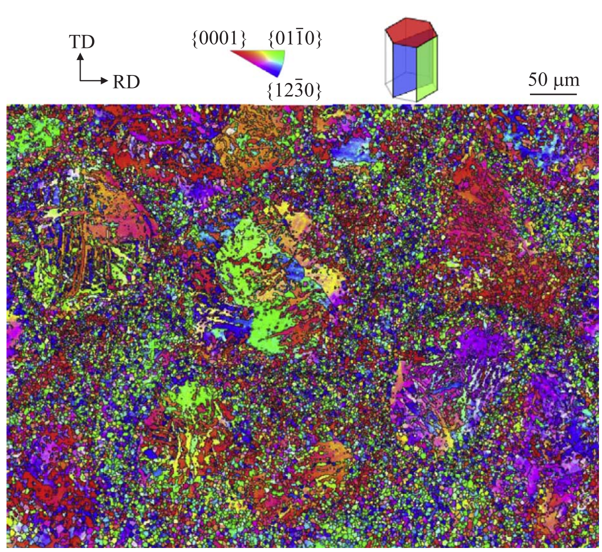

Fig. 1. IPF map obtained by EBSD analysis for MM series with a continuous connected three-dimensional network structure of fine equiaxed grains that surrounded the coarse acicular microstructure.

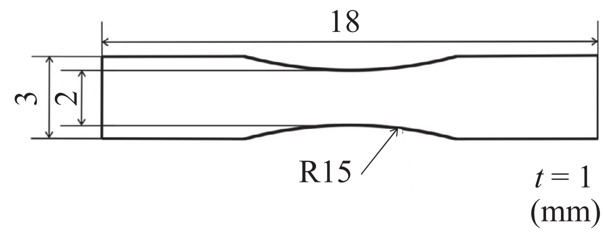

Fig. 2. Specimen configuration for four-point bending fatigue tests.

2.2. Fatigue tests

The sintered materials (10 mm thick, 25 mm diameter) were sliced into disks approximately 1.5 mm thick and machined into a blunt notched specimen with the dimensions shown in Fig. 2. After machining, the specimen surface was polished with emery paper (#240–#4000) to a thickness of 1 mm and polished in a SiO_2 suspension to obtain a mirror finish. The notch roots of the specimen were also polished with emery paper (#240) to remove the electro-discharge machined layer.

Four-point bending fatigue tests were performed in an electro-dynamic fatigue testing apparatus under a stress ratio R of 0.1. The frequency of stress cycling was 10 Hz, and the tests were conducted in the ambient laboratory atmosphere. Fatigue tests were interrupted at a given number of cycles and acetyl cellulose films were placed on the specimen surface based on the replica method to examine the propagation of fatigue cracks. The stress intensity range, ΔK, was calculated based on the crack length observed by optical microscopy [40], where the aspect ratio, c/a, for small cracks was estimated by the following equations:

$$c/a = 1 - 1.607(a/t) + 1.080(a/t)^2 - 0.2149(a/t)^3 \quad \text{for } a/t < 1 \tag{1}$$

$$c/a = 0.259 \quad \text{for } a/t \geq 1 \tag{2}$$

where a is the crack length in the surface, c is the crack length in thickness directions and t is the thickness of the specimen.

After the fatigue tests, the fracture surfaces and crack profiles were observed using scanning electron microscopy (SEM) and the microstructure around the crack paths was analyzed using EBSD to examine the mechanism of small fatigue crack propagation in the harmonic structured Ti-6Al-4V alloy.

3. Results and discussion

3.1. S-N characteristics of harmonic structured Ti-6Al-4V alloy

Fig. 3 shows the results of four-point bending fatigue tests for the

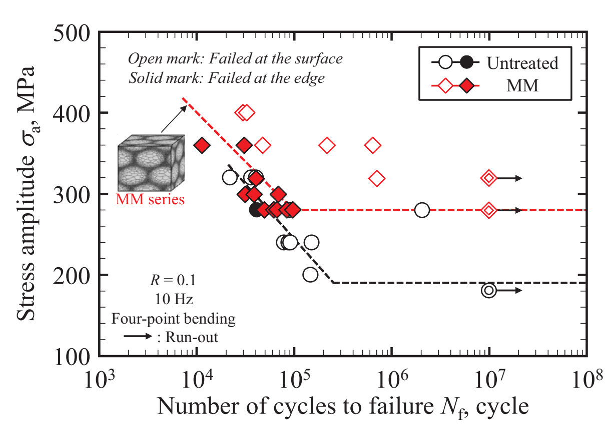

Fig. 3. Results of four-point bending fatigue tests, showing stress amplitude as a function of cycles to failure explaining that MM series has the higher fatigue limit and fatigue life.