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Effects of stress ratio on high-cycle and very-high-cycle fatigue behavior of a Ti–6Al–4V alloy

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ABSTRACT

The effects of stress ratio on high-cycle fatigue (HCF) and very-high-cycle fatigue (VHCF) behavior of a Ti–6Al–4V alloy were systematically investigated in this paper. Fatigue tests with ultrasonic frequency (20 kHz) were performed on specimens of a bimodal Ti–6Al–4V alloy with stress ratios of −1, −0.5, −0.1, 0.1 and 0.5. Three types of crack initiation mode were observed on the fracture surfaces of the specimens that failed in the HCF and the VHCF regimes, which were explicitly classified as surface-without-facets, surface-with-facets and interior-with-facets. With the increase of stress ratio from −1 to 0.5, the number of specimens for surface-without-facets decreased, that for surface-with-facets increased, and that for interior-with-facets increased first and then decreased. For the failure types of surface-with-facets and interior-with-facets, the fatigue strength decreased sharply in the VHCF regime, and the *S–N* curve switched from an asymptote shape to a duplex shape. Then, a new model based on Poisson defect distribution was proposed to describe the effects of stress ratio on the occurrence of different failure types, i.e., the competition of alternative failure types. The observations also showed that there is a rough area at the crack initiation region for interior initiation cases, and the values of the stress intensity factor range for the rough area are within a small range, with the mean value being close to the threshold for the crack starting to grow in vacuum environment of the alloy. The estimated value of plastic zone size at the periphery of rough area is close to the average diameter of the primary α grains of the alloy.

1. Introduction

Titanium alloys have been widely used as superior engineering materials because of their high specific strength, high temperature resistance and high corrosion resistance. In their engineering applications, such as in aircraft engines, titanium alloys may experience even 10^{10} fatigue cycles [1,2]. The fatigue behavior of titanium alloys in the very-high-cycle fatigue (VHCF) regime has drawn great attention in recent years. Neal and Blenkinsop [3] revealed that fatigue cracks initiated from the interior of the specimen with facet morphology of a Ti–6Al–4V alloy for the fatigue life exceeding 10^7 cycles at stress ratio (R) of zero, for which the nucleation of fatigue cracks was attributed to the cleavage of primary α grains. No pre-existing defects were observed at the initiation region for that case. A similar phenomenon was reported in other titanium alloys, such as Ti-6246 [4] and Ti–15Mo–5Zr–3Al [5]. Chandran et al. [6–9] investigated the effects of the volume fraction of primary α nodules on the preference of crack initiation types for a homogeneous titanium alloy Ti–10V–2Fe–3Al. They proposed a model based on a two-dimensional Poisson defect distribution to describe the competition of failure modes.

It is known that many factors, such as stress ratio [10–12], environment [13] and surface treatment [14–16], may affect fatigue crack initiation and propagation behavior of metallic alloys. As an important topic, the effects of stress ratio on fatigue crack initiation and propagation of titanium alloys were investigated in previous papers [17,18]. For $R = -1$, the results by Morrissey et al. [19] indicated that a Ti–6Al–4V alloy exhibited a fatigue limit and the *S–N* curve presented a continual downward shape in the high-cycle fatigue (HCF) and the VHCF regimes with crack initiation only from the specimen surface. No facet was found at the crack initiation region, and the mechanism for crack initiation was attributed to localized slip deformation. However, with the similar microstructure of the Ti–6Al–4V alloy, Zuo et al. [20] revealed that cracks initiated from the specimen's interior in the HCF and the VHCF regimes. Takeuchi et al. [21,22] invesigated the effects of frequency on the VHCF behavior of a Ti–6Al–4V alloy from three

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factories with the same heat treatment. Their results showed that cracks initated from the surface for one of them and from both the surface and the interior for two of them. The reason for crack initiation from the surface or from both the surface and the interior at $R=-1$ is not clear. For the positive stress ratio, the results for a Ti–6Al–4V alloy [23,24] indicated that the fatigue strength exhibited a sharp decrease in the HCF and the VHCF regimes for the crack initiation from the interior with facets. It was also reported that cracks initiated occasionally from the surface with subsurface facets at the initiation region [25,26]. The formation of facets was due to the cleavage of primary α grains. Therefore, it is suggested that with the increase of stress ratio, an alternative failure mode of crack initiation is triggered, and the fatigue strength is decreased in the HCF and the VHCF regimes for the Ti–6Al–4V alloy.

The process of crack initiation consumes most of the fatigue life in the VHCF regime. For the VHCF of high-strength steels, more than 90% of fatigue life is consumed by the formation of the crack initiation region of fine granular area (FGA) [27]. Therefore, the mechanism of crack initiation and the competition among different mechanisms of crack initiation have attracted attention of researchers [9,28–30]. For example, Chandran [9] investigated the effects of the volume fraction of primary α nodules on the competition among crack initiation types for Ti–10V–2Fe–3Al alloys. Hong et al. [28] simulated the competition mechanism of fatigue crack initiation at the specimen surface or at the subsurface for high strength steels and concluded that large inclusion size, small grain size and high strength of the material promote the subsurface mode of crack initiation. Murakami [29] discussed the competition between surface defects initiation and interior inclusion initiation of steels, in which the crack initiation site was determined by the threshold value of the stress intensity factor range for surface defects and interior inclusion. Stanzl-Tschegg et al. [30] analyzed the proportion of surface and interior initiation of an aluminum–silicon alloy in the HCF and the VHCF regimes and indicated that the proportion of crack interior initiation in the VHCF regime is more than that in the HCF regime. However, the competition among different mechanisms of crack initiation for the Ti–6Al–4V alloy in the HCF and the VHCF regimes with the variation of stress ratio has not yet been studied.

For the case of crack initiation from the interior of the specimen, the morphology of rough area containing flat facets was observed at the crack initiation region for titanium alloys, which is similar to the FGA with rough surface at the interior initiation region of high-strength steels in the VHCF regime [31–33]. Shiozawa et al. [34] analyzed the effects of stress ratio on the value of the stress intensity factor range (SIF), which is calculated from the size of facets for a beta-type titanium alloy Ti–15V–3Cr–3Sn–3Al. The calculated value was smaller than the threshold for crack growth. Oguma et al. [24] also discussed the variation of SIF at the crack initiation region of a Ti–6Al–4V alloy. Indeed, the formation mechanism of rough area for titanium alloys is without in-depth investigation so far.

In this paper, a titanium alloy of Ti–6Al–4V was used for investigating the effects of stress ratio on the HCF and the VHCF behavior of the material. Fatigue tests were performed with an ultrasonic fatigue test machine, for which a mean stress is able to be superimposed. Stress ratios of −1, −0.5, −0.1, 0.1 and 0.5 were chosen, and relevant *S*–*N* curves were obtained. Three failure types of crack initiation, which were in relation with fatigue resistance, were explicitly identified on the fracture surfaces for the specimens that failed in the HCF and the VHCF regimes. A new model based on the Poisson defect distribution was developed to describe the competition of the failure types. In addition, the value of SIF and the size of the plastic zone for the rough area in the crack initiation region were calculated and discussed.

2. Test material and experimental methods

2.1. Test material

The material used in this investigation is an α–β titanium alloy (Ti–6Al–4V). The chemical compositions (mass percentage) are 5.8 Al, 4.2 V, 0.12 Fe, 0.03 N, 0.02 C, 0.005 H, 0.15 O and balance Ti. It was supplied as unidirectional rolled bars of 14 mm in diameter with equiaxed microstructures. A typical processing procedure (920 °C/1 h + air-cooling and 550 °C/4 h + air-cooling) was performed to produce bimodal microstructures consisting of equiaxed α grains and lamellar structure for the test material. The obtained microstructure is shown in Fig. 1. The microstructure is a homogeneous duplex pattern with about 50% volume fraction of primary α grains, and the remaining 50% is the lamellar structure of secondary α_s plates embedded in β matrix, which was taken from three microstructure photographs as shown in Fig. 1. The average diameter of primary α grains was measured as 5.89 μm by electron back-scattered diffraction with a measuring area of 200 μm × 200 μm.

Before performing fatigue experiments, the mechanical properties of the material were measured by tensile testing on an MTS 810 system with cylindrical specimens of 6 mm in diameter and at a strain rate of $10^{-4}\ s^{-1}$. Five specimens were tested to obtain the yield strength of 812 MPa and the tensile strength of 945 MPa for the material. Microhardness measurement was performed with a Vickers hardness tester at a load of 50 g with the load holding time of 15 s. Twenty indentation points for each of the three specimens were performed. The average value of the hardness is 310 Hv.

2.2. Fatigue testing method

Fatigue testing was conducted on an ultrasonic fatigue test machine at a resonance frequency of 20 kHz at room temperature in air. The ultrasonic fatigue machine was equipped in a conventional tensile machine (capacity 20 kN) to enable the ultrasonic cycling under an amount of mean stress which was superimposed to each test of stress ratio of −0.5, −0.1, 0.1 or 0.5. Compressive air was used to cool the specimen during ultrasonic fatigue testing. The diameter of the minimum section for the specimen is 3 mm. For the case of $R=-1$, no mean stress was added, and the cyclic stress was solely loaded by the ultrasonic fatigue machine. For the stress ratio of −0.5, −0.1, 0.1 or 0.5, a value of mean stress was superimposed by the tensile machine. For the broken specimens, the fracture surfaces were examined by using a field-emission type of scanning electron microscope (SEM).

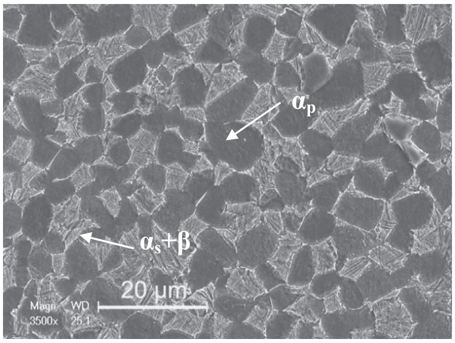

Fig. 1. Microstructure of the bimodal Ti–6Al–4V alloy (α_p: primary α grain, $\alpha_s+\beta$: lamellar structure).