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Low Cycle Fatigue Behavior of TC21 Titanium Alloy with Bi-Lamellar Basketweave Microstructure

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Abstract: Low cycle fatigue (LCF) behaviors of TC21 alloy with a bi-lamellar basketweave microstructure were investigated in this paper. The strain fatigue tests were carried out at total strain amplitudes of 1.4% to 2.0%. The cyclic stress response showed the cyclic softening behavior. In addition, the shape of the hysteresis rings exhibited a non-Masing model behavior. The cyclic stress–strain as well as the strain-life equations were obtained. The fatigue life decreased significantly with an increasing total strain from 1.4% to 2.0%. The cyclic softening behavior was interpreted by cyclic back stress and friction stress. Low cycle fatigue cracks were predominantly initiated on the surface of the samples. The relationship between the fatigue sub-critical crack and microstructure was also discussed. The cyclic deformation behavior and crack initiation mechanism were revealed on the basis of the deformation microstructure under different strain amplitudes.

Keywords: low cycle fatigue; titanium alloy; basketweave microstructure; crack initiation

1. Introduction

Titanium alloys are generally used in landing gear and other key load-bearing components in aircrafts [1,2]. As critical load-bearing components, titanium alloy components usually suffer a high cyclic loading during service, which may result in a low cycle fatigue (LCF) fracture. Thus, LCF behavior and properties are essential for the safety and reliability of titanium alloy components.

The microstructure of titanium alloys significantly influences the LCF behavior and properties [3–8]. Lei [9] investigated the LCF properties of TA15 titanium alloy with a tri-modal microstructure, Widmanstatten microstructure and bimodal microstructure, and found that the fatigue properties of the tri-modal microstructure were higher than that of the Widmanstatten microstructure and were equivalent to that of the bimodal microstructures. The fatigue crack propagation was more tortuous and had a higher fatigue crack propagation resistance than that of bimodal microstructures. Xu [10] suggested that titanium alloys with lamellar and bimodal microstructures had a different LCF behavior due to their response to the cyclic strain. As for titanium alloys with a tri-modal [11] and bimodal [12,13] microstructure, LCF cracks were initiated from the coarsened slip band in the soft αp phase. However, the shear deformation and spheroidization of β lamellar contributed to the LCF crack initiation for titanium alloys with a Widmanstatten microstructure [14]. Furthermore, the dislocation evolution and the deformation twins were considered as important factors for the cyclic softening of titanium alloys with a lamellar microstructure [15,16].

TC21 titanium alloy was used in aircraft key load-bearing components owing to its high strength and damage tolerance. TC21 titanium alloy was manufactured by a quasi-β...
forging process to obtain the basketweave microstructure [1]. The LCF behavior of TC21 titanium alloy has attracted much attention. Du [17] reported that the residual compressive stress of both surface shot peening and high velocity oxygen fuel (HVOF) improved the LCF properties of TC21 alloy. Yu [18] found that TC21 alloy with a bimodal microstructure illustrated the characteristic of cyclic softening. The research of Tan [19] suggested that the low cycle fatigue property of a bimodal structure was higher than that of a lamellar structure, and that the low cycle cracks initiated from the slip band in the α phase for a bimodal microstructure and the α/β phase interface for a lamellar microstructure. However, few investigations on cyclic deformation and fatigue crack nucleation have been reported for titanium alloys with a basketweave microstructure. The LCF behavior of TC21 alloy with a basketweave microstructure is discussed in this paper. Cyclic deformation and the crack initiation mechanism are further investigated to support the application of titanium alloy components.

2. Materials and Methods

2.1. Materials

The nominal composition of TC21 titanium alloy used in this study is: Ti-6Al-2Zr-2Sn-2Mo-2Nb-1.5Cr (wt%). TC21 alloy was manufactured by a quasi-β forging process [1], and the alloy was heat-treated as follows: 900 °C/2 h + 600 °C/4 h. A lamellar α (αL) and β transformed matrix (β) microstructure are observed (Figure 1a), and the mean width of αL is 3.4 μm. Furthermore, the fine lamellar α phase, which is also called secondary αs phase, is detected in the β phase with a mean width of 500 nm (Figure 1b). The samples exhibit a high tensile strength of up to 1070 MPa and a high yield ratio (Figure 2).

![Microstructures of TC21 titanium alloy: (a) optical micrograph (OM) and (b) backscattered electron micrograph (BEM).](image)

**Figure 1.** Microstructures of TC21 titanium alloy: (a) optical micrograph (OM) and (b) backscattered electron micrograph (BEM).

![Tensile stress–strain curve of TC21 titanium alloy.](image)

**Figure 2.** Tensile stress–strain curve of TC21 titanium alloy.
2.2. Low Cycle Fatigue

LCF tests were carried out using a servo-hydraulic testing machine (Instron 8801, Norwood, MA, USA) under the condition of strain-controlled conditions ($R_e = -1$), sinusoidal waveforms, and a constant strain rate ($d\varepsilon/dt$) of $4 \times 10^{-3}$ s$^{-1}$. A round bar specimen was used for the low cycle fatigue test, as shown in Figure 3. The total strains were loaded at 1.4%, 1.6%, 1.8% and 2.0%. Each fatigue test was carried out until the cyclic stress decreased to 90% of the fatigue stable stress, which was considered as the LCF life.

![Figure 3](image_url)

Figure 3. Geometric dimensions of specimens for the strain-controlled low cycle fatigue test.

The fracture surfaces and side crack morphology were observed by scanning electron microscopy (Ultim® Max 65, Oxford, UK). A thin sample was cut close to the fatigue fracture and ground into 50–70 μm, then stamped into a small round sheet with a diameter of 3 mm. Double jet electrolytic thinning was adopted in the electrolyte of 59 pct methanol, 35 pct n-butanol, 6 pct perchloric acid at a voltage of 15 V and a current of 15 mA. The fatigue dislocation structure was observed by Transmission electron microscope (TEM) (JEM-2100, Tokyo, Japan).

3. Results and Discussion

3.1. Cyclic Stress–Strain Behavior

The cyclic stress curves with respect to different total strain of TC21 titanium alloy are shown in Figure 4. In the range of the total strain from 1.4% to 2%, the cyclic stress decreased rapidly at the initial stage of fatigue, illustrating the typical characteristic of cyclic softening. It is observed that the cyclic stress decreased faster and that the cyclic softening behavior of TC21 titanium alloy was more obvious with the increasing of the total strain from 1.4% to 2%. Similar results have been reported by Xu [15] and Sen [16], for whom titanium alloys with both a bimodal microstructure and lamellar microstructure presented cyclic softening characteristic at a high strain amplitude due to the dislocation annihilation, twins in the $\alpha$ phase [15] and the spheroidization of $\beta$ lamellar [14].

![Figure 4](image_url)

Figure 4. The cyclic stress curves corresponding to different total strain.
The cyclic stress–strain relationship under LCF is usually described as [20]:

\[
\frac{\Delta \sigma}{2} = K'(\frac{\Delta \varepsilon_p}{2})^{n'}
\]

(1)

where \(\Delta \varepsilon_p\) is the total plastic strain range, \(\Delta \sigma\) is the total stress range, and \(K'\) and \(n'\) are the cyclic strength coefficient and cyclic strain hardening index, respectively.

\(\Delta \varepsilon_p\) and \(\Delta \sigma\) can be obtained based on the cyclic hysteresis loop for a half life. According to Equation (1), the data are linearly regressed using double logarithmic coordinates. The obtained \(K'\) value is 1067.3 MPa and \(n'\) value is 0.07326; then, we obtain the expression for the cycle stress–strain of TC21 titanium alloy. The fitted cyclic stress–strain curves were compared to the experimental results from uniaxial tension, as shown in Figure 5. It revealed that the cyclic stress was less than the unidirectional tensile stress under the same plastic strain. Thus, the cyclic softening characteristic of TC21 alloy is demonstrated.

![Figure 5. Comparison of uniaxial tension and cyclic stress–strain curves.](image)

3.2. Hysteresis Loop Analysis

Figure 6 displays the area of the hysteresis loop as well as the consumed energy increase with the increasing total strain. It can be inferred that the fatigue damage of plastic deformation increased with the total strain. It is obvious that the hysteresis loops with total strains of 1.4% and 1.6% are relatively small in comparison with those of 1.6% and 2.0%, suggesting that fatigue damage caused by plastic deformation is much less at total strains of 1.4% and 1.6%.

![Figure 6. The superimposed hysteresis loops of the specimens at different strain levels for TC21 alloy.](image)
As for the half-life hysteresis loops for the different total strain, the bottoms of the hysteresis loops were moved to the same lowest points to analyze the Masing characteristics, which presented the same proportional limit. The J-integral can be used to deal with the LCF behavior when metal displays Masing characteristics [21]. Figure 7 illustrates that the upper half of the hysteresis loops are non-overlapping under the different total strain; thus, the alloy exhibits a non-Masing behavior.

![Figure 7. The superimposed hysteresis loops along the linear portion to match upper branch for TC21 alloy.](image)

**3.3. Strain–Life Relationship**

Based on Basquin and Coffin–Manson formulations, the relationship between fatigue and the total strain can be expressed as [22]:

\[
\Delta \varepsilon / 2 = \varepsilon_f (2N_f)^c + \frac{\sigma_f'}{E} (2N_f)^b
\]  

where \( \sigma_f' \) is the fatigue strength coefficient, \( b \) is the fatigue strength exponent, \( \varepsilon_f' \) is the fatigue ductility coefficient, and \( c \) is the fatigue ductility exponent. The strain fatigue parameters, evaluated by linear regression using the least square method, are listed in Table 1.

**Table 1. Strain fatigue parameters of TC21 titanium alloy.**

|       |       |       |       |
|-------|-------|-------|-------|
| \( \sigma_f' \) | \( b \) | \( \varepsilon_f' \) | \( c \) |
| 1634.7 | -0.0821 | 12.428 | -1.108 |

Figure 8 shows that the Coffin–Manson linear curves are well-fitted; however, Gao [11] reported that the LCF of titanium alloy illustrated a bilinear characteristic due to the different fatigue damages between plastic deformation and elastic deformation. It is indicated that the fatigue damage of TC21 alloy is mainly controlled by elastic strain. Figure 8 also reveals that the transition life from elastic deformation to plastic deformation is only 350 reversals, which is in agreement with that of Ti1023 titanium alloy with 140 cycles [23]. The low transition life can be attributed to the low elastic modulus and high yield ratio of titanium alloy. The fatigue life dominated by plastic deformation was only at \( 10^2 \) orders of magnitude; thus, it was inferred that LCF of TC21 alloy was actually controlled by an elastic deformation in a range over \( 10^3 \) cycles.
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Figure 8. Number of half-cycle reversals vs. strain amplitude in log-log coordinates.

3.4. TEM Observation of Fatigue Microstructure

As for TC21 titanium alloy with a bi-lamellar basketweave microstructure, the β phase containing the secondary αL phase obtained a high hardness, and the soft αL phase preferentially deformed in the fatigue process. Thus, the fatigue microstructure in the α phase was investigated. Figure 9 shows the deformation microstructure in the αL phase after low cycle fatigue. There are a few free dislocations at the initial state (Figure 9a). At a total strain of 1.4% and 1.6%, the fatiguedislocations in the αL phase exhibit a plane slip (Figure 9b,c) and pile-up at the αL/β interface (Figure 9d). The dislocation density increases with the total strain (Figure 9e), but the alloy has a relatively low dislocation density in the α phase. It is worth noting that the β phase can be sheared at a high total strain (Figure 9f), and accordingly the alloy exhibited the cyclic softening characteristic. A similar result was also reported for Ti-6242S titanium alloy with a Widmanstatten microstructure [14].

3.5. Cyclic Back Stress-Friction Stress Analysis

The cyclic softening and non-Masing behavior can be interpreted by the evolution of back stress and friction stress, which can be calculated from each hysteresis loop according to the reference [11]. As shown in Figure 10a, back stress can be divided into two types for the different total strain. At a low total strain (ε < 2.0%), the back stress increased slowly at a total strain of 1.8%, while the back stress increased rapidly at total strains of 1.4% and 1.6%. Furthermore, the increase of back stress in the total strain can be attributed to the increase in dislocation density. However, the back stress firstly decreased and then maintained a constant value at a total strain of 2.0%, which can be attributed to the shear of the β phase (Figure 9f).

Friction stress had a decreasing trend with the number of cycles for each total strain. Friction stress can also be divided into two types, as shown in Figure 10b. Friction stress decreased continuously at total strains of 1.8% and 2.0%, while friction stress decreased at two different rates under total strains of 1.4% and 1.6%. The decrease in friction was related to the deformation dislocation. Multiple slip systems of dislocations were activated at a high total strain and promoted the mobility of dislocations [11], which can reduce the frictional internal stress of dislocations.

Cyclic softening behavior can be explained with the evolution of back stress and friction stress. The cyclic softening for each strain amplitude (Figure 4) was attributed to the competition effects between the increase in back stress and the decrease in friction stress. As the decrease in friction stress was larger than the increase in back stress for total strains of 1.4%, 1.6% and 1.8%, respectively, the alloy displayed the cyclic softening characteristic. The cyclic softening at a total strain of 2.0% resulted from the superposition of the decreases in both the back stress and friction stress.
The Masing behavior was the result of the cyclic deformation microstructure stability [21]. As for the total strains of 1.4% and 1.6%, a low density of dislocation was observed in the $\alpha_L$ phase, while the $\beta$ phase was sheared at a total strain of 2.0% (Figure 9f). The alloy exhibited a different deformation microstructure at a different total strain. Meanwhile, there was no direct relationship between the cyclic back stress, friction stress and cyclic strain (Figure 10), suggesting the instability of the fatigue microstructure under cyclic deformation. Therefore, TC21 titanium alloy with a basketweave microstructure displayed a non-Masing behavior.

Figure 9. The microstructure of the $\alpha$ phase after low cycle fatigue deformation under different total strain amplitudes: (a) initial state; (b) $\Delta \varepsilon_t = 1.4\%$, $N_f = 7988$ cycles; (c) $\Delta \varepsilon_t = 1.6\%$, $N_f = 3200$ cycles; (d) the dislocation pile-up at $\Delta \varepsilon_t = 1.6\%$, $N_f = 3200$ cycles; (e) multiple dislocations at $\Delta \varepsilon_t = 1.8\%$, $N_f = 1731$ cycles; (f) the shear of $\beta$ phase at $\Delta \varepsilon_t = 2.0\%$, $N_f = 1302$ cycles.
Figure 10. The evolutions of back stress and friction stress with \( n/N \) at different strain amplitudes: (a) back stress; (b) friction stress.

3.6. Fatigue Fracture and Crack Analysis

The typical fracture morphologies for TC21 titanium alloy are shown in Figure 11. In the strain range from 1.4% to 2.0%, the fatigue cracks originated from the sample surface. The fatigue crack was initiated from the linear source on the sample surface at a high strain, where there were many edges with a large height difference (Figure 11a,b). It can be observed in Figure 11d that many radial edges presented on the fracture surface, which was the typical fatigue fracture morphology. Two similar fractures morphologies were observed in Figure 11c. Thus, the fatigue crack was initiated from a multi-point source on the specimen surface at a low strain, where the fatigue crack initiation was determined by micro-plastic damage under macroscopic elastic deformation.

Figure 11. Typical morphology of low cycle fatigue fracture: (a,b) \( \Delta \varepsilon_t = 2.0\% \), \( N_f = 1302 \) cycles; (c,d) \( \Delta \varepsilon_t = 1.4\% \), \( N_f = 7998 \) cycles.
The characteristics of a side crack were observed for LCF at a strain amplitude of 2.0%. Z-shaped steps were presented on the side of the fatigue crack source, and some Z-shaped small cracks were also observed near the crack initiation site (Figure 12). The relationship between the fatigue sub-crack and microstructure is shown in Figure 13. Slip bands at 45° to the load direction can be observed on the αL phase and promoted the initiation of fatigue sub-cracks. However, the αL/β interface cannot prevent the β phase from being shear at the total strain of 2.0% (Figure 9f). The connection of these sub-cracks led to the characteristics of Z-shaped steps. Actually, the propagation of sub-cracks was controlled by mechanics rather than the microstructure, and cracks can pass through the three sequential αL phases as a straight line. At a low total strain, slip bands were not obviously observed on the αL phase, and the dislocations were piled up at the αL/β interface (Figure 9d), resulting in the initiation of a crack at the αL/β interface.

![Figure 12](image1.png)

**Figure 12.** The morphology of the side crack at the crack initiation site at Δεt = 2.0%, Nf = 1302 cycles.

![Figure 13](image2.png)

**Figure 13.** The morphology of the fatigue sub-crack and microstructure (Backscatter electron microscopy): (a) Δεt = 2.0%, Nf = 1302 cycles; (b) Δεt = 1.4%, Nf = 7988 cycles.

4. Conclusions

1. TC21 titanium alloy displayed cyclic softening and non-Masing behavior that were interpreted on the basis of the cyclic back stress, friction stress and fatigue deformation microstructure.

2. Low cycle fatigue cracks were predominantly initiated from the slip bands on the surface of the samples at a high total strain, and the crack initiation occurred at the αL/β interface at a relatively low total strain.
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