Microstructure and fatigue properties of TC4 titanium alloy treated by $\alpha+\beta$ forging process

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Abstract. As aero engine life increases, blade fatigue has become one of the key factors restricting the high reliability and long service life of aero engine. In this paper, TC4 bar was treated by $\alpha+\beta$ forging process. The microstructure and mechanical properties of the treated material were observed and tested at room temperature, and the three point bending ultrasonic fatigue test was carried out. The results show that the $S-N$ curve of the $\alpha+\beta$ forging material presents a double platform shape. The high cycle showed surface cleavage mode, the very high cycle showed internal cleavage mode, and the very high cycle cracks originated from the primary phase cleavage plane.

1. Introduction

As the third largest structural metal after aluminum and iron, titanium alloy has excellent mechanical properties such as high specific strength and weldability, and has been widely used in other industrial fields such as aviation and aerospace [1-3]. The application of titanium alloy in aero engine can achieve good weight reduction benefits and meet the design requirements of high thrust-to-weight ratio, low fuel consumption rate and long service life of the engine, which has become a firm cornerstone to support engine development. Research and engineering technicians found that the blade fatigue failure phenomenon would occur under the condition of low stress value, and the stress cycle would generally exceed the traditional fatigue life, that is very high cycle fatigue problem (refers to the material under the action of cyclic load, the cycle of fatigue failure is more than $10^7$).

The very high cycle fatigue damage mechanism of titanium alloy is complex, and the effects of microstructure, surface treatment and loading environment have also been studied by scholars. Oguma et al. carried out uniaxial tensile test to study the very high cycle fatigue of Ti-6Al-4V after different heat treatments, and concluded that the influence of on the relative internal damage of different tissues was different [4]. Crupi et al. carried out a contrastive study on ultrasonic loading of two typical Ti-6Al-4V basket and two state tissue. The results showed that when very high cycle fatigue occurs due to the difference in microstructure, the cracks in the basket structure tend to sprout on the surface, while the bistate structure is the internal cleavage initiation mechanism [5]. Gao et al. used mechanical wear technology to treat the surface of TC11 titanium alloy, and ultrasonic loading comparison test showed that the performance of low cycle and high cycle was improved after treatment [6]. Kikuchi et al. studied the influence of low temperature nitriding treatment on the very high cycle fatigue performance of Ti-6Al-4V by means of ultrasonic loading, and found that the surface of the treated specimens was covered with a high hardness layer that introduced compressive stress, and the...
occurrence of very high cycle fatigue could effectively prevent the initiation and expansion of internal cracks, thus improving the very high cycle fatigue performance [7].

2. \( \alpha + \beta \) forged microstructure and its mechanical properties

2.1. Morphology

This article selects the TC4 bar (\( \phi = 28 \) mm) to test and experiment, the main elements as shown in table 1, \( \alpha + \beta \) forging process parameters are shown in table 2. Annealing treatment: heating to 720°C and holding for 1h, then air cooling to room temperature.

| Table 1. Elemental content of TC4 titanium alloy (mass fraction, %). |
|-------------------------|
| Al  | V   | O    | Fe  | C   | Si  | Ti  |
|-----|-----|------|-----|-----|-----|-----|
| 6.1 | 4.2 | 0.17 | 0.04| 0.01| <0.02| Bal.|

| Table 2. \( \alpha + \beta \) forging process |
|-------------------------|
| forging temperature | forging time | deformation extent |
| 950 \(^\circ\)C | 15' | 39.3% |

Figure 1 shows the microstructure and metallographic diagram of TC4 titanium alloy by forging processes. The distribution of tissue morphologies includes equiaxed primary phase and transformed tissue, which are refined to form evenly distributed long and short phase. The content of isoaxial primary phase is less, and the irregular block phase is composed of many blocks adhesion, which has a stacking morphology. There are small isoaxial alpha phase and small acicular secondary alpha phase in the transformed tissue. Primary content is about 35%, average size is about 43\( \mu \)m, and belongs to isoaxial structure.

![Figure 1](image)

2.2. Mechanical property

TC4 titanium alloy after \( \alpha + \beta \) forging process was used to process 3 test pieces respectively, and tensile property test was carried out at room temperature. EBS-3000 type tensile testing machine was used for tensile test. Moreover, IET-01 elastic modulus tester was used to test its elastic modulus and Poisson's ratio. The test results are shown in Table 3.

| Table 3. Tensile mechanical properties test results at room temperature |
|-------------------------|
| \( R_m \)/MPa | \( R_{p0.2} \)/MPa | \( A \)/% | \( Z \)/% | \( E \)/GPa | \( V \) |
| 979 | 913 | 16 | 51 | 113.50 | 0.320 |

The stress-strain curve is shown in Figure 2. Alpha and beta phase in the forging axis of organizations such as the ability to resist crack initiation, strong tensile primary alpha at the beginning of each grain slip lead to deformation, in the subsequent deformation process, the slip to occupy more and more grain and extend to the beta around the organization, and the occurrence and spread of hole is relatively slow, before breaking under plastic deformation ability increases, so has the very strong shape.
2.3. SEM analysis of tensile fracture

Figure 3 (a) and (b) show the microstructure of the tensile fracture of equiaxial tissue. The fiber region and shear lip region of crack propagation can be clearly observed from Figure 3 (a). The whole fracture is dark black, in which the fibrous region and the shear lip region occupy most of the fracture area, and the radiative region between them is almost not observed, which indicates that the isoaxial tissue has high shaping and toughness. In Figure 3 (b), a large number of dimples of different sizes can be clearly observed, and tiny holes can be found at the grain boundary, which conforms to the microscopic characteristics of ductile fracture. The fiber region at the center of the fracture is the initial location of the specimen. Under the action of tensile stress, the microvoid is formed and grows continuously. After being connected with each other, it develops into cracks and further expands, and finally becomes unstable. In summary, the isoaxial structure presents a ductile fracture mechanism.

3. Ultrasonic testing system and three point bending specimen design

3.1. Testing system

The ultrasonic fatigue testing system used in this paper includes piezoelectric transducer, connecting rod, amplitude transformer, pressure head, optical fiber displacement sensor, load bearing device, base and measurement and control device [8], as shown in Figure 4. Computer numerical control ultrasonic generator converts 50Hz alternating Current electric signal into 20kHz ultrasonic signal, and converts it into mechanical vibration of the same frequency through transducer, and then amplifies the vibration required by the test by the amplitude transformer. Based on the principle of resonance, the three point bending ultrasonic fatigue testing system ensures that the bending fatigue specimens have the same resonance frequency with the ultrasonic fatigue testing system, and realizes the composite loading of different static and dynamic loads. Transducers, connectors, lug bars and presser constitute a longitudinal resonance system, and the longitudinal vibration load is transferred to the bending fatigue specimen through the presser, so that the bending fatigue specimen generates bending vibration.
3.2. Specimen design and loading

According to the ultrasonic fatigue vibration principle, based on the theory of linear elastic deformation, combined with the three point bending fatigue sample design method [9], numerical analysis and Abaqus simulation were used to calculate the size of the specimen, as shown in Figure 5.

![Equiaxed structure](image)

**Figure 5.** Specimen size

At the beginning of the experiment, a microcomputer controlled electronic universal testing machine is used to apply static load to the specimen through the head. During the test, MTI-2100 optical fiber displacement sensor was used to measure the displacement at the bottom of the specimen, with the precision of 0.1 μm and the peak-to-peak range. In normal test, the resonance frequency is 20± 0.5kHz, so bending resonance occurs to the sample, and the displacement value basically remains unchanged. When the frequency drops sharply below 19.5kHz and the displacement value changes greatly, the system automatically stops the experiment, and then the failure of the specimen can be judged. The computer controlled system records the stress amplitude set during the experiment and the cycle times of the sample when fracture occurs.

4. Results and discussion

4.1. S-N curve

The fatigue test data of equiaxed structure were plotted on the S-N curve using point by point tracing method, as shown in Figure 6. The solid dots indicate that fatigue originates from the surface, and the upper half-solid dots indicate fatigue originates from the subsurface.
Figure 6. The fatigue S-N curve of equiaxed structure

The S-N curve of equiaxed structure has two horizontal sections, which are located in the high cycle and very high cycle fields respectively. There is no fatigue limit in the traditional sense, but a platform characteristic similar to the fatigue limit appears in the high cycle field. After the cycles enter the very high cycle field, the curve drops again and gradually approaches the level.

4.2. Fatigue fracture characteristics

JSM-6460 scanning electron microscope (SEM) was used to analyze the fracture of three point bending fatigue specimens. Figure 7 shows the initiation of high cycle cracks in equiaxed structures. It can be found that the crack originates on the surface of the specimen and the pattern is concentrated and densely distributed near the crack origin point. Cleavage planes, tear ridges and grooves appeared in the field of view. The cracks between cleavage planes of different heights were connected to form cleavage steps, indicating the existence of transgranular and intergranular propagation modes of the cracks. It can be concluded that the high cycle fatigue of equiaxial structures mainly presents quasi-cleavage cracking mode.

Figure 7. SEM images of equiaxed structure high cycle fatigue fracture ($\sigma_a=294\text{MPa}, N_f=8.96 \times 10^5$)
Figure 8 shows the initiation of very high cycle cracks in equiaxed structure. It was found that the crack origin point was about 55 μm on the subsurface of the specimen. The crack originates from the cleavage plane in the middle of the field of view and extends along a slip plane in the grain, forming smooth planar fracture and then radially extending in all directions. It can be concluded that the superhigh cycle fatigue of equiaxial structures mainly presents quasi-cleavage cracking mode.

5. Conclusions
1) The equiaxed structure obtained by α+β forging has a strong plastic shape, and the tensile behavior presents a ductile fracture mechanism.
2) Specimens were designed in combination with the design method of three point bending fatigue specimens, and Abaqus modeling and simulation analysis were used. Besides, ultrasonic loading was used to carry out high cycle and very high cycle three point bending fatigue tests, which greatly shortened the test period and improved the test efficiency.
3) Under the condition of stress ratio \( R = 0.5 \) at room temperature, the \( S-N \) curve of equiaxed structure presented a double platform type.
4) The high cycle and very high cycle cracks of the equiaxed structure originated from the surface and the subsurface of the specimen respectively, showing the quasi-cleavage fracture mode, and the very high cycle cracks originated from the primary phase cleavage plane.

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