Fatigue property and failure mechanism of TC4 titanium alloy in the HCF and VHCF region considering different forging processes

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Abstract
Based on the self-built three point bending ultrasonic fatigue test system, fatigue behavior of TC4 titanium alloy after different forging processes in high cycle fatigue (HCF) and very high cycle fatigue (VHCF) regimes was discussed in this paper. The experimental results showed that the fatigue S-N curves of TC4 titanium alloy with three different structures presented different characteristics: continuous decline; double platform; linear decline. The fatigue property of TC4 titanium alloy is closely related to the content of primary α phase and β-transformed microstructure. For TC4 titanium alloy, grain refinement and certain volume fraction of the primary α phase contributed to enhancing fatigue property. The fatigue performance of bimodal structure by near β forging was obviously better than two structures by α + β forging in HCF and VHCF regime. It was found that failure mode shifted from the surface at relatively high stress to the subsurface at relatively low stress. For three kinds of structures, crack initiations were observed at the surfaces of specimens in HCF regime. Meanwhile, cracks of the three structures all originated from primary α cleavage planes in the interior. The fatigue life of VHCF is dominated by the crack initiation stage.

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 cornerstone to support engine development. With the significant increase of the working speed and boost ratio of aero engines, the blades are subjected to more complex and strong vibration impact and cyclic load. The overall thin and thin structure, such as the blade disk, makes it easier for pneumatic and mechanical reasons to induce forced vibration and asynchronous vibration of the blades with higher and wider frequency. Many studies have shown that blade fatigue failure occurs when the stress value is low and there is no traditional fatigue limit [4–9]. The study on the VHCF failure of aero engines is becoming more and more important and urgent.

Different from low and high cycle fatigue, many special mechanical properties of VHCF have not been conclusively concluded. Fatigue mechanism is far more complex than low and high cycle fatigue, and it is largely influenced by factors such as microstructure [10, 11], internal inclusion characteristics [12, 13] and processing technology of materials [14, 15]. Researchers have found that the initiation points of VHCF cracks in high strength steel [16, 17], aluminum alloy [18, 19] and cast iron [20, 21] shift from the surface to the interior of the material, and proposed corresponding mechanisms and models that conform to the characteristics of VHCF. Comparatively, there is a lack of research on VHCF of titanium alloy. With the development of titanium industry in aviation, VHCF of titanium alloy has attracted the attention of scholars all over the world. Atrens et al reported for the first time that the S-N curve of Ti-6Al-4V presented double lines and crack initiation occurred on the subsurface [22]. Pan et al investigated the fatigue crack initiation behavior of TC4 titanium alloy with
equiaxed structure under ultrasonic loading. The results showed that there were three types of crack initiation. VHCF data showed a large deviation from Goodman’s curve and was on the dangerous side of the curve [23].

The VHCF damage mechanism of titanium alloy is complex. The influence of microstructure and loading environment has been studied by scholars at home and abroad. Oguma et al studied the VHCF of Ti-6Al-4V after different heat treatments, and concluded that there were differences in the influence on the relative internal damage of different structures [24]. The investigation by Chandran et al indicated a significant difference in very high cycle behavior between two Ti-22V-4Al alloys, whose proportions of primary \( \alpha \) phase were 10% and 45%, respectively [25]. Nie et al studied the fatigue performance of TC21 titanium alloy with two sizes of basketweave in the life span of \( 10^9 \). They pointed out that the fatigue property of the short size basketweave was higher. However, the origin mechanism of fatigue cracks in the two materials was semblable [26]. Crupi et al carried out a contrastive study of two typical Ti-6Al-4V with basket and bimodal structure. The results showed that the VHCF crack of the basket structure tended to surface initiation, while the bimodal structure is the internal cleavage initiation mechanism [27]. Morrissey et al revealed the pull-down fatigue test results of Ti-6Al-4V at 60Hz and 20kHz frequency. The similarity of S-N curves indicated that Ti-6Al-4V did not have frequency effect [28]. The same conclusion was obtained in other literatures [29–31].

It is noteworthy that the research results above were carried out by uniaxial tension or rotating bending. However, under the service condition of aero engine blades, they are mainly subjected to the bending stress along the blade radiation direction and the excitation force of vibration due to incoming flow. The VHCF property under bending vibration loading for the titanium alloys have not been very well understood till now. In addition, VHCF property of titanium alloy is closely related to the structure. The influence of forging process in engine manufacturing process on fatigue property has yet rarely studied. In this study, TC4 titanium alloy was firstly forged by three different processes. On this basis, three point bending ultrasonic test was carried out to investigate HCF and VHCF property of TC4 titanium alloy with three different structures. The effect of microstructure and mechanical property on fatigue life was obtained by comparing the fatigue S-N curve. The HCF and VHCF crack initiation mechanism was revealed using SEM and EDS analysis. Besides, The relationship between VHCF life and crack initiation behavior was investigated.

![Figure 1. Microstructure metallographic of TC4 titanium alloy after three forging processes.](image)
2. Materials and test system

2.1. Materials
In this paper, TC4 bar ($\phi = 28$ mm) was selected to experiment and the main elements as shown in table 1. The forging process parameters are shown in table 2. The procedures for heat treatment is: $720^\circ$C for 1h $+$ air quenching. According to literature [32], the phase transition temperature of TC4 titanium alloy is $990^\circ$C. The first two forging processes are conventional $\alpha + \beta$ forging, and the third is near $\beta$ forging. As is shown in figure 1, TC4 titanium alloy possess Bimodal I structure, equiaxed structure and bimodal II structure after three forging processes. The three kinds of structures all contain equiaxed primary $\alpha$ phase and $\beta$-transformed microstructures with different content and morphology. Equiaxed primary $\alpha$ phase content is 28%, 35% and 10%, respectively, with average size of 30, 43 and 12 $\mu$m.

The tensile property was tested using EBS-3000 tensile machine at room temperature. The stress-strain curve is shown in the figure 2. The elastic modulus and Poisson’s ratio were tested using IET-01 elastic modulus machine. The mechanical property results are shown in the table 3.

![Figure 2. Stress-strain curves of three kinds of structure.](image)

**Table 3.** Tensile properties of three structures at room temperature.

| Structure     | Tensile strength (MPa) | Yield strength (MPa) | Elongation (%) | Reduction (%) | Young’s modulus (GPa) | Poisson’s ratio |
|---------------|------------------------|----------------------|----------------|---------------|-----------------------|----------------|
| Bimodal I     | 962                    | 905                  | 14             | 50            | 112.20                | 0.33           |
| Equiaxed      | 979                    | 913                  | 16             | 51            | 113.50                | 0.32           |
| Bimodal II    | 990                    | 910                  | 19             | 49            | 118.57                | 0.34           |

2.2. Test system
On the basis of the tensile and compression fatigue test system, the three point bending ultrasonic fatigue test system was built in combination with the real bearing mode of engine blade. The test system was divided into four subsystems: load applying subsystem; compressed air cooling subsystem; displacement measurement and
heat effect monitoring subsystem; software control and data acquisition subsystem. The test system composition is shown in the figure 3.

The load applying subsystem consists of static loading system, ultrasonic resonance system and supporting device, which can apply static load and ultrasonic dynamic load to the specimen. The compressed air cooling subsystem is an auxiliary system of the fatigue test system, as shown in figure 4. It is composed of an air compressor, an air storage tank, an oil-water separator and an eddy current cooling gun, which can output a
high-pressure dry and clean air flow at $-5^\circ$C. It can restrain the phenomenon of temperature rise of load applying subsystem and the specimen during test. The displacement measurement and thermal effect monitoring subsystem is composed of capacitive vibration displacement measurement system and infrared thermal imager. On the one hand, it provides vibration displacement amplitude measurement and calibration of the load applying subsystem. On the other hand, it can monitor the temperature throughout test. The software control and data acquisition subsystem carries out integrated design for each experimental subsystem. The specific function is to collect test data in real time based on software and control the whole test process.

2.3. Specimen design and loading

Based on the bending vibration equation of elastic beam [33], this paper carried out the design work of three point bending specimen. The length of specimen, span between fulcrum and stress-displacement coefficient of specimen were calculated. In addition, the finite element simulation based on ABAQUS software was carried out, making the natural frequency of three point bending specimen meet the requirement of loading frequency of test system. The shape and dimension of the specimen with bimodal I structure are shown in figure 5. Both sides of the bottom of the specimen were chamfered preventing stress concentration. The length $L$ of three point bending specimen with bimodal I structure, equiaxed structure and bimodal II structure is 31.2, 31.4 and 31.6 mm, respectively. For example, the modal analysis field diagram of specimen with bimodal I structure is shown in figure 6. The fourth order resonance frequency is 19796Hz, which is close to 20 kHz. According to the different colors of the specimen stress field, maximum tensile stress area was found at the bottom section. The maximum compressive stress existed on the upper surface, as shown in figure 6(a). From the displacement field diagram in figure 6(b), two symmetrically distributed displacement stagnation points can be clearly seen. When the three point bending ultrasonic fatigue test was carried out, the two fulcrum positions were present (displacement stagnation points). The ratio of the vibration bending normal stress and the vibration displacement at the bottom of the specimen was equal to the numerical value of stress-displacement coefficient. According to the displacement field simulation results, the span $L_0$ between two fulcrums for bimodal I structure, equiaxed structure and bimodal II structure is 17.0 mm, 17.1 mm and 17.2 mm.

![Figure 6. The modal analysis field diagram of specimen with bimodal I structure (a) Stress field, (b) Displacement field.](image-url)
The test was carried out at the stress ratio of $R = 0.5$. Its calculation formula is as follows:

$$\begin{equation}
0.5 = \frac{\sigma_m - \sigma_u}{\sigma_m + \sigma_u}
\end{equation}$$

where $\sigma_m$ stands for the mean stress (applied by static loading system), and $\sigma_u$ stands for the vibration stress amplitude (applied by ultrasonic resonance system) at the bottom of the specimen.

At the beginning of the test, the specimen was subjected to a static load and resonated with the test system, as shown in figure 7. During the test, the capacitive vibration displacement measurement subsystem was used to measure the displacement at the bottom of the specimen, with an accuracy of 0.1 μm. In normal tests, the resonance frequency was $20 \pm 0.5$ kHz, which caused the bending resonance of the specimen while the displacement remained unchanged. When the frequency dropped sharply below 19.5 kHz and the displacement changed significantly, the system automatically interrupted the test. At this time, it can be determined whether the specimen was damaged or not. The software control and data acquisition subsystem recorded the stress amplitude during the test and cycle times when fracture occurred.

3. Results

3.1. S-N curve

The S-N curves in HCF and VHCF regimes of the three kinds of structures are shown in figure 8. Square, right triangle and hexagonal points respectively represent the bimodal I, equiaxed and bimodal II structure obtained at the forging temperatures of 920 °C, 950 °C and 985 °C. Solid points represent the surface initiation, and the semi-solid points represent the subsurface initiation. In the three point bending test with stress ratio of $R = 0.5$, the test was carried out at the stress ratio of $R = 0.5$. Its calculation formula is as follows:

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the fatigue S-N curves of TC4 titanium alloy with three different structures present different characteristics respectively: continuous decline type, double platform type and linear decline type. The fatigue life of bimodal I and II decreases with the increase of stress amplitude, without the traditional fatigue limit. The S-N curve of equiaxed structure appears a platform similar to the fatigue limit in HCF regime, but the curve drops again and gradually approaches the level while entering VHCF regime.

Overall, bimodal II structure has the best fatigue strength in the HCF regime. The primary $\alpha$ phase size of bimodal II structure was small, and the refinement of the structure made the deformation better coordinated. It was hard to generate cavities and crack initiation during loading. Therefore, bimodal II structure had a good high cycle fatigue strength. The comprehensive fatigue strength of bimodal I structure was the lowest, and the fatigue property of bimodal II structure was the best in the VHCF regime. There were more $\beta$-transformed structures in bimodal II structure and less in bimodal I structure. The $\beta$-transformed structure in the material had a variety of morphological and directional changes. The morphology distribution of short and thick bar, long bar and crisscross had a big impact on the fatigue crack growth, which can cause the crack growth path to be zigzagged continuously and increase the energy required for crack growth. At the same time, the stress field at the

![Figure 9. Typical fatigue fracture surface SEM morphology of 'surface crack initiation.' (b), (d), (f) The enlarged images at crack initiation regions of (a), (c), (e), respectively. (a), (b) Bimodal I, $\sigma_a = 313$ MPa, $N_f = 1.23 \times 10^6$; (c), (d) Equiaxed, $\sigma_a = 294$ MPa, $N_f = 8.96 \times 10^5$; (e), (f) Bimodal II, $\sigma_a = 294$ MPa, $N_f = 2.31 \times 10^6$.]
crack tip weakened and the propagation behavior slowed down. The existence of $\beta$-transformed structure was helpful to improve the VHCF property.

In conclusion, the microstructure of TC4 titanium alloy is the decisive factor for fatigue property. As can be seen from figure 1, the microstructure of the titanium alloy with bimodal II structure obtained after near $\beta$ forging was effectively refined, with equiaxed primary $\alpha$ phase content of 10% and average size of 10 $\mu$m. For the bimodal II structure, the size of primary $\alpha$ phase is small. The microstructure was refined and the deformation coordination was good [34, 35]. The cavity was not easy to appear in the loading process, and the crack was difficult to initiate. The near $\beta$ forging temperature was close to the phase transition point, causing most of the primary $\alpha$ phases were transformed into $\beta$ phases. The $\beta$-transformed structures presented lumpy, equiaxed and short rods. The existence of $\beta$-transformed structures made the crack propagation branch more and the path zigzag in the process of crack propagation. Therefore, it was found that the property of the bimodal II structure obtained by near $\beta$ forging was the best in the HCF and VHCF regime. In addition, the equiaxed primary $\alpha$ phase content of bimodal I structure and equiaxed microstructure was greater than that of bimodal II structure, but the HCF and VHCF performance was weak. It can be concluded that too much equiaxed primary $\alpha$ phase in titanium alloy will inhibit the fatigue performance on the contrary.

Figure 10. Typical fatigue fracture surface SEM morphology of ‘subsurface crack initiation.’ (b), (d), (f) The enlarged images at crack initiation regions of (a), (c), (e), respectively. (a) Bimodal I, $\sigma_a = 225$ MPa, $N_f = 6.51 \times 10^7$; (c), (d) Equiaxed, $\sigma_a = 213$ MPa, $N_f = 3.04 \times 10^7$; (e), (f) Bimodal II, $\sigma_a = 213$ MPa, $N_f = 6.14 \times 10^8$.
3.2. Fatigue fracture characteristics

For three kinds of structures, fracture occurred at the bottom of the specimen under the maximum tensile stress. Typical fatigue fracture surface SEM morphology is exhibited in Figure 9. It can be seen that the crack initiation region of the three kinds of structures fluctuated obviously on the whole and there were tearing ridge and cleavage step characteristics. The morphology of crack propagation was haphazard, like a bright river and tongue. According to the reverse direction of river path, it can be judged that the fatigue cracks of three kinds of structures originated from the surface of the specimen.

As shown in figure 9(a), the crack initiation region of bimodal I structure had some small cleavage planes with different fluctuations, which was consistent to typical cleavage fracture feature. The circle area in figure 9(b) showed the cleavage step and resident slip zone generated by the crack initiation. It can be concluded that bimodal I structure presents cleavage crack mode in HCF regime \[36, 37\]. As shown in figure 9(c), the pattern was concentrated and densely distributed near the crack initiation point of the equiaxed structure. Cleavage planes, tear ridges and grooves were observed in the field of view. The cracks between cleavage planes with different heights were connected. The cleavage steps indicated the existence of transgranular and intergranular propagation modes of the cracks. The circle area was the cleavage plane generated by crack initiation, as is shown in figure 9(d). It was observed that secondary cracks with different orientations exist in the surrounding region. It can be concluded that the equiaxed structure mainly presents quasi-cleavage crack mode in HCF regime \[27, 38\]. As shown in figure 9(e), the traces of tearing appear on the surface of the crack initiation region. The crack initiation point within the circle region in figure 9(f) showed the surface slip initiation mechanism. After the crack initiation, the crack propagated by plastic deformation and cleavage mechanism. The cleavage steps with different orientations were formed around the initiation point and the traces of propagation along the crystal were formed. It can be concluded that the bimodal II structure mainly presented cleavage crack mode in HCF regime \[39, 40\]. To sum up, the crack initiation in HCF regime is as follows: bimodal I structure and equiaxed structure are surface cleavage, and bimodal II structure is surface slip.

Figure 11. Morphology of VHCF crack growth zones ($\sigma_a = 225$ MPa).
Typical fatigue fracture surface SEM morphology is exhibited in figure 10. Different from the crack initiation region in HCF regime, the VHCF cracks of three structures all originated from the subsurface of the specimen. It was determined that the VHCF crack initiation point was located from the bottom of specimen about 35, 55 and 30 μm through the reverse crack growth path.

As shown in figure 10(a), the crack initiation region of bimodal I structure was relatively smooth. The crack propagation included intergranular and transgranular fracture mode. The circle area in figure 10(b) showed the cleavage facets generated by the crack initiation. It can be concluded that bimodal I structure presented cleavage crack mode in VHCF regime. As shown in figure 10(c), the equiaxed structure crack originated from the cleavage plane in the middle of the field of vision. It firstly expanded along a slip plane in the grain, and then extended radially to all directions. The circle area was the cleavage plane generated by crack initiation, as is shown in figure 10(d). It was found that the expansion pattern exist along the crystal around the cleavage plane. It can be concluded that the equiaxed structure mainly presented quasi-cleavage crack mode in VHCF regime. As shown in figure 10(e), a large number of gray-black plane features were observed in the crack initiation region of bimodal II structure. The region take up a large proportion in the field of view. It showed that cleavage fracture is the main crack propagation. The crack initiation point within the circle region in figure 10(f) showed cleavage initiation mechanism. After the crack initiation, cleavage behavior occurred further on the adjacent grains and crack propagated along the grain boundary. The cleavage planes and tear ridges were formed around the initiation point. It can be concluded that the bimodal II structure mainly presents cleavage crack mode in VHCF regime. To sum up, the crack initiation of three structures in VHCF regime are all internal cleavage mechanism [41, 42].
3.3. Morphology of crack growth zone

Under the same stress amplitude of 225 Mpa, the crack growth zone near the junction between the crack growth zone and the transient fracture zone was selected for SEM observation. The VHCF crack growth characteristics of three structures were analyzed. The morphology of crack growth zone is shown in the figure 11. It can be seen that small fault blocks with different heights and inconsistent sizes appear on the crack growth zones. The fatigue strip was parallel to each other, presenting a slightly curved wave shape. The fatigue strips on different small fault blocks presented discontinuous distribution and belong to different series. However, the fatigue strip extended in the same direction and shows thick, deep and long characteristics on the whole.

4. Discussions

4.1. VHCF initiation mechanism

In addition, EDS analysis was performed on the facets of the crack initiation points in VHCF regime to confirm the initiation mechanism of fatigue crack. For TC4 titanium alloy, elemental Al is the $\alpha$ phase stabilizer, and elemental V is the $\beta$ phase stabilizer. The EDS results on crack initiation points of the three microstructures are shown in figures 12–14. According to the figure, the Al element content at the initiation point of bimodal I structure, equiaxed structure and bimodal II structure was 7.29 wt%, 7.16 wt% and 6.82 wt%. The aluminum content of the facet at the crack initiation point was higher than the average value of the TC4 titanium alloy substrate, and the content of V element was below average. Therefore, the facets in the fracture surface of three structures formed due to the cleavage of $\alpha$ grains [43–45].

4.2. Crack propagation characteristic

Figure 15 shows the mean fatigue strip spacing and fatigue cycles of the three structures when $\sigma_a = 225$ Mpa. It can be found that the VHCF strips and fatigue life of the three structures showed the same trend, which first decreases and then increases. The bimodal II structure with the best comprehensive VHCF property hads the biggest strip spacing and the fastest crack propagation rate. Since the fatigue life is mainly composed of two processes of crack initiation and crack propagation, the VHCF lives of the three structures are opposite to the trend of crack propagation. The crack propagation time of bimodal II structure was the shortest under same stress. This indicates that VHCF life of TC4 titanium alloy under three point bending test is dominated by the fatigue crack initiation stage [46–48].

5. Conclusions

In this paper, the influence of forging process on HCF and VHCF of TC4 titanium alloy was studied. The main conclusions are as follows:

1. Three completely different shapes of S-N curve were presented for bimodal I, equiaxed structure and bimodal II structure. They showed continuous decline, double platform and linear decline type respectively.
2. The fatigue performance of bimodal II structure forged at 985 °C was obviously better than bimodal I and equiaxed structure in the HCF regime. The VHCF property of bimodal I structure forged at 920 °C was the weakest. Moreover, the fatigue performance of equiaxed structure forged at 950 °C lied between bimodal II and bimodal I structure.

3. S-N curve results highlighted that forging treatments should be carefully optimized to enhance the mechanical and fatigue property. Compared with $\alpha + \beta$ forging, near $\beta$ forging can refine the morphology distribution of titanium alloy and control the content of microstructure effectively. Meanwhile, it was found that too much equiaxed primary $\alpha$ phase in titanium alloy will inhibit the fatigue performance.

4. For three kinds of structures, crack initiations were observed at the surfaces of specimens in the HCF regime. SEM observation indicated that bimodal I and equiaxed structure by $\alpha + \beta$ forging presented surface cleavage, while bimodal II structure by near $\beta$ forging presented surface slip fracture mechanism.

5. Fatigue failure still occurred in the VHCF regime. For equiaxed and bimodal structure, the VHCF crack initiated due to primary $\alpha$ cleavage planes from subsurface.

6. VHCF life of TC4 titanium alloy consists of fatigue crack initiation and propagation phases, but is dominated by crack initiation phase.

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