Effect of texture characteristics on the high-cycle fatigue properties of a Ti-6Al-4V alloy

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Abstract

A Ti-6Al-4V alloy was rolled at different temperatures and subsequently annealed to obtain fatigue samples with different texture characteristics. The samples were then subjected to tension-tension high-cycle fatigue (HCF) tests and the fracture morphology was observed to correlate the texture characteristics with the HCF properties. The results show that the texture intensity significantly affects the HCF strength for the equiaxed microstructure of Ti-6Al-4V alloys with an equivalent grain size and the same texture type; also, the HCF strength decreases with increasing texture intensity. The fracture morphology observation and Schmid factor calculation show that planar facets, which are a characteristic feature of crack initiation sites, are formed due to the strength mismatch caused by the inhomogeneous slip distribution favored either for prismatic or basal slip. The effect of the texture intensity on the HCF properties can be explained by the influence of the number of pile-up locations of ‘soft’ grains neighboring ‘hard’ grains in the typical Stroh model that elucidates the planar facet formation mechanism.

1. Introduction

Titanium alloys are widely used instead of heavy steel components for manufacturing critical systems, such as airfoils, undercarriages, and airframes, because of their high specific strength, good corrosion resistance and high fatigue strength. Titanium structures are often exposed to high-cycle fatigue (HCF) loading in these applications, and hence, fatigue fracture is an important failure mode in these structures. The fatigue properties of titanium alloys can be effectively improved by the application of different plastic deformation and heat treatment processes, which significantly influence their microstructure and texture.

As a widely used titanium alloy, Ti-6Al-4V can exhibit three typical microstructures depending on specific thermomechanical treatment processing, namely, fully lamellar structures, fully equiaxed structures and the so-called bimodal microstructures, and many microstructure parameters such as the α lamellar width, the α grain size, the content and volume fraction of the primary α (αp) phase are involved. Therefore, extensive studies have been focused on the influence of microstructure characteristics on fatigue performance and have shown that HCF properties are strongly determined by microstructure types and microstructure parameters [1–9]. Among the three types of microstructure, there is still controversy as to which has higher HCF strength [4–8]. But based on statistical analysis of a large number of literature data, Wu et al reported that HCF strengths of different microstructures decreased in the order of bimodal, lamellar and equiaxed microstructure [8]. Among the various microstructure parameters, because the lamellar width or the grain size determines the slip length, a high HCF strength can be achieved in the lamellar microstructure with a small α lamellar width and in the bimodal and the equiaxed microstructures with a small α grain size. The HCF strength of Ti-6Al-4V alloys with a bimodal microstructure is also influenced by the αp content and exhibits a nonlinear relationship as the αp volume fraction increases in the range of 30%–50% [1, 8].

Apart from the microstructure, the effects of the crystallographic texture, including the microtexture and macrotexture, on the HCF properties have also been studied extensively [10–16]. A microtextured region
containing grains of similar orientations, referred to as a macrozone, is often present in Ti-6Al-4V alloys, and grains with misorientations between 15° and 40° from the loading direction are favored for crack initiation [13]. The unfavorably oriented macrozones are responsible for large regions of continuous faceted cracking and are found to degrade the HCF performance [10–14]. Moreover, the macrotexture types remarkably influence the fatigue performance [16]. Two typical textures that are frequently formed in Ti-6Al-4V alloys, namely basal/transverse (B/T) texture and transverse (T) texture, have been reported to affect HCF strength. The specimens with B/T texture show higher HCF strength when loaded along the same direction, and when the texture types are the same, the specimens loaded along the rolling direction (RD) show higher HCF strength than those loaded along the transverse direction (TD) [16]. Briefly, although texture characteristics significantly affect the HCF strength, studies on the effect of the texture intensity on the HCF performance have rarely been reported. However, different texture intensities are often obtained because of varying deformation processing and subsequent heat treatments. Therefore, this study discusses the effect of texture characteristics, especially the texture intensity, on HCF properties.

2. Experimental procedure

The as-received Ti-6Al-4V sheets with an initial thickness of 5 mm were warm rolled by 60% at temperatures of 450 °C, 600 °C, 750 °C, and subsequently annealed at 800 °C for 4 h and air cooled to study the effect of the texture characteristics on the fatigue properties. The specimens rolled at 450 °C, 600 °C, 750 °C are denoted as WR450, WR600, and WR750, respectively. The composition of the alloy used herein is shown in table 1. And the static tensile properties of the specimens in the RD are shown in table 2, and three specimens are used in each tension test to obtain statistical data.

The texture was measured using x-ray diffraction and characterized by an orientation distribution function (ODF), which was calculated by the (0002), (1010), (1011), (1012) and (1120) pole figures.

The tension–tension fatigue tests were conducted under stress control with a stress ratio (σmin/σmax) of 0.1 and a frequency of 90 Hz. The S–N curve was obtained at different stress levels using ten or more specimens with σmax ranging from 310 MPa to 600 MPa, and the ratio of the stress difference between the last broken specimen and the unbroken specimen to the stress of the last broken specimen was less than 2%. The smooth fatigue specimen used is shown in figure 1.

3. Results

3.1. The textures of different fatigue specimens

The microstructure of the different fatigue specimens, namely WR450, WR600 and WR750 (figure 2), shows that all the specimens exhibit equiaxed grains, and there is no appreciable differences among the average grain sizes measured by the linear intercept method, which is ~5.9 μm, ~5.7 μm and ~5.7 μm, respectively.

The textures of the different fatigue specimens, namely WR450, WR600 and WR750, were characterized by (0002) pole figures, as shown in figure 3. The main texture can be described as the basal poles being tilted from the normal direction (ND) toward the TD, which is a typical rolling or recrystallization texture of titanium alloys [17, 18]. The texture represented by the ODF constant φ2 = 0° and φ2 = 30° sections is shown in figure 4, which quantitatively compares the difference in the texture among the different fatigue samples. All specimens exhibit a strong texture, with maximum intensity of 7.5 times random among them. Moreover, there is no

| Table 1. Chemical composition of the Ti-6Al-4V alloy (wt. %). |
|-------------|---|---|---|---|---|---|---|---|
| Element | Al | V | Fe | C | N | H | O | Ti |
| Content | 5.970 | 4.030 | 0.060 | 0.013 | 0.069 | 0.004 | 0.050 | Bal. |

| Table 2. The static tensile properties of the Ti-6Al-4V alloy. |
|-------------|-------------|-------------|-------------|
| Specimens | Yield strength σy and standard deviation Sy | Tensile strength σb and standard deviation Sb | Elongation |
| WR450 | 804 | 28.2 | 892 | 27.4 | 10.3% |
| WR600 | 827 | 12.2 | 929 | 21.6 | 9.6% |
| WR750 | 841 | 27.0 | 955 | 10.4 | 7.1% |
Figure 1. Geometric size of the fatigue specimen.

Figure 2. Microstructure of the different fatigue samples: (a) WR450, (b) WR600, and (c) WR750.

Figure 3. (0002) pole figures of the different fatigue samples: (a) WR450, (b) WR600, and (c) WR750.
appreciable difference in the texture type among the different fatigue specimens. The texture can be characterized by two types of fiber texture, namely, the partial fiber texture $RD/\langle 10\bar{1}0 \rangle$ and the fiber texture $ND/\langle [12\bar{1}2] - [1\bar{2}1\bar{9}] \rangle$, with the maximum and secondary intensity peaks at $\langle 1\bar{2}1\bar{9} \rangle \langle 10\bar{1}0 \rangle$ and $\langle 1\bar{2}1\bar{9} \rangle \langle 4\bar{3}\bar{1}1 \rangle$, respectively. However, the texture intensity is different from specimen to specimen and increases in the order from WR450 to WR600 to WR750.

### 3.2. Fatigue properties of different specimens

The S-N curves of different fatigue specimens are shown in figure 5. The S-N curves show a continuous increase in fatigue life with decreasing stress level, and they have general characteristics of the reported HCF S-N curves of Ti-6Al-4V alloys [1–4, 9, 16]. Besides, the fatigue performance data is scattered and partially overlapped in the three samples. More specifically, sample WR600 and WR750 have relatively large scatter in fatigue performance data, while the fatigue data of sample WR450 are relatively closely around the S-N curve. The HCF strength at $10^7$ cycles is taken as the endurance limit. The endurance limit is 310–325 MPa, which is lower than the reference data for Ti-6Al-4V alloys with an equiaxed microstructure collected by Wu et al [8]. Although this is not the focus of the present paper, it should be pointed out that the relatively low fatigue limit may be caused by a large $\alpha$ average grain size of $\sim 6 \mu m$ [8] and low oxygen content of 0.05 wt. % [19, 20]. And it can be seen that the HCF strength varies significantly with the specimen. Sample WR450 shows the highest fatigue strength herein, whereas sample WR750 shows the lowest fatigue strength herein for the same number of cycles. In other words,
sample WR450 has the highest fatigue life under the same fatigue load, whereas sample WR750 has the lowest fatigue life.

The fatigue properties are primarily determined by the microstructure and crystallographic texture. As for the microstructure, the fatigue specimens exhibit an equiaxed microstructure, in which the mechanical properties are mainly determined by the $\alpha$ grain size \[^1\]. Considering the negligible difference in the $\alpha$ grain size among different specimens, the mechanical properties is mainly determined by the texture characteristics, which can be verified from the static tensile and fatigue properties. Generally, samples with high yield strength have high HCF strength. However, it can be noted from table 2 and figure 5 that sample WR450 with the lowest yield strength has the highest HCF strength, while sample WR750 with the highest yield strength has the lowest HCF strength. In other words, in strongly textured materials, samples with high yield strength do not necessarily have high HCF strength due to the influence of slip reversibility \[^16\]. In the present work, since the texture types are the same, the difference in the HCF strength is caused by the variation in the texture intensity. It can be seen from a combination of figures 4 and 5 that the HCF strength decreases as the texture intensity increases.

3.3. The fatigue fracture facet

The fatigue damage begins with crack initiation and subsequent propagation. However, the fatigue performance is dominated by crack initiation if the sample is subjected to HCF load. Therefore, the crack initiation mechanism appears to be important, and hence, the fracture morphology of a fatigue crack is observed herein, and its scanning electron micrograph is shown in figure 6. Crack initiation sites are characterized by a planar facet, just as reported in a wide range of titanium alloys \[^6, 13–15, 21\]. Studies of fracture morphologies have shown that fatigue cracks initiate in the primary $\alpha$ grains of equiaxed microstructures \[^6, 22\] and crack initiation is associated with the faceting of unfavorably oriented $\alpha$ grains \[^23, 24\]. The faceting may result from a particularly unfortunate combination of crystallographic orientations in adjacent grains with respect to the loading direction \[^23, 24\]. Thus, the fatigue performance can be largely influenced by controlling the formation of facets and the number of grains favorably oriented for facet formation.

![Figure 5. S-N curves of the fatigue samples: (a) WR450, (b) WR600, (c) WR750 and (d) all samples.](image-url)
4. Discussion

The results described above show that the different fatigue strengths are due to the differences in the texture intensity. Because of the HCF load applied in this work, the fatigue property is determined by crack initiation, which is characterized by planar facets. Therefore, the influence of the texture characteristics on the fatigue properties can be discussed from the viewpoint of the effect of the crystallographic orientation on faceting. Although facets are generally considered to be formed by a cleavage mechanism, evidence shows that facets are induced by slip [10, 25]. However, slip activity is influenced by the grain orientation, and grains with different orientations deform through different slip mechanisms. The relative strength mismatch between neighboring grains due to different slip distributions results in a redistribution of the stress, which eventually causes the development of faceted cracks [26, 27]. Therefore, the crystal orientation and its slip activity are first discussed, followed by the effect of the texture intensity on the faceting phenomenon.

4.1. The texture and its favored slip system

During fatigue loading, grains with different orientations achieve plastic deformation through different slip systems, depending on which slip system is the most favorable. Activation of a specific slip system can be evaluated by the Schmid factor. Therefore, the Schmid factors of all potential slip systems were evaluated.

The prismatic (a), basal (a) and pyramidal (c + a) slip systems have been reported in deformed Ti-6Al-4V alloys [28, 29]; therefore, these systems were considered in this study. The corresponding slip plane, slip direction and the number of slip systems are shown in table 3. For a given orientation, the slip system with a large Schmid factor is usually preferentially activated. Thus, the maximum of the absolute values of the Schmid factors of all the crystallographically equivalent slip systems was selected as the Schmid factor for this slip system.

Moreover, because the critical resolved shear stress (CRSS) required to activate the slip system varies with different slip systems, the ratio of the CRSS values of the prismatic, basal and pyramidal slip systems was taken as 1:1:2.64, just as used in Refs. [13, 30] and the ‘normalized’ Schmid factor was used as follows:

\[ m = (n \cdot e_i) \cdot (s \cdot e_i) \]  

(1)
where $m$ is the Schmid factor, $n$ is the unit slip plane normal vector, $s$ is the unit slip direction vector, $e_1$ is the axis of the external load, $\tau$ is the CRSS, and $m'$ is the 'normalized' Schmid factor.

Under fatigue loading, the relationship between fatigue performance and texture is always discussed based on the angle between the $c$-axis and the loading direction [2, 13]; hence, the variation of the 'normalized' Schmid factor $m'$, with the angle $\beta$ is presented in figure 7. Two critical values of $10^\circ$ and $66.7^\circ$ can be observed, and the pyramidal, basal and prismatic slip are dominant within $0^\circ$–$10^\circ$, $10^\circ$–$66.7^\circ$, and $66.7^\circ$–$90^\circ$, respectively, which is in accordance with the results calculated by Bantounas et al [13].

Obviously, the dominant slip system is determined by the angle $\beta$. However, each angle $\beta$ may correspond to many different grain orientations. Therefore, to directly obtain the relationship between a grain orientation and its slip activity, the Euler space was discretized as $5^\circ \times 5^\circ \times 5^\circ$ and the angle $\beta$ corresponding to each group of Euler angles was calculated and plotted on ODF constant $\phi_2 = 0^\circ$ and $\phi_2 = 30^\circ$ sections, as shown in figure 8, which clearly shows the grain orientation and its favored slip system. Figure 8 was further superimposed to directly correlate the macrotexture and slip activity, which is shown in figure 9. Different crystal orientations

$$m' = m \cdot \left( \frac{\tau_{\min}}{\tau_{(hkl)} \langleuvw\rangle} \right) \quad (2)$$

Figure 7. Graph of the ‘normalized’ Schmid factor $m'$ variation with the angle $\beta$ for prismatic $\langle a \rangle$, basal $\langle a \rangle$ and pyramidal $\langle c + a \rangle$ slip.

Figure 8. Angle $\beta$ superimposed on ODF constant $\phi_2 = 0^\circ$ and $\phi_2 = 30^\circ$ sections.
make the angle $\beta$ lie between 10° and 90°; hence, the texture of different fatigue samples is favored for prismatic and basal slip, which are often reported as the actually activated slip systems in Ti-6Al-4V alloys that are subjected to fatigue or tension load [11, 25]. The main texture with the angle $\beta$ between 66.7° and 90° is primarily favored for prismatic slip, while only a few orientations with the angle $\beta$ between 46° and 66.7° are favored for basal slip. In other words, the RD $\parallel$ $\bar{1}$010 fiber texture and most of the ND $\parallel$ $\{\bar{1}2\bar{1}1\}$–{$\bar{1}2\bar{1}9$}) fiber texture are favored for prismatic slip, while a small part of the ND fiber texture is favored for basal slip. Moreover, the intensity of the texture favored for prismatic slip increases in the order of WR450 to WR600 to WR750, while the intensity of the texture favored for basal slip does not change substantially.

### 4.2. Effect of the texture intensity on the faceted crack initiation

As mentioned above, the textures of the fatigue specimens make the angle $\beta$ lie in different ranges, and therefore they favor prismatic or basal slip differently. Experiments employing electron backscatter diffraction (EBSD) in a scanning electron microscope have shown that the relative strength of different grains is highly dependent on the angle $\beta$ [31]. Grains with the $c$-axis parallel to the loading direction (the angle $\beta$ equal to 0°) are termed as ‘hard’ grains, while the grains with the $c$-axis perpendicular to the loading direction (the angle $\beta$ equal to 90°) are termed as ‘soft’ grains [23, 24, 27]. In other words, the grains with an orientation that favors pyramidal slip are

![Figure 9](image-url)
'hard' grains, while the grains with an orientation that favors prismatic slip are 'soft' grains. The grains with an orientation that favors basal slip are the grains with a medium strength that is between 'hard' and 'soft' grains. Therefore, in this study, the main texture with the angle \(\beta\) between 66.7° and 90° corresponds to 'soft' grains. Compared with 'soft' grains, a few orientations with the angle \(\beta\) between 46° and 66.7° correspond to 'hard' grains. The strength mismatch due to different grain orientations results in a stress gradient across the interface, and such a stress redistribution among regions with different strengths has been proposed as the fundamental cause of the development of faceted cracks [26, 27].

The Stroh model is widely used to describe the planar facet formation mechanism [32] and is illustrated in figure 10(a). Based on the theory by Stroh, fatigue crack formation is due to a restricted slip on certain planes. The 'soft' grains are thought to deform first, leading to a pile-up of dislocations at the boundaries of the 'hard' grains. The inhomogeneous distribution of the slip systems results in the slip activity of well-oriented grains to transfer a shear stress onto neighboring unfavorably oriented grains, which generates the required combination of shear and tensile stresses on the unfavorably oriented plane. This, in conjunction with the applied stress, induces facet formation. It has been indicated that the crystallographic orientation, grain size, and number of pile-up locations influence the facet crack formation [27, 33, 34].

The above results indicate that the relatively 'hard' grains of the WR450, WR600 and WR750 fatigue specimens have nearly the same texture intensity, while the texture intensity of the 'soft' grains increases. Hence, from this study, the effect of the texture intensity on the fatigue properties can be explained by the influence of the pile-up of 'soft' grains, as shown in figure 10(b). When the texture intensity of 'soft' grains increases, the frequency of the occurrence of 'soft' grains also increases, which means that the number of pile-up locations increases, that is reportedly responsible for the fatigue life degradation [34]. It can be reasonably inferred that with an increase in the number of pile-up locations of the 'soft' grains, an increased stress is accumulated in the 'hard' grains that quickly leads to crack initiation under the same applied stress, resulting in a decreased fatigue life. In other words, when a large stress is accumulated in the 'hard' grains, applying a small stress causes crack initiation; that is, the grains can share a decreased external load, resulting in a decreased HCF strength. The proposed approach to investigate the effect of texture intensity on planar facet crack formation, which takes the effect of the pile-up of 'soft' grains into consideration in the Stroh model, is meaningful for experimental and simulation studies of fatigue.

5. Conclusion

(1) The HCF property is primarily determined by the texture intensity in the equiaxed microstructure of Ti-6Al-4V alloys with the same grain size and texture type, and the HCF strength decreases with increasing texture intensity.

(2) The crack initiation sites are characterized by a typical planar facet. The Schmid factor calculation indicates that the texture is mainly favored for prismatic and basal slip, corresponding to 'soft' and 'hard' grains, respectively, and that the relative strength mismatch provides the prerequisite for planar facet formation, which can be explained by the widely accepted Stroh model.

(3) The effect of the texture intensity on the HCF properties can be ascribed to the influence of the pile-up of 'soft' grains neighboring 'hard' grains in the Stroh model. An increase in the number of pile-up locations leads to an elevated stress accumulated in the 'hard' grains and thus a decrease in the HCF strength.
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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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