FATIGUE CRACK GROWTH ANISOTROPY IN ANNEALED AND PRE-STRAINED COMMERCIALLTY PURE TITANIUMS

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Abstract: Fatigue crack growth tests were carried out on commercially pure titanium sheets with a drilled hole and a center notch, in order to clarify anisotropy of fatigue crack growth and the influence of pre-straining on the anisotropy. The crack growth resistance in rolling direction was higher than that in a direction transverse to the rolling direction for surface cracks longer than 2.5mm initiated at a drilled hole, and for cracks initiated at a center notch at $\Delta K$ higher than 10 MPa$m^{-1/2}$, in contrast to the growth behavior of various steels. Fractography observations showed that the anisotropy became remarkable after transition from cleavage-like facet dominant fracture surface to ductile appearance dominant one. The transition occurred when reversed plastic zone size at the crack tip was comparable to the grain size of the metal during crack growth. Pre-straining had only a little effect on the crack growth anisotropy.

Key words: Fatigue, Crack growth, Small fatigue crack, Anisotropy, Pre-straining, Pure titanium

1. INTRODUCTION

Commercially pure titanium is a valuable material for various chemical plants or power generation systems, because of its excellent resistance to corrosion. Many members used in those systems such as plates, pipes and containers are usually deformed plastically. At an ambient temperature, pure titanium has hcp structure, which has few slip systems. However, pure titanium possesses a good plastic forming characteristic [1]. We reported the fatigue strength, crack initiation behavior and notch sensitivity characteristics of a 10% tensile pre-strained commercially pure titanium [2]. It was shown that fatigue microcracks initiated along boundaries of deformation twin, and the notch sensitivity increased due to pre-straining.

It is well known that heavy work with large deformation forms texture in hcp metals [3]. Therefore, rolled hcp metals exhibit anisotropy in deformation characteristics and mechanical properties. From this point of view, Sugano et al. [4] reported the anisotropy of fatigue crack growth rates in laboratory air and in vacuum. However, research on the anisotropy of fatigue crack growth including small fatigue crack behavior is seldom found.

In this report, we examined the anisotropy of fatigue crack growth under push-pull loading as well as the effect of 5% tensile pre-straining.

2. MATERIALS AND EXPERIMENTAL PROCEDURE

Material used for this research is a commercially pure titanium sheet (JIS TP28) with a thickness of 2mm, of which chemical composition is shown in Table 1. Two types of sheet were cut out from rolled titanium plates. One is L-T type of which rolling direction is parallel to the longitudinal direction, and the other is T-L type that is perpendicular to the longitudinal direction. Both sheets were annealed at 973K in one hour in vacuum. Optical micrograph of microstructure after the annealing is shown in Fig.1. The average grain size, $d$, was 50 μm.

Table 1. Chemical composition in wt%.

<table>
<thead>
<tr>
<th>H</th>
<th>O</th>
<th>N</th>
<th>Fe</th>
<th>C</th>
<th>Ti</th>
</tr>
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<tbody>
<tr>
<td>0.001</td>
<td>0.078</td>
<td>0.007</td>
<td>0.014</td>
<td>0.007</td>
<td>bal.</td>
</tr>
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Table 2. Mechanical properties.

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<tr>
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<th>$\sigma_{02}$</th>
<th>$\sigma_y$</th>
<th>$\phi$</th>
<th>$E$</th>
<th>$d$</th>
</tr>
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<tbody>
<tr>
<td>L-T</td>
<td>280 MPa</td>
<td>426 MPa</td>
<td>34.9%</td>
<td>107 GPa</td>
<td>50 μm</td>
</tr>
<tr>
<td>T-L</td>
<td>345 MPa</td>
<td>412 MPa</td>
<td>32.6%</td>
<td>115 GPa</td>
<td>50 μm</td>
</tr>
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Received August 7, 1997
starts to occur suddenly at a certain stress and 0.2% proof stress $\sigma_{0.2}$ is larger than that of L-T specimen. Thus the plastic deformation properties, especially at the initial stage, show more remarkable anisotropy.

The specimen configurations are shown in Fig. 3. One of them was used for small crack growth tests, which has a drilled hole with diameter of 1mm and depth of 0.5mm. The other was used for large crack growth tests, which has a center notch with a length of 3mm (CCT). A 5% tensile strain was given to some specimens in advance in shape of rectangular with 100 $\times$ 30mm and then the edge was finished with electric discharge wire cutting machine.

Crack growth tests were performed using a servo-hydraulic fatigue testing machine under constant stress amplitude and a frequency of 20Hz. Stress ratio $R$ is $-1$ for small crack growth tests and $R=0$ for large crack growth tests. For specimens with a drilled hole, crack length $l$ is defined as total length including hole diameter. For CCT specimens, crack length $2a$ is defined in the same way. Crack length was measured with a replication technique and a traveling microscope. Crack growth rates $\frac{dl}{dN}$ and $\frac{da}{dN}$ were determined using a secant method. The stress intensity factor range $\Delta K$ was evaluated by the secant law [5]. Crack opening load was measured from a load-displacement curve obtained from signals of load cell and strain gage mounted over the notch through subtraction circuit. Fracture surface observation was performed using SEM.

3. EXPERIMENTAL RESULTS

3.1. Small Crack Growth Behavior

Figure 4 shows the relationship between small fatigue crack growth rate $\frac{dl}{dN}$ and crack length $l$ at stress range of $\Delta \sigma=150$ MPa. After crack grows beyond 2.5mm, $\frac{dl}{dN}$ of L-T specimen is faster than that of T-L specimen. When crack is short (<2.5mm), $\frac{dl}{dN}$ of both specimens scattered and there is little difference in $\frac{dl}{dN}$ between both specimens. On the surface of T-L specimen, cracks grow in a zigzag way and multiple cracks were observed. The similar cracking behavior was also observed on pre-strained specimens. On the other hand, there is no effect of pre-straining on $\frac{dl}{dN}$ as shown in Fig.5.

3.2. Large Crack Growth Behavior

Figure 6 shows the relationship between crack growth rate, $\frac{da}{dN}$, and $\Delta K$ for annealed CCT specimens. These data were obtained at stress ranges of $\Delta \sigma=120$ MPa for L-T and T-L specimens, $\Delta \sigma=70$ MPa for L-T
specimen and $\Delta \sigma =75\text{MPa}$ for T-L specimen. For both materials, the $da/dN-\Delta K$ relationships can be characterized by Paris' law as expressed in Eq. (1) and both slopes of two lines, $m$, were equal to 3.9.

\[
\frac{da}{dN} = C(\Delta K)^m.
\]  

(1)

In the same range of $\Delta K$, $da/dN$ of L-T specimen is about twice as that of T-L specimen. However, at lower $\Delta K$ ($\lesssim 10\text{ MPam}^{1/2}$) such a difference in $da/dN$ was not observed.

Figure 7 shows the $da/dN-\Delta K$ relationship for pre-strained material. The $m$ value is 3.5 and $da/dN$ of L-T specimen is faster than that of T-L specimen as well as the annealed materials. Figure 8 shows the comparison between $da/dN$ of annealed material and pre-strained material for T-L specimen. Pre-straining tends to increase $da/dN$ and decrease $m$. For identical specimens, the relationships between $da/dN$ and $\Delta K_{eff}$ determined by crack opening load $P_{op}$ is shown in Fig.9. This suggests that the $da/dN-\Delta K_{eff}$ relationships roughly coincide mutually. However, the same relationships of T-L and

![Diagrams](image1.png)

**Fig. 4.** Small fatigue crack growth rates of annealed Ti at $\Delta \sigma =150\text{MPa}$.  

**Fig. 5.** Small fatigue crack growth rates of T-L specimen under $\Delta \sigma =150\text{MPa}$.  

**Fig. 6.** Relationship between $da/dN$ and $\Delta K$ for annealed Ti.  

**Fig. 7.** Relationship between $da/dN$ and $\Delta K$ for pre-strained Ti.
L-T specimens did not coincide as shown in Fig. 10. The difference in \( da/dN \) between T-L and L-T specimens cannot be explained by crack closure.

3.3. Fractographic Observations

Macroscopic SEM micrographs of fracture surfaces in annealed specimens with a drilled hole are shown in Fig. 11. The fracture appearances of T-L and L-T specimens are different. For T-L specimen, there are remarkable irregularities around the drill hole, and the surrounding area is covered with furrow type appearance. In this area, striations are observed locally. The same ductile appearance is observed in both T-L and L-T specimens.
specimens. However, the irregularities are hardly observed on the fracture surface of L-T specimen.

Figure 12 shows magnified view of the irregular appearance as shown with the frame in Fig.11. Most of them are cleavage-like facets and in some regions intergranular facets.

Macroscopic photographs of fracture surface in annealed CCT specimens are shown in Fig.13. Macroscopic appearance in fracture surface changed at certain crack lengths in both specimens. The change corresponded to a transition from ductile appearance to cleavage-like facet, as observed on the specimens with a drilled hole. The crack length at which the transition appeared was 4.3mm for L-T specimen and 7mm for T-L specimen.

4. DISCUSSION

It is well known that the texture of rolled pure titanium shows (0001)-[1010] parallel to the rolling direction which has a inclination of about ±27-30 degrees to the normal of the rolling plane [6]. Figure 14 shows the schematic illustration of the above-mentioned relation between the texture and the loading direction. It has been confirmed by Sugano et al. [4] that cleavage facets appeared when normal line of (0001) plane makes an angle less than 65 degrees with the loading axis. Therefore, it is considered that cleavage-like appearance was observed frequently in T-L specimens as shown in Fig.12.

The following results were obtained in crack growth tests. For small surface cracks, the anisotropy of d\(\Delta \sigma\)/dN was not observed in the crack length shorter than 2.5 mm and the crack growth resistance of L-T specimens was lower than that of T-L specimens in the crack length longer than 2.5mm. Also, for large through cracks, there found no anisotropy of da/dN in \(\Delta K\) less than 9 MPam\(^{1/2}\).

As shown in Fig.13, in L-T specimens the transition of fracture morphology appears in the shorter crack length than in T-L specimens. At the transition point, the reversed plastic zone sizes, \(R_p\), at crack tips are calculated for each specimen and summarized in Table 3. It should be noted that \(\Delta K\) is nearly equal to 10 MPam\(^{1/2}\) and \(R_p\) is comparable to the grain size.

From the above fractographic observation and Figs.4 and 6, it is confirmed that the anisotropy of crack growth resistance is small, when \(R_p\) is relatively smaller than the average grain size, i.e., fracture morphology is facet dominant. On the other hand, as crack grows, fracture appearance turns into the ductile mode and anisotropy becomes more remarkable. In other words, the crack growth resistance of L-T specimens which have an advantageous direction on a primary slip system {1010}-{1120}, decreases as compared to that of T-L specimens.

<table>
<thead>
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<th>Table 3. Reversed plastic zone size at transition appeared on fracture surface.</th>
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<td>(\Delta \sigma)</td>
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<tr>
<td>MPa</td>
</tr>
<tr>
<td>L-T</td>
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<tr>
<td></td>
</tr>
<tr>
<td>T-L</td>
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The gradual commencement of plastic deformation on the stress-strain curve in L-T specimens as shown in Fig. 2, seems to be related to this crystallographic condition.

Pre-straining affects remarkably the initial cracking behavior [2], while it does not significantly affect the crack growth resistance as shown in Figs. 5 and 8. For large cracks, there is a little difference in da/dN between an annealed material and a pre-strained one. This seems to be influenced by crack closure, because the da/dN- ΔK_eff relationships in both materials almost coincide as shown in Fig. 9. Furthermore, pre-straining does not affect the anisotropy in da/dN. It is considered that the amount of pre-straining is only 5% and development of texture is insufficient to affect the crack growth rate.

5. CONCLUSIONS

The following conclusions were obtained. (1) The fatigue crack growth resistance of T-L specimens is greater than that of L-T specimens, in regions of l>2.5mm for small cracks and ΔK>10MPa m^1/2 for large cracks. The anisotropy of crack growth is related to texture caused by rolling.

(2) When the size of reversed plastic zone at a crack tip is larger than the average grain size, ductile appearance is dominant in fracture surface. In such a case, the crack growth behavior shows anisotropy.

(3) For large through cracks, pre-straining decreases crack growth resistance irrespective of growth direction. The crack growth acceleration can be explained by the crack closure.

REFERENCES