EFFECT OF GRAIN SIZE ON DEFORMATION TWINNING IN COMMERCIAL PURITY TITANIUM

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ABSTRACT

The effect of grain size on deformation twinning in commercially pure titanium was investigated. In order to generate different grain sizes, the samples were subjected to cold rolling followed by annealing. Tensile tests were carried out on material with a range of different grain sizes (10-70 µm) at room temperature. To investigate twinning formation during plastic deformation, separate tensile tests were carried out to strains of 5% and 10%. The number of twins per grain and volume fraction of twins was measured. The results reveal the important influence of grain size on deformation twinning activity. The results will lead to better material models.

1 INTRODUCTION

Although deformation twinning behavior in metals has been extensively studied, only few papers examine the grain size effect on deformation twinning. Generally, it is stated that grain refinement increases the twinning stress. For instance, El-Danaf et. al have shown that 70/30 brass with a grain size of 250 µm displays far more twins compare with a 9 µm grain size. Meyers et al found the same effect for pure copper in a shock loading condition. Also, where a comparison is possible, grain refinement increases the yield stress of materials deforming by mechanical twinning much more than it does materials deforming by slip. In another words, the Hall-Petch slope for the twinning stress is higher than for slip stress. Armstrong and Worthington suggest that this discrepancy can be related to the different dislocation pile up conditions required for the initiation of the two modes. However, there is still no widely accepted explanation for it.

The focus of this investigation is to examine and measure the twin parameters such as number of twins per grain, \( N_{tg} \) and volume fraction of twins, \( \chi \), for commercial purity titanium, CP Ti, with different grain sizes in tension condition. It is hoped that the results will reveal how grain size controls the nucleation and growth of twins.

2 EXPERIMENTAL

A 12.7 mm in thickness CP Ti sheet, supplied by ATI titanium international Ltd., was used in this investigation. The as-received sheet was cold rolled and annealed repeatedly from a thickness of 12.7 mm to 2.9 mm. The resulting microstructure was further cold rolled and annealed at different temperatures and times to develop different grain sizes. Tensile samples were cut parallel to the rolling direction for each chosen condition. Tensile tests were performed up to failure at room temperature at the strain rate of \( 10^{-3} \text{s}^{-1} \). In order to measure twin parameters at those strains, the microstructure of the plane normal to the rolling direction was optically analysed by using polarized light. Samples were ground from 600 down to 4000 SiC paper and then electro-polished with a propriety solution (Struers A2 solution).

The intercept line method was used for estimation of the grain size, \( d \). The volume fraction of twins, \( \chi \), was measured using the standard point counting method. The method employed for measuring the number of twins per grain, \( N_{tg} \), has to count both the number of twins and grains in each image and to divide the number of twins by the number of grains.

In order to have an estimation of mean twin volume, \( v_t \), the average thickness, \( t \), and average length, \( l \), of twins were measured for selected conditions.

3 RESULTS

Table 1 shows the heat treatment conditions and average grain size for each condition. True stress-true strain curves obtained from the tensile tests are given in figure 1. As expected, yield stress and flow stress increase with decreasing grain size. The typical microstructures for selected grain sizes after a strain of 10% are shown in Figure 2. A few deformation twins are evident at all grain sizes.

### Table 1- Heat treatment conditions and grain sizes.

<table>
<thead>
<tr>
<th>Cold rolling</th>
<th>Annealing</th>
<th>Mean grain size, µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduction, %</td>
<td>Temperature, °C</td>
<td>Time, min</td>
</tr>
<tr>
<td>52</td>
<td>600</td>
<td>10</td>
</tr>
<tr>
<td>30</td>
<td>650</td>
<td>9</td>
</tr>
<tr>
<td>30</td>
<td>700</td>
<td>15</td>
</tr>
<tr>
<td>30</td>
<td>700</td>
<td>250</td>
</tr>
</tbody>
</table>
Figure 1- True stress-true strain curves of tensile test for different grain size of CP Ti.

Figure 2- Polarised micrograph after a strain of 10% for different grain sizes, a) 10 \( \mu m \), b) 20 \( \mu m \), c) 30 \( \mu m \) d) 70 \( \mu m \).

Figure 3 shows the effect of grain size on the number of twins per grain for two different strains. It is seen that the number of twins per grain increases with increasing grain size and strain. The same trend can be seen for the volume fraction of twins (figure 4).

Figure 3- Effect of grain size on the number of twins per grain.
Figure 4- Effect of grain size on the volume fraction of twins.

Figure 5 shows the effect of grain size on the average length and thickness of twins. It can be seen that the average length of twins is strongly dependent on the grain size while the average of thickness remains nearly constant with increasing grain size.

According to the literature $^{10,13}$, the most common twinning modes in α-Ti are \{10\overline{1}1\}, \{11\overline{2}1\}, \{10\overline{1}2\}, and \{11\overline{2}2\}. The frequency of different twin modes varies with temperature, grain size and mechanical load condition $^{10,13}$. In present study, the average number of twins per grain, volume fraction of twins, length and thickness of twins are measured regardless of the twin modes.

4 DISCUSSION

The results (Figures 3 and 4) verify the previous studies $^{1,5,8}$ which imply that twin activity increases with increasing grain size. In order to ascertain the twin activity in the bulk, the number of twins per unit volume, $N_{tv}$, can be estimated by the equation:

$$N_{tv} = N_{tgb} \cdot N_g$$  \hspace{1cm} (1)

Where $N_g$ is number of grains per unit volume and is estimated by the equation $^{14}$:

$$N_g = 0.57(d^{-3})$$  \hspace{1cm} (2)

Figure 6 illustrates the $N_t$ values, extracted from data in figure 3, against grain size. The results reveal that at the same amount of strain, the total number of twins in the fine grain sample is much higher than in the coarse grain sample, as previously pointed out $^{15}$. If we assume that each twin is an indicator of one twin nucleation, it can be concluded that in the fine grain material, the amount of twin nucleation is higher than in the coarse grain sample. This argument is consistent with the fact that the grain boundary area, which is a site of inhomogeneous twin nucleation, increases with decreasing grain size.

Although nucleation sites for deformation twinning increase with decreasing grain size, the local shear stress required for twin nucleation should be considered. Generally, it is stated that the local shear stress can be provided by a dislocation pile up $^8$ or some other stress localisation such as autocatalytic mechanism $^4$. However, we can assume that deformation twins mostly nucleate on the grain boundary. The number of twins per unit grain boundary area, $N_{tgb}$, can be extracted using the equation:
\[ N_{tgb} = \frac{1}{2} d \cdot N_{t_v} \] (3)

Where the \( 2/d \) is equal to the grain boundary area in per unit volume\(^{16}\). Figure 7 illustrates the relationship between number of twins per unit grain boundary area, \( N_{tgb} \), and the corresponding imposed stress. As can be seen, all points regardless of their strain and grain size appear to fall in one curve. As a result, it seems that twin nucleation on the grain boundary is independent of the grain size and is only determined by the stress. However, more data is required to completely explain the relationship between stress and nucleation of twins on grain boundary area. Work on this matter is in progress.

Both parameters which are important is the mean twin volume, \( v_t \). This value can be estimated by the equation:

\[ v_t = \frac{N_t}{N_{t_v}} \] (4)

Comparing data from figures 4 and 6 indicates that although the total number of twins decreases with increasing grain size, volume fraction increases. This behavior reveals that the mean twin volume, \( v_t \), increases with increasing grain size. Generally, it is assumed that the shape of a twin can be penny-like or oblate spheroidal.

\[ v_t = \frac{\pi}{4} t l^2 \] penny-like \( \sim \) Eq. 5

\[ v_t = \frac{\pi}{6} t l^2 \] oblate spheroidal \( \sim \) Eq. 6

Using data extracted from the average thickness and length of twins (figure 5), and employing different twin geometries, the mean twin volume can be estimated. It can be seen in figure 8 that although different methods for obtaining the mean twin volume give different values, all curves have the same trend and the difference can be considered as error of measurements. The \( v_t \) parameter can be considered as a twin growth indicator. Therefore it is possible to conclude that decreasing grain size prevents twin growth.

![Figure 7- Effect of stress on the number of twins per unit grain boundary area.](image)

![Figure 8- Effect of grain size on mean twin volume at a strain of 5%.](image)

5 CONCLUSIONS

1- Number of twins per unit grain boundary area in cold rolled and annealed CP Ti tested in tension appears to be only dependent on the imposed stress.
2- The mean twin volume decreases with decreasing grain size.
3- The net result is that the twin volume fraction increases with grain size.

REFERENCES

7. M.A. Meyers, U.R. Andrade and A.H. Chokshi,