THE EFFECT OF SLIP LENGTH AND SLIP CHARACTER ON THE PROPERTIES OF TITANIUM ALLOYS

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Introduction

The fracture-related mechanical properties of high strength aluminum, nickel, iron and titanium base alloys show a particularly strong dependence on deformation characteristics, two of which are slip character and slip length[1-3]. Such sensitivity is typically manifested by low tensile ductility and alterations in other properties such as fatigue life, fatigue crack propagation rate and fracture toughness. The purpose of this paper is to summarize the available data for binary Ti-Al α-phase alloys and for an α+β alloy Ti-6Al-4V, and then to analyze these data in terms of the role of slip character and slip length on such features as crack nucleation and crack propagation. The former of these features is measured by tensile ductility and fatigue life, whereas the latter of these is more appropriately measured in fracture toughness or fatigue crack propagation rate.

In this paper we will first describe the effects of composition and heat treatment on slip character in the α-phase of binary Ti-Al alloys and show how this pertains to the α-phase in α+β alloys. We will then discuss the effect of slip character and slip length on crack initiation in binary Ti-Al alloys. This will be followed by a discussion of the effect of the same factors on crack propagation, i.e. $K_{IC}$ and $da/dN$. Following this we will attempt to extend the discussion of the binary alloy systems to our understanding of the effect of slip length and slip character on the fracture behavior of the α+β alloy Ti-6Al-4V.

Slip Character and Slip Length

The principal parameters which affect the slip character of α-phase Ti-Al alloys are the aluminum concentration, the oxygen concentration and the grain size. Each of these factors will be discussed individually in this section. In addition, there is interaction between them and this also will be described.

It is well known that increasing aluminum concentrations alter the slip character in the α-phase. Such alterations initially start at ~2wt%Al where δ dislocations are seen to become straight and are of screw character. At higher Al contents the arrangement of these straight screw type dislocations becomes less uniform and they are eventually confined to very planar arrays at ~6%Al as shown in Figure 1[4]. This figure shows the dislocation arrangements in nominally 2, 4, and 6%Al alloys of relatively low oxygen concentration. From this, it can be seen that the most dramatic slip character transition occurs between 4 and 6%Al. It is worth mentioning that this transition

*All concentrations of chemical elements will be expressed at wt%.
also depends on oxygen content and, therefore, the exact aluminum concentra-
tion which corresponds to the slip character transition is somewhat variable. 
The planarity of slip in dilute Ti-Al alloys is caused by short range order 
in the α-phase. In the more concentrated alloys, the planar slip is more in-
tense and this is due to the presence of small, coherent, ordered α_{2}-particles 
which are based on the composition Ti₃Al[5,6]. It is important to emphasize 
that the planar slip in Ti-Al alloys is the result of a declining resolved 
 shear stress in the active slip planes, rather than any intrinsic change in 
the ability of screw dislocations to cross slip. This is in contrast to the 
situation in fcc alloys where increasing solute concentrations reduce the 
stripping fault energy and inhibit cross slip.

In addition to the effects of aluminum discussed above, increasing oxy-
gen concentrations also promote planar slip in the α-phase. This is shown in 
Figure 2 for α-phase alloys of .05 and .3wt% oxygen[7]. The reason for this 
effect of oxygen on slip character is somewhat less clear than for Al but 
also seems to be connected to ordering of the interstitial atoms in the 
α-phase lattice[8]. X-ray diffraction evidence for such ordering has been re-
ported elsewhere[9].

As mentioned earlier, Al and oxygen have an additive effect on slip 
character. These combined effects of oxygen and aluminum on the wavy to plan-
ner slip transition in the α-phase are interesting because this system seems 
to exhibit additive effects of substitutional and interstitial ordering. 
However, from an atom percent standpoint, the effect of oxygen is much strong-
er (~10 times) than that of aluminum.

The foregoing has shown that planar slip leads to relatively intense 
dislocation pile-ups. These pile-ups in turn lead to crack initiation, as 
shown in Fig. 3(a), (b)[10]. Fig. 3(a) shows a dislocation pile-up at a 
grain boundary in a Ti-8.6%Al alloy. Fig. 3(b) shows the shearing of the 
grain boundary and the consequent initiation of a crack. An analysis pre-
sented elsewhere[11] has shown that the local stress required to produce such 
a crack is essentially constant. It is this analysis which provides the 
central link between slip character, slip length and crack initiation. Thus, 
the important parameters which control the onset of fracture in α-phase 
alloys are those which control the slip character or slip planarity, i.e. 
aluminum and oxygen concentration, and those which control the pile-up 
length, i.e. grain size. It has been reported that the cracks shown in Fig. 
3(b) can propagate along slip bands or by cleavage[12,13]. If the disloca-
tion density within dislocation pile-ups is not high enough for propagation 
along these slip bands, the cracks tend to propagate along grain boundaries 
[12]. Fig. 3(c) shows a fracture surface in which some transgranular crack-
ing and some intergranular cracking has occurred.

Properties of Binary Ti-Al Alloys

1. Tensile ductility

We will now consider directly the effect of slip character on tensile ductility. Fig. 4 shows the dependence of fracture strain and fracture stress 
on the extent of age hardening in Ti-8.6%Al[10]. Here the alloy is aged for 
different times to produce varying amounts of ordered precipitates which con-
tral the slip planarity. This figure shows that the fracture stress and the 
fracture strain both fall as the aging time and thus the slip planarity in-
creases. However, analysis of the data indicates that these macroscopic 
values correspond to constant local fracture stresses due to internal stress
Figure 1: Dislocation arrangement after 3% deformation, (TEM), [4],
a) Ti-2.1%Al, b) Ti-4.0%Al, c) Ti-6.1%Al.

Figure 2: Dislocation arrangement after 3% deformation, (TEM), [7],
a) Ti-0.05% oxygen, b) Ti-0.5% oxygen.

Figure 3: Ti-8.6%Al, aged at 600°C, tensile tests [10],
a) Dislocation pile-up, (TEM).
b) Grain boundary cracking by dislocation pile-up, (TEM).
c) Fracture surface, (SEM).
intensification at dislocation pile-ups. The combined effects of oxygen and age hardening on the fracture of Ti-8.6%Al is shown in Fig. 5[14]. This figure shows that the fracture strain decreases substantially as the oxygen content is increased. There are two factors which are important here. First, increasing the oxygen increases the volume fraction of ordered Ti3Al-particles and result in further slip intensification. Second, oxygen also promotes planar slip in the matrix and, therefore, inhibits pile-up relaxation by slip band broadening due to cross slip between the particles, as mentioned earlier.

The previous examples have demonstrated the effect of slip character on tensile ductility under circumstances of constant slip length. Fig. 6 and 7 illustrate the effect of slip length on tensile ductility under circumstances of constant slip character[10]. From these figures it can be seen that the fracture strain increases as the inverse of the grain diameter (L^{-1}), whereas the fracture stress increases as the inverse sq. root of the grain diameter (L^{-1/2}). While it is generally recognized that there is a relationship between grain size and tensile ductility (εf), we would like to emphasize here that grain size also affects the fracture stress[15] as shown in Fig. 7.

2. Fatigue strength

The intense planar slip bands present in the Ti-Al alloys can lead to early fatigue crack initiation at sites where these planar bands intersect the specimen surface. Persistent slip bands are also formed in these alloys and these, too, can serve as crack nucleation sites. An example of the latter is shown in Fig. 8[16]. Thus the occurrence of planar slip can be detrimental to fatigue strength. However, it is also important to consider the stress at which dislocations begin to move. This is especially important since it is customary to compare the fatigue strength of alloys in terms of absolute stress. Factors which simultaneously increase the yield stress but decrease the slip homogeneity can change the fatigue strength in either direction, depending on which factor dominates. For example, the effect of aluminum content, especially in the presence of ordered precipitates, is to increase the yield stress of Ti-Al alloys but to decrease the slip homogeneity. Comparable results are observed when the oxygen content is increased.

In contrast, decreasing the grain size increases the yield stress and also increases the slip homogeneity due to a slip length reduction. Thus, decreasing the grain size always tends to improve the fatigue strength, whereas other factors which change the yield stress but decrease the slip homogeneity may have offsetting effects. The effect of grain size on fatigue strength of Ti-8.6%Al is shown in Fig. 9[16]. In the above connection we would point out that the yield stress probably dominates the fatigue performance of an alloy in the long life regime, whereas the slip character may be more important in the medium to short life regimes.

3. Fracture toughness

The effect of planar slip in Ti-Al alloys on crack propagation characteristics such as KIC is not particularly well understood. We suggest that the following trends may pertain.

As the aluminum content increases, particularly in the presence of ordered particles, the fracture toughness appears to decrease as has been reported previously[17]. The known effect of oxygen content on slip character and on tensile ductility suggests that higher oxygen alloys will also show lower toughness values. This view is supported by results on a binary Ti-Al alloy with varying oxygen level[18]. We have shown earlier that small grain
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Figure 4: Ti-8.6%Al, aged at 600°C, tensile tests[10]. Fracture stress and strain as a function of aging time.

Figure 5: Ti-7.8%Al, aged 200h at 695°C, tensile tests[14]. Fracture strain as a function of oxygen content.

Figure 6: Ti-8.6%Al, tensile tests[10]. Fracture strain as a function of grain size (L^{-1}).

Figure 7: Ti-8.6%Al, tensile tests[10]. Fracture stress as a function of grain size (L^{-1/2}).

Figure 8: Ti-8.6%Al, aged 10h at 500°C, fatigue crack nucleation mechanism, (SEM)[16].

Figure 9: Ti-8.6%Al, aged 10h at 500°C, S-N curves for two grain sizes[16].
sizes lead to improvements in tensile ductility. Therefore, we suggest that smaller grain sizes also lead to improvements in fracture toughness. In this connection, similar trends have been demonstrated in a relatively wide range of other alloy systems.

4. Fatigue crack propagation

The effect of slip character and slip length on fatigue crack propagation rate \((\frac{da}{dN})\) is quite different than the trends exhibited for the other properties described above. In general, inhomogeneous slip and large slip length tend to reduce the rate of crack propagation because of improved slip reversibility in the crack tip region\[19\]. This is particularly true in the low crack propagation rate regime where the plastic zone size is small and the tendency for crystallographic cracking is especially pronounced. Fig. 10 shows an extreme example of crystallographic cracking in a Ti-8.6%Al alloy\[20\]. Moreover, it has been shown elsewhere that the \(\Delta K_{th}\) values increase with increased age hardening and this has been explained by improved slip reversibility in the crack tip region\[16\]. No information has been generated regarding the role of oxygen content on \(\frac{da}{dN}\) in Ti-Al alloys. However, we speculate that, if the only role of oxygen is to increase the slip planarity, increasing oxygen should lead to lower crack propagation rates. The effect of grain size or slip length on crack propagation rate is shown in Fig. 11\[20\]. This figure shows that increasing grain size raises the \(\Delta K_{th}\) value and leads to a general reduction in \(\frac{da}{dN}\) over the entire range tested. The reason for this is thought to be the more inhomogeneous slip character associated with the larger grain size and, therefore, an improved slip reversibility.

Properties of Ti-6Al-4V

Although the constitution of this alloy is predominantly (~85%) \(\alpha\)-phase, the vanadium in this alloy results in stabilization of some of the bcc \(\beta\)-phase. As a result, the morphology and distribution of microstructural constituents can be manipulated through heat treatment and thermomechanical processing\[21\]. Two common microstructures which can be produced in this alloy are the equiaxed microstructure and the coarse lamellar microstructure. These are shown in Fig. 12(a) and (b)\[22\]. In these two microstructures, the slip length is controlled by the primary \(\alpha\) grain size in the equiaxed structure and by the \(\alpha\) plate size or colony dimension in the lamellar structure. Since the \(\alpha\)-phase in this alloy contains about 7% aluminum, it exhibits a planar slip character which can be intensified by increasing the oxygen content or by aging to precipitate ordered \(\alpha_2\)-particles. TEM examination after deformation shows that the slip bands in this alloy are blocked by the \(\alpha\) grain boundaries in the equiaxed microstructure and are partially blocked by the thin \(\beta\) lamellae in the lamellar microstructure. The fact that the slip bands in the lamellar microstructure cross more than one \(\alpha\) plate suggests that the effective slip length in this microstructure is greater than the individual \(\alpha\) plate width. Slip bands in both equiaxed and lamellar microstructures are shown in Fig. 13\[15,23\].

1. Tensile ductility

There are two principal factors which affect the tensile ductility of Ti-6-4. The first is aging to precipitate ordered particles which tend to intensify the planar slip character. The second is heat treatment which alters the microstructural geometry and, therefore, alters the effective slip length. In cases where the fracture is initiated at dislocation pile-ups by exceeding a critical local stress value, the planarity of slip and the slip length are
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Figure 10: Ti-8.6%Al, aged 10h at 500°C, fatigue crack propagation mechanism, (SEM),[20].

Figure 11: Ti-8.6%Al, aged 10h at 500°C, da/dN vs. ∆K curves for two grain sizes[20].

Figure 12: Coarse microstructures in Ti-6Al-4V, (LM),[26].
   a) Equiaxed, b) Lamellar.

Figure 13: Ti-6Al-4V, aged 24h at 500°C, dislocation pile-ups after tensile deformation, (TEM).
   a) Equiaxed, 0.2% deformed,[15].
   b) Lamellar, 1% deformed,[23].
directly related to ductility. Evidence has been obtained in Ti-6-4 to support this point of view because low ductilities are obtained in lamellar structures and these ductilities are even further degraded by aging and increase in oxygen level[21]. On the other hand, however, equiaxed microstructures show virtually no interdependence between ductility and aging history or variation in oxygen content between 0.08 and 0.20%[15,23]. The reason for this is that the pile-up length is always too short to exceed the fracture stress. In contrast to the equiaxed structures, a possible additional factor which contributes to the low tensile ductility in lamellar α+β alloys is the early initiation of fracture at α+β interfaces[24].

A comparison between the strength and fracture strain in equiaxed and lamellar microstructures can be seen in Table 1[25,26]. These data and the foregoing discussion suggest that equiaxed microstructures of short slip length can be strengthened to a significant degree without incurring significant losses of ductility.

2. Fatigue strength

The effect of slip length on fatigue life of Ti-6-4 has been discussed extensively in the literature and evidence can be found which suggests that refinement of the microstructure leads to substantial improvements in fatigue strength[21,27]. This view is consistent with the discussion presented earlier on the binary alloys. The effect of aging to further increase the yield stress and simultaneously intensify the planar slip is similar in this alloy to that described earlier for binary Ti-Al alloys. That is, aging can be beneficial to fatigue life but the effect depends on grain size. The effect of oxygen on fatigue strength is similar to that of aging and this is illustrated in Fig. 14[1]. This figure shows that the fatigue strength of fine lamellar structures with high oxygen are significantly better in the long life regime than are the lower oxygen materials. This effect is thought to reflect the effect of oxygen on yield stress and thus the fatigue strength is better in the regime which is dominated by yield stress. The effect of slip length under conditions of constant slip planarity is shown in Fig. 15[25,26]. This figure shows that shorter slip lengths lead to substantial improvements in fatigue strength both in equiaxed and lamellar microstructures.

3. Fracture toughness

The effect of microstructure on the fracture toughness of Ti-6-4 is complicated by a major change in fracture path between equiaxed and lamellar microstructures. There is evidence which suggests that this factor outweighs the effects of slip length or slip character on fracture toughness[21]. As a result, the role of slip length or slip character can only be discussed within a single class of microstructures. However, the factors which promote more intense planar slip, such as aging or increasing oxygen, tend to reduce the fracture toughness[18]. There is presently no clear-cut evidence to indicate what role grain size has on the fracture toughness of equiaxed microstructures in this alloy. The limited data available are complicated by lack of accompanying data on other important factors, such as texture. In the lamellar microstructures, it is interesting to note that fine structures show lower toughness values than coarse structures[28]. One possible explanation for this is additional variations in fracture path, for example, along prior β-grain boundaries for the fine lamellar structure.

4. Fatigue crack propagation

The effect of aging and oxygen content on the fatigue crack propagation rate in this alloy have not been extensively studied. However, limited evi-
Figure 14: Ti-6Al-4V, fine lamellar structure, aged 24h at 500°C, S-N curves for different oxygen content, [1].

Figure 15: Ti-6Al-4V, aged 24h at 500°C, S-N curves for different microstructures,[25,26].

Figure 16: Ti-6Al-4V, aged 24h at 500°C, da/dN vs. ΔK curves for different microstructures,[25,26].

Table 1: Yield stress and tensile ductility of Ti-6Al-4V aged 24h at 500°C[26]

<table>
<thead>
<tr>
<th>Microstructure</th>
<th>$\sigma_{0.2}$ (MPa)</th>
<th>$\varepsilon_F$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine grained (2µm) equiaxed</td>
<td>1120</td>
<td>0.70</td>
</tr>
<tr>
<td>Coarse grained (12µm) equiaxed</td>
<td>1030</td>
<td>0.55</td>
</tr>
<tr>
<td>Fine lamellar (β-quenched)</td>
<td>985</td>
<td>0.26</td>
</tr>
<tr>
<td>Coarse lamellar (β-slow cooled)</td>
<td>945</td>
<td>0.17</td>
</tr>
</tbody>
</table>
dence suggests that slow cooling (comparable to aging) and increasing oxygen [21] both lead to accelerated crack growth rates. It should be mentioned, however, that these data have been gathered in laboratory air tests or in more aggressive environments and, therefore, may reflect an additional environment effect, rather than an intrinsic effect on fatigue crack propagation rate. In this connection, it is noted that, although environmental effects have not been discussed here, they had been shown to be very important, especially in long duration tests such as fatigue strength or fatigue crack propagation rate[25].

The effect of microstructural scale or slip length is shown in Fig. 16 which shows that refinement of the microstructure in both equiaxed and lamellar structures tends to accelerate the fatigue crack growth rate and lead to lower ΔK threshold values[25,26]. Moreover, lamellar structures consistently show lower fatigue crack growth rates and higher ΔK threshold values than equiaxed structures. Some convergence of these data can be produced by correcting for the respective modulus values but one is still left with the conclusion that lamellar structures are superior with respect to fatigue crack growth rate. The principal difference between equiaxed and lamellar microstructures in fatigue crack growth rate is a strong tendency for crack branching in the case of the latter[28]. In addition, some differences in slip reversibility would be expected as a function of grain size (slip length). Both of these factors operate in parallel to help account for the superior crack growth rate characteristics of coarse lamellar microstructures.

Summary and Conclusions

In this paper we have summarized the available evidence and shown that fine grain size, i.e. slip length, improves the tensile ductility and fatigue strength of binary titanium aluminum alloys and of α+β alloys which are predominantly α-phase. Moreover, we have shown that, if the slip length is short enough, the yield stress can be increased significantly by aging or by increasing the oxygen content without seriously degrading these properties. However, it should be emphasized that the beneficial effects of reduced grain size do not carry over into fatigue crack propagation rate. Thus, the manipulation of microstructure to optimize properties must be done with a particular limiting property in mind.

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