THE EFFECT OF MICROSTRUCTURE ON FRACTURE OF A NEW HIGH TOUGHNESS TITANIUM ALLOY


INTRODUCTION

The design requirements for current and near-future high performance, lightweight aircraft has emphasized the need for titanium alloys with strength-toughness combinations exceeding those presently available in alloys such as Ti-6Al-4V. This paper briefly describes the development of such an alloy and discusses methods of controlling the fracture properties of the alloy through manipulation of microstructure by thermomechanical processing and heat treatment.

The alloy, Ti-4.5Al-5Mo-1.5Cr (CORONA-5), was developed under Naval Air Systems Command sponsorship [1,2] to meet a fracture toughness goal of 110 MPa.m$^{1/2}$ at a minimum ultimate tensile strength of 930 MPa. During the first year of the program, studies were conducted to select the alloy composition, and during the second year the effect of processing on microstructure and fracture properties was investigated. Results of this study showed that fracture properties could be significantly affected by microstructural features such as α-phase along prior β grain boundaries and by α-phase size, distribution and morphology. The remainder of this paper will describe some of the microstructures achieved by using various thermomechanical processing sequences and the effect of these microstructures on fracture properties.

RESULTS

The results will be divided into two sections. The first describes the variations of microstructure and the second describes the effect of microstructure on fracture toughness and fracture topography.

Microstructure

CORONA-5 is a two phase, α + β titanium alloy which exhibits a duplex microstructure. The microstructure consists of relatively coarse primary α and finer precipitated α. The volume fraction, size and morphology of the primary α is dependent on prior forging history, whereas the spacing and volume fraction of the precipitated α depends largely on the post-forging heat treatment. The morphology and distribution of the primary α appears to influence the fracture path to a predominant degree while the precipitated α largely controls the strength of the alloy. Examples of these two microstructural variables will be illustrated below.

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of other high strength titanium alloys, such as Ti-6Al-4V, Ti-6242, and Ti-64 [4].

A tortuous fracture path which is caused by microstructural features of a different scale is achieved in the high αβ-forged material, Figure 3(b). This path results from the high aspect ratio of the primary α, Figure 3(1b). The elongated α particles provide preferential crack paths either along the major axis of the particle or at the interface between the particle and the β matrix. In addition, remnant grain boundary α may provide a preferential path as it does in the β-forged material. These preferential crack paths lead to crack branching and to secondary cracking similar to that in the β-forged material, but on a finer scale, of Figure 3(b) and 3(a). Comparing the data for the low αβ-forged material with that of the high αβ-forged material, indicates that as the primary α particle aspect ratio is reduced, the fracture toughness decreases significantly. This decrease in fracture toughness is accompanied by a fracture which is characterized by a flat, smooth fracture face comprised of small, equiaxed dimples, Figure 3(c). In titanium alloys, this type of fracture is often associated with low toughness/high strength conditions, especially in higher strength alloys [4].

Since either prior β grain boundaries or high aspect ratio primary α provide a more tortuous fracture path and thereby enhance toughness to a similar degree, considerable latitude is available for microstructural control of fracture properties. This would permit use of an αβ-forged condition with high aspect ratio primary α in those situations in which a β-processed microstructure might degrade other significant properties. Finally, it should be noted that several of the ultimate strength values reported in Table I are 2-3% below the goal value; experience from previous work [2] has shown that minor adjustments of the final heat treatment will permit achievement of goal strength at toughnesses in excess of goal toughness.

CONCLUSIONS

It has been shown that the microstructure of CORONA-forged Ti-6Al-4V can be significantly altered by thermo-mechanical processing and heat treatment, and that the microstructures produced affect fracture properties. Specifically, finish forging above the beta transus results in a coarse Widmanstätten α, while finishing below the beta transus results in a primary α aspect ratio directly related to the temperature (below the beta transus) to which the alloy is exposed; i.e., the higher the forging temperature (either blocking or finishing), the greater will be the primary α aspect ratio. The microstructures that were developed do not affect the fracture toughness of these forgings on three distinct scales:

1. Large, equiaxed prior β grains of the β-processed conditions promote crack branching and enhance toughness.
2. Primary α particles with large aspect ratios provide more tortuous crack paths with an attendant toughness increase, while equiaxed primary α provides a lower energy fracture path, since the fracture can propagate in an almost planar manner.
3. The α phase precipitated in the retained β during final anneal and aging can promote strength at the expense of toughness (fine α from a low temperature anneal and age) or toughness at the expense of strength (coarse α from a high temperature anneal and age). The effect probably results from a localized effect of the precipitate on yield strength and thereby toughness.
In summary, manipulation of processing parameters to produce β or α/β structures, to affect primary α aspect ratios, and to affect α precipitation in the retained β provides strong methods for tailoring toughness and strength properties in CORONA-5.

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REFERENCES


Table 1 Mechanical Properties of CORONA-5

<table>
<thead>
<tr>
<th>Forging No.</th>
<th>Microstructural Condition</th>
<th>Final Heat Treatment</th>
<th>0.2% Offset Yield Stress MPa</th>
<th>Ultimate Tensile Strength MPa</th>
<th>Fracture Toughness MPam²</th>
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<tbody>
<tr>
<td>1</td>
<td>β Forged</td>
<td>High¹</td>
<td>910</td>
<td>911</td>
<td>151</td>
</tr>
<tr>
<td>2</td>
<td>β Forged</td>
<td>Low²</td>
<td>891</td>
<td>991</td>
<td>112</td>
</tr>
<tr>
<td>3</td>
<td>High α/β Forged</td>
<td>High¹</td>
<td>828</td>
<td>903</td>
<td>144</td>
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<tr>
<td>4</td>
<td>Low α/β Forged</td>
<td>High¹</td>
<td>846</td>
<td>906</td>
<td>109</td>
</tr>
</tbody>
</table>

1. 843°C/8 hr + air cool + 704°C/4 hr + air cool
2. 802°C/16 hr + air cool + 607°C/4 hr + air cool

Figure 1 Light Micrographs Illustrating the Effect of Forging on Microstructure:
(a) β-Forced
(b) High α/β-Forced
(c) Low α/β-Forced

198
Figure 2  Transmission Electron Micrographs Illustrating the Effect of Final Heat Treatment on β-Forged Material:
(a) Coarse α-Phase Particles Precipitated During High Final Treatment
(b) and (c) Fine α-Phase Particles Precipitated During Low Final Treatment

Figure 3  Scanning Electron Fractographs of:
(a) TL Specimen from β-Forged Material
(b) TL Specimen from High α/β-Forged Material
(c) TL Specimen from Low α/β-Forged Material