Observations on Microstructurally Sensitive Fatigue Crack Growth in a Widmanstätten Ti-6Al-4V Alloy

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Fatigue crack growth rates in commercial purity Ti-6Al-4V can be substantially reduced with a beta anneal from levels associated with the mill anneal, owing primarily to crystallographic crack bifurcation in the Widmanstätten packets. This microstructurally sensitive fatigue crack growth occurs when the reversed plastic zone is less than the packet size and results in a fracture surface with a faceted morphology. It appears from replica and scanning electron microscopic examination that the facets are comprised of three superposed features, viz cleavage-like river-line patterns, very fine striations and traces of slip lines (and slip-band cracks). Limited X-ray evidence suggests a facet orientation some 8 to 10 degrees off the basal plane.

The influence of microstructure upon the fatigue crack growth rates in Ti-6Al-4V is not well understood. Moreover, the limited data available on this subject seem to be in considerable disagreement. For example, consider what appears to be a contradiction between two papers published in 1974 with regard to the effect of a beta anneal on the Region 2 fatigue crack growth rates. On the one hand, Ref. 1 reported a five-fold reduction in growth rates relative to those associated with the conventional mill-annealed microstructure of an α/β-rolled plate, viz, for stress-intensity ranges, 13 < ∆K < 30 MPa·m$^{1/2}$. On the other hand, Ref. 2 reported no effect for ∆K < 12 MPa·m$^{1/2}$, although the reported alloy chemistry and microstructures associated with the mill anneal and beta anneal appear comparable to those given in Ref. 1. More recent work reported in Ref. 3 tends to agree with the former result, while that in Ref. 4 tends to support the latter. Though texture can influence fatigue crack growth in titanium alloys, the disparity in results from these four studies is not clearly attributable to differences in preferred orientation. In fact, the two papers which contain basal pole figures, viz Refs. 1 and 4, indicate very similar transverse textures for the respective α/β processed, mill-annealed materials; yet, the contrasting results from these studies were obtained with the same crack orientation (LT).

In an attempt to elucidate this seemingly discrepant behavior, a study of fatigue crack growth in Widmanstätten Ti-6Al-4V of commercial purity was initiated as part of a more extensive program at NRL to metallurgically optimize the crack tolerance properties of titanium alloys. As reported herein, our work indicates a substantial reduction in fatigue crack growth rates associated with a beta anneal, owing primarily to a sharply defined transition to microstructurally sensitive crack growth with a faceted morphology. This crack growth appears to be more complex than that described in a recent, comprehensive survey of the faceted mode of fatigue crack growth, as well as elsewhere. The structure-sensitive crack growth has been examined by replica and scanning electron fractography, metallographic crack-path sectioning and by Laue back-reflection X-ray photography. A straightforward continuum mechanics analysis supports experimental evidence that the Widmanstätten packet is of key importance to the appearance of the structure-sensitive crack growth and the reduced growth rates.

EXPERIMENTAL PROCEDURES

The alloy studied was received in the form of 25.4 mm thick α/β-rolled plate with the composition: Ti-6.7 pct Al, 4.3 pct V, 0.10 pct Fe, 0.20 pct O, 0.03 pct C, 0.011 pct N, and 0.006 pct H. This alloy was studied in microstructural conditions which correspond to the original mill anneal (1 h at 788°C, air cool) and a subsequent beta anneal (0.5 h at 1038°C, cooled to RT + 2 h at 732°C, cooled to RT). The beta anneal was performed in a vacuum furnace; cooling was done in a helium atmosphere at a rate which approximates that in air. Metallographic samples were etched with Kroll’s reagent. For fractographic studies, two-stage, platinum-shadowed, plastic-carbon replicas were employed to supplement the results from scanning electron microscopy. Facet orientations were determined with the X-ray back-reflection Laue technique and apparatus described in Ref. 12.

Determinations of crack growth rates were made from 25.4 mm thick compact tension specimens of the configuration depicted in Fig. 1 and stress-intensity calibration,

$$K_I = \frac{P\sqrt{a}}{BW} \left[ 30.96 - 195.8 \left( \frac{a}{W} \right) + 730.6 \left( \frac{a}{W} \right)^2 - 1186.3 \left( \frac{a}{W} \right)^3 + 754.6 \left( \frac{a}{W} \right)^4 \right]$$

where $P = load$, $a = crack length$, $B = thickness$, and $W = width (64.8 \text{ mm})$. Specimens were loaded on a 490 kN capacity closed-loop hydraulic test machine in ambient laboratory air. For each heat treatment, duplicate specimens were subjected to cyclic tension-to-tension loading with a haversine waveform, a frequency of 5 Hz and a load ratio of $R = P_{\min}/P_{\max} = 0.1$. The amplitude of loading, while maintained at a constant level throughout the growth rate test of each specimen,
RESULTS AND ANALYSIS

A. Cyclic Crack Growth Behavior

The microstructures which correspond to the mill anneal and beta anneal are shown in Fig. 2. For each of these, fatigue crack growth rates \( (\frac{da}{dN}) \) are plotted logarithmically in Fig. 3 as a function of stress-intensity range. These data indicate that a much enhanced resistance to fatigue crack growth is associated with the beta anneal, owing primarily to a transition \( (T) \) which occurs at \( \Delta K = 23 \text{ MPa} \cdot \text{m}^{1/2} \). At this point, the exponent in the growth rate law, \( da/dN = C(\Delta K)^m \) changes from \( m = 3.1 \) above to \( m = 6.3 \) below. Consequently, growth rates below the transition are reduced by as much as an order of magnitude from those for the mill anneal. Immediately above the transition, growth rates are about a factor of three less for the beta anneal. For comparison, the Region 2 exponent for the mill anneal is \( m = 3.6 \).

The concomitant differences in fracture toughness and tensile properties associated with the two microstructures are given in Table I. Note that the beta anneal serves to double the fracture toughness (to a level of \( K_{IC} = 87 \text{ MPa} \cdot \text{m}^{1/2} \)), although the yield strength is somewhat less than for the mill anneal (6 and 14 pct for the L and T directions, respectively). Surfaces of the fracture toughness specimens indicate a small degree of crack front curvature, such that the average crack length measured by ASTM Method E399-74 ex-

was different for each of the paired specimens so that crack growth rate data could be generated over different, yet overlapping, ranges of \( \Delta K \). With the first specimen, growth rate data were obtained between \( 0.26 \leq a/W \leq 0.53 \); subsequently, the plane strain fracture toughness \( (K_{IC}) \) was determined in accord with ASTM Method E399-74. With the second specimen, cycled at the higher loading amplitude, crack growth rate data were obtained over the range, \( 0.26 < a/W < 0.62 \). Measurements of crack length were made optically at 15 times with a Gaertner travelling microscope. Tensile properties were obtained from standard 12.8 mm diam specimens of 50.8 mm gage length. Fatigue crack growth rates and the fracture toughness were determined for the \( TL \) orientation, while tensile properties were obtained for both the \( T \) and \( L \) directions.\(^{11} \)