EFFECTS OF FIBRE VOLUME FRACTION ON FATIGUE CRACK GROWTH IN TITANIUM METAL MATRIX COMPOSITES

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Fatigue crack growth from a through thickness notch has been considered at ambient temperature in 8 ply Ti-6Al-4V alloy matrix composites, uniformly reinforced with volume fractions of 12, 24 and 35% continuous SiC monofilament fibres.

The effects of varying the volume fraction of fibres, on the fatigue crack growth resistance of these composites, have been illustrated at a stress ratio of 0.1. Increased crack growth resistance and higher crack arrest limits have been observed as the volume fraction of reinforcing fibres in the composite is increased. A simple model for predicting crack arrest limits in such composites as a function of fibre volume fraction is presented. The potential deleterious effect of increased fibre volume fraction on the resistance to transverse damage in clad selectively reinforced testpieces is also outlined briefly.

INTRODUCTION

Titanium metal matrix composites have been the subject of much research interest within the aerospace industry for a number of years. During this time, attention has been focused on the defect tolerance and resistance to fatigue crack growth of these materials, since components are likely to operate under high stresses. Fatigue crack growth studies on uniformly reinforced titanium alloys have illustrated the presence of dominant mode I cracks and the phenomenon of fibre bridging of these cracks in the crack wake (1) . This may give rise to excellent fatigue crack growth resistance. However, to date effects of varying the reinforcing volume fraction on the fatigue crack growth resistance of such composites have not been investigated systematically.

In addition, in this present paper this behaviour has been compared briefly to that of selectively reinforced clad composites. These have been investigated as a function of volume fraction previously (**2**). In practice components might be expected to include such a monolithic surface layer to facilitate the joining of components and to aid assembly.

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EXPERIMENTAL

The materials used in this present study were Ti-6Al-4V alloy composite plates which had been uniformly reinforced throughout with unidirectional 8 ply Sigma (SM1140+) SiC fibres, to produce nominal volume fractions of 12 and 24%. The plates were produced by DRA (Sigma) from a lay-up of Ti-6Al-4V foils and mats of Sigma fibres as appropriate, before consolidation in a single stage HIPping process.

Testpieces were machined from the as received plate using electro -discharge machining (EDM). The testpiece dimensions for the composites with fibre volume fractions of 12 and 24%, were approximately (2.7 x 4.5 x 75) mm^3 and (1.75 x 4.5 x 75) mm^3 respectively. All tests were performed using single edge notched specimens such that $a_o/W = 0.25$ and were loaded in a three point bending configuration using a total loading span of 60 mm. An Instron servo-hydraulic testing machine, fitted with a 10 kN load cell was used to perform the tests which were all carried out at room temperature, with an R ratio of 0.1 [where $R = P_{min}/P_{max}$ and P_{min}, P_{max} are the minimum and maximum loads applied during the fatigue cycle respectively]and a cyclic frequency of 10 Hz . Although the load range, ΔP, remained constant throughout each test, different initial stress intensity ranges were used to determine the levels that would permit crack arrest in each volume fraction.

Fatigue crack propagation was monitored by means of a direct current potential difference technique (3). Acoustic emission was used on most of the uniformly reinforced composites to identify and monitor fibre failure throughout the tests (4).

RESULTS AND DISCUSSION

Figure 1. shows the fatigue crack growth resistance of a 12% volume fraction composite for a stress ratio $R = 0.1$, $\upsilon = 10$ Hz at three different load ranges, ΔP, 108,123, and 150N. These correspond to initial ΔK_{app} values of 10.3, 12.1 and 14.1 MPa√m respectively (calculated assuming that the initial cut notch length can be treated as a sharp crack). It can be seen as the applied stress intensity increases from the initial ΔK_{app} value of 14.1 MPa√m, that crack growth rates decrease slightly after an initial increase, before increasing rapidly until catastrophic failure in the specimen at an applied nominal ΔK of approximately 32 MPa√m.

Decreasing the initial nominal ΔK_{app} values from 14.1 to 12.1 and to 10.3 MPa√m, results in lower crack growth rates and da/dN is then observed to decrease gradually, despite increases in nominal ΔK_{app} as the crack length increases. During the test where the initial applied ΔK value was 10.3 MPa√m, crack growth rates decreased under these circumstances, to such a rate as to be considered to have arrested (defined here as $da/dN \leq 2 \times 10^{-8}$ mm/cycle). These observations are attributed to a reduction in the effective stress intensity range, ΔK, at the crack tip. This "crack tip shielding" arises from the bridging of intact fibres in the crack wake, and is consistent with the reduction in crack growth rates observed. Figure 1 also includes data from a test on a monolithic testpiece, produced by the same foil route, for an R ratio of 0.1(1). Under the test conditions employed here, at nominal ΔK values between 13 and 17 MPa√m, the growth rates from the monolithic alloy and the 12% volume fraction composites are very similar. This reflects that during the initial stages of testing, it is unlikely the growing crack will have encountered any intact fibres in the composites, thus eliminating any opportunity for crack bridging, and hence giving results broadly consistent with the monolithic alloy.

At an initial applied stress intensity range, ΔK_{app} of 14.1 MPa√m acoustic emission data recorded a large number of fibre failures throughout the test, but the majority occurred immediately prior to catastrophic failure. In contrast, only one fibre failure was recorded during the initial stages of the test carried out with an initial ΔK_{app} value of 10.3 MPa√m, which eventually arrested. It has been reported elsewhere (5) that crack arrest is likely in specimens where no or few fibres fail in the crack wake, and is a result of bridging fibre tractions reducing the effective ΔK values to below threshold levels for the particular matrix alloy.

Figure 2 shows a series of fatigue crack growth resistance curves for a 24% volume fraction composite, at five different load ranges, ΔP, 105,106,120,127 and 135 N. These correspond to initial ΔK_{app} values of 16, 16.1, 18.1, 19.3 and 20.1 MPa√m respectively. For an initial ΔK_{app} of 20.1 MPa√m, the fatigue crack growth rates, da/dN, increase with increasing crack length (i.e.the nominal ΔK_{app} is increasing) until catastrophic failure occurs at a relatively low number of cycles, i.e. 18000 cycles. The effect of decreasing the nominal ΔK_{app} values to 19.3 and 18.1 MPa√m, is to reduce the crack growth rates observed progressively. These growth rates then decrease for some time, until a sudden increase immediately prior to failure; consequently the number of cycles to failure increases dramatically; for instance the number of cycles to failure for an initial ΔK_{app} of 19.3 MPa√m is 340,000. Acoustic emission data from this test established that large numbers of fibres failed, in the final stages of the test before failure. At an initial ΔK_{app} value of 16 MPa√m, the growth rates decreased continually until the crack arrested. Acoustic emission data recorded only two fibre failures, and these occured during the first few thousand cycles of the test.

Contrasting figures 1 and 2, the most noticeable difference is that crack arrest will occur in the 24% volume fraction composite at higher initial ΔK_{app} values than in the 12% composite. The effects of varying the reinforcing fibre volume fraction on fatigue crack growth resistance are summarised in Table 1, this also compares these present results with those obtained for a similar composite with a nominal reinforcing volume fraction of 35% (6). It is possible to see that as the volume fraction of reinforcing fibres increases from 12 to 24 and 35% in these composites, the nominal ΔK that may be applied without causing catastrophic failure increases and this is a direct result of increasing the reinforcing volume fraction; a growing crack will ideally sample twice the number of fibres in the 24% volume fraction composite than in the 12% volume fraction composite *for the same absolute increment of matrix crack extension..*

It can be seen that in reducing the fibre volume fraction by approximately one third, from 35% to 24% and then to 12%, that the initial ΔK values at which crack arrest will occur also decrease, from 25 to 16 and to 10 MPa√m respectively. This trend does not appear to follow a directly proportional reduction. However, if we consider the data for the monolithic alloy alone, shown in figures 1 and 2, it can be

TABLE 1 - Comparison of Fatigue Crack Growth Resistance for Ti-6Al-4V/Sigma Composites with varying Fibre Volume Fractions.

Volume Fraction (%)	Nominal Initial ΔK (MPa√m)	Crack Growth Resistance
12	10.3	Arrest
12	12.1	Near Arrest
12	14.1	Failure
24	16.1	Arrest
24	18.1	Near Arrest
24	19.3	Failure
35	22	Arrest
35	25	Arrest
35	27	Failure

seen that this has a threshold stress intensity of approximately 4 MPa√m, so the composite can be considered to have an intrinsic fatigue crack growth resistance of 4 MPa√m, contributed by the matrix. In the case of a 35% volume fraction composite the extrinsic crack growth resistance contributed by 35% fibres may then be deduced to be only 21 MPa√m i.e. (25 - 4) MPa√m. The 12 and 24% volume fraction composites could subsequently be considered in terms of their extrinsic components of crack growth resistance, determined by the relative fraction of reinforcing fibres in each case. It would then be possible to predict the initial ΔK values at which crack arrest would occur from the experimental data for the 35% volume fraction composite, using the following relationship:

$$\Delta K = \left[\frac{V_f\%}{35} x (\Delta K_{35\%} - \Delta K_{\text{threshold}}) \right] + \Delta K_{\text{threshold}}$$

Where ΔK is the predicted initial ΔK value at which crack arrest will occur; $V_f\%$ is the volume fraction of fibres in the composite whose crack growth resistance is to be predicted; $\Delta K_{35\%}$ is the initial ΔK value at which crack arrest will occur in the 35% volume fraction composite and $\Delta K_{\text{threshold}}$ the initial ΔK value at which crack arrest will occur in the monolithic Ti-6Al-4V alloy.

In this fashion the 24% volume fraction fibre reinforced composite would be predicted to arrest if an initial ΔK value of 18 MPa√m was applied and a 12% volume fraction fibre reinforced composite would be expected to arrest if and initial ΔK of 11 MPa√m was applied.These predictions are closely similar to the experimental results (see Table 1). For the purposes of designing with these materials, it would now seem to be possible to predict the ΔK values at which crack arrest would occur in any uniformly reinforced SM1140+ composite, provided the volume fraction is known accurately.

Fatigue crack growth studies on selectively reinforced Ti-6Al-4V composites, with a fibre volume fraction of 37% and monolithic cladding, have highlighted the problem of transverse fatigue damage along the fibre-matrix interface and premature catastrophic failure before the growing mode I crack reaches the reinforced region (7). It has also been observed in such materials that reducing the reinforcing volume fraction to 27 and 14%, in the central composite region, increases the composites' resistance to transverse fatigue crack growth (3).

Transverse damage along the fibre-matrix interfaces is still observed but in these cases is not catastrophic. In the 14% volume fraction composite this transverse fatigue damage does not initiate ahead of the growing mode I crack, and mode I fatigue damage will also sometimes extend into the reinforced region. Most importantly, these composites do not exhibit the same trend for increased fatigue crack growth resistance with increasing volume fraction, seen in the uniformly reinforced composites. The 27% volume fraction clad composite could not be cycled beyond 44,000 cycles, at an initial nominal ΔK of 10 MPa√m. Whereas, under the same ΔK conditions the 14% volume fraction material was cycled for over 80,000 cycles. This highlights some of the complex issues that may have to be addressed in designing real components using such composites .

CONCLUSIONS

The fatigue crack growth resistance of Ti-6Al-4V alloy matrix composites, reinforced unidirectionally with 12 and 24% volume fraction of Sigma (SM1140+) fibres has been studied, and a simple model to predict crack arrest limits developed. The fatigue crack growth resistance of these composites is markedly superior to that of the unreinforced alloy at room temperature and at a stress ratio of 0.1. This fatigue crack growth resistance increases, as the volume fraction of reinforcement is increased from 12 to 24%, and is attributed to the additional fibre bridging which is possible in the higher volume fraction composite. Acoustic emission has been used to determine the onset of fibre failure in these composites. Although the fatigue crack growth resistance of uniformly reinforced composites increases with increases in volume fraction, a comparison with selectively reinforced, clad testpieces suggests that in these composites decreasing the volume fraction of reinforcing fibres from 14 to 27 and to 37% provide better resistance to fatigue crack growth.

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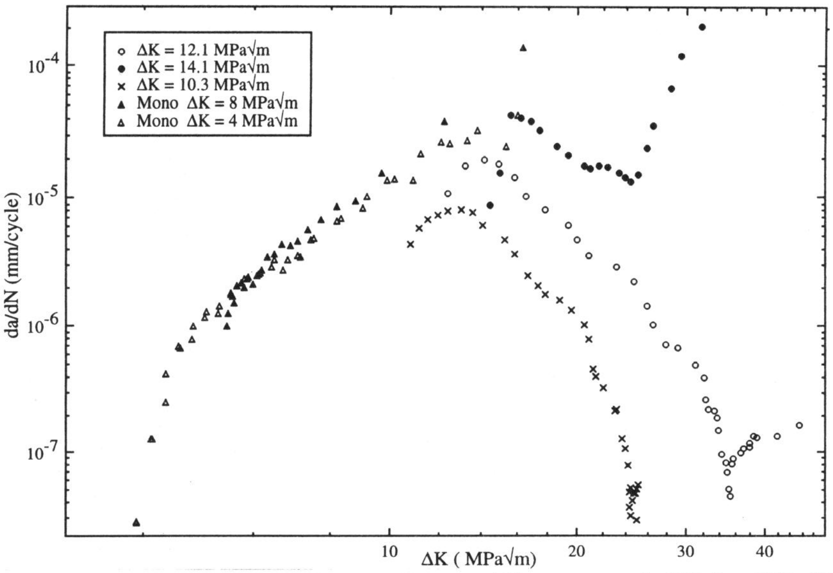

Figure 1 Crack Growth Resistance Curves: ΔKapp vesus da/dN for 12% Vf Uniformly Reinforced Ti-6Al-4V Composites and monolithic Ti-6Al-4V alloy.

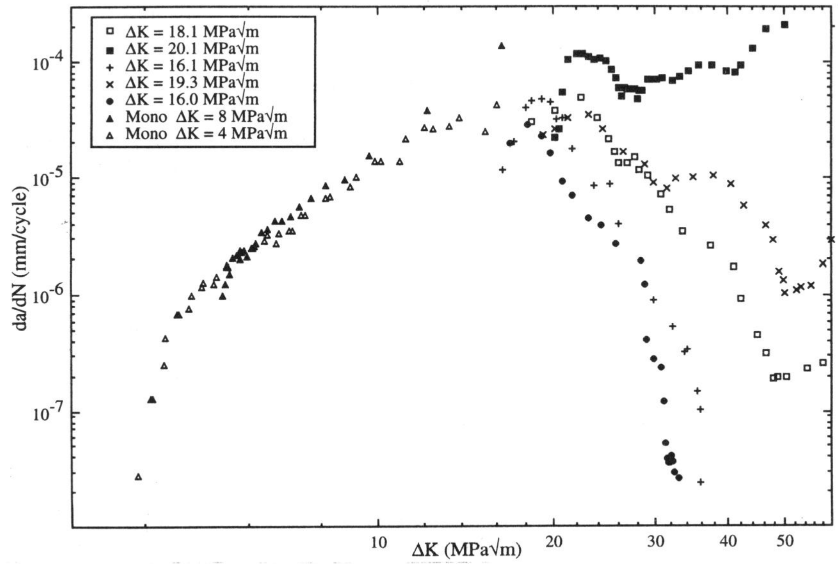

Figure 2 Crack Growth Resistance Curves: ΔK_{app} vesus da/dN for 24% V_f Uniformly Reinforced Ti-6Al-4V Composites and monolithic Ti-6Al-4V alloy.