Mixed-mode fracture characteristics of a laminated metal matrix composite

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In this study, the fracture behavior of a laminated composite, composed of layers of metal matrix composite having 20 vol% particulate SiC and 2014-aluminum matrix and 6061-aluminum as the ductile layers, was investigated under mixed-mode (mode-I and mode-II) loading. The results indicate that the increase in the fracture toughness of the metal matrix composite due to lamination with more ductile 6061-aluminum under pure mode-I loading condition diminishes significantly with increasing load-mixity. The interfacial behavior of the layers is shown to be the reason for this reduction in the fracture toughness values. The predicted growth directions of the cracks during the fast fracture agree reasonable well with experimental observations, in spite of the laminated microstructure of the composite.

1. Introduction

It is generally recognized that fracture properties (e.g., fracture toughness, fatigue crack growth resistance and impact resistance) of metal matrix composites can be improved using both intrinsic and extrinsic mechanisms. Intrinsic mechanisms involve close control of the microstructure such as grain and particle size, reinforcement shape and distribution of reinforcements in the composite microstructure. In contrast, extrinsic mechanisms aim at to reduce the driving force ahead of the crack tip in the material by shielding the crack tip from applied stress intensity factor through various processes. Previous studies on discontinuously reinforced metal matrix composites [1–6] have shown the possibility of marked improvements in fracture resistance by producing laminate structures having alternating layers of ductile metal and discontinuously reinforced composite. For this extrinsic toughening mechanism, two crack propagation orientations have been studied in these investigations under mode-I loading conditions: crack-arrestor orientation, wherein the crack plane intersects perpendicular to the laminate interfaces; and crack-divider orientation, in which crack extension may take place simultaneously in all layers.

Crack propagation in the crack-divider orientation may be most probable in plates or sheet products that are predominantly loaded under complex loading conditions. The approach of fracture mechanics has concentrated mainly on mode-I (i.e. pure tensile opening of crack faces); the effects of mixed-loading on the fracture behavior of these engineered materials have not yet been fully explored.

In this study, the fracture behavior of laminated metal matrix composites under mixed-loading conditions (mode-I and mode-II) is investigated and the resulting fracture toughness values are correlated with the fractographic studies.

2. Experimental procedures

Laminated composite having 20 vol%SiC particulate reinforced 2014-aluminum matrix composite as the hard layers and 6061-aluminum alloy as the soft layers with stacking sequence as shown in Fig. 1 was produced by roll bonding. The metal matrix composite was produced by powder metallurgy routes by DWA Inc and received as plate having thickness of about 3.2 mm. The initial thickness of the commercial grade 6061-aluminum alloy was 6.3 mm. Each layer was polished to 400 grid, then chemically cleaned. Stacks were inserted into a stainless-steel container with wall thickness of 3 mm. The rolling was carried out at 475 °C and billets were reduced to give 3.6 mm thick-laminated composite. After rolling, the stainless-steel container was removed by surface machining.

For the mixed-mode fracture toughness tests, the loading fixture and sample geometry shown in Fig. 2 was utilized. The mode-I and mode-II components of the stress intensity factor acting on the crack tip can be calculated from:

$$K_I = \frac{F\sqrt{\pi a}}{WB}\frac{\cos\alpha}{\left(1-\frac{a}{W}\right)} \times \sqrt{\frac{0.26+2.65\frac{a}{W-a}}{1+0.55\frac{a}{W-a}-0.08\left(\frac{a}{W-a}\right)^2}}$$

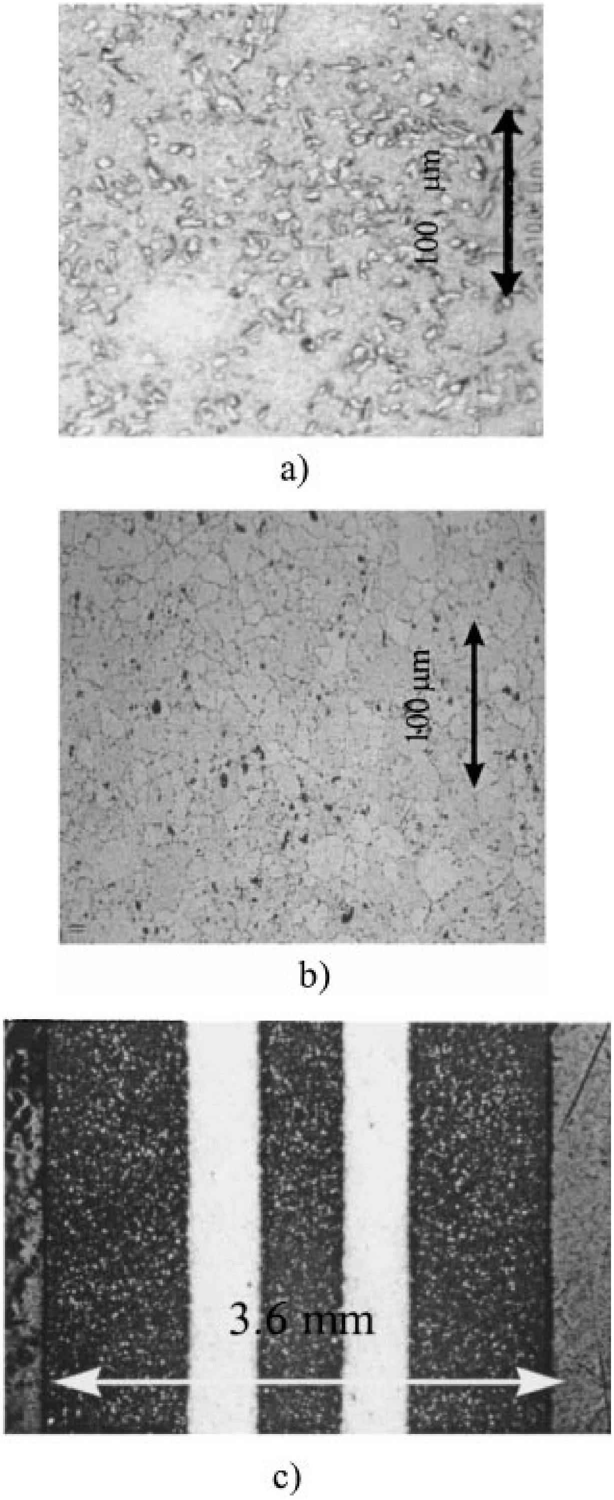

Figure 1 (a) Microstructure of 20 vol% particulate SiC reinforced 2014-aluminum matrix composite, (b) Microstructure of 6061-aluminum and (c) General appearance of the laminated composite.

$$K_{II} = \frac{F\sqrt{\pi a}}{WB} \frac{\sin\alpha}{\left(1 - \frac{a}{W}\right)} \times \sqrt{\frac{-0.23 + 1.40\frac{a}{W-a}}{1 - 0.67\left(\frac{a}{W-a}\right) + 2.08\left(\frac{a}{W-a}\right)^2}} \quad (1)$$

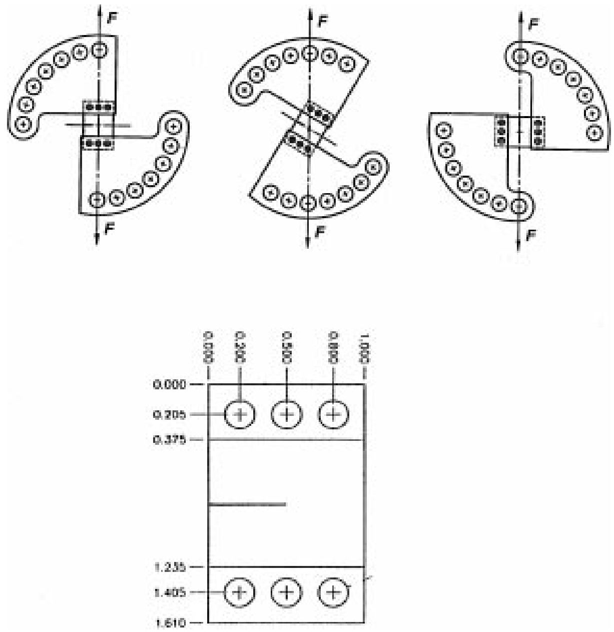

Figure 2 Top, general appearance of the loading grips were used in mixed-mode fracture toughness tests and bottom, the dimensions of the testing samples were used for mixed-mode fracture toughness tests.

where F is the applied force, W is the width of the sample, B is the thickness of the sample, a is the crack length and α is the angle of the loading direction with respect to the crack plane. This mixed-mode fracture testing technique was originally developed in ref. [7], although it is not shown here, our stress intensity calculations, utilizing a hybrid-FEM technique described in ref. [8], gave results that differ by less than $\pm 1\%$ from those obtained using Equation 1 for $0.5 < a/W < 0.7$.

The degree of mode-mixity and resulting effective stress intensity acting on the crack tip are expressed in the form:

$$M = \frac{2.0}{\pi} a \tan\left(\frac{K_I}{K_{II}}\right) \quad (2)$$

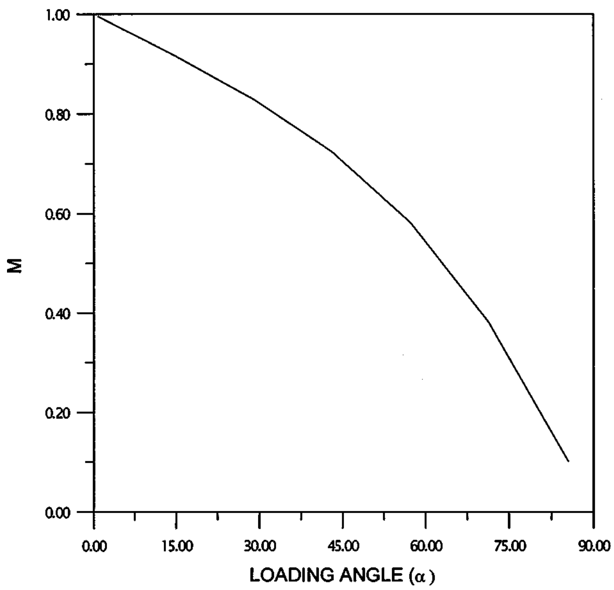

Figure 3 Variation of mode-mixity with respect to orientation of the crack plane to the loading angle.

and

$$K_{\text{effective}} = \sqrt{K_I^2 + K_{II}^2} \tag{3}$$

The values of M as a function of loading angle for a crack tip located at $a/W = 0.5$ are shown in Fig. 3. As can be seen from the figure, very large mode-mixities can be achieved with this loading geometry in comparison to ones that can be obtained from asymmetric four-point bend tests [9].

The initial fatigue cracks were introduced into the samples in the crack-divider orientation under pure mode-I condition (i.e. $\alpha = 0^\circ$ in Equation 1) from initial machined notch depth of $a/W = 0.5$ to about $a/W = 0.65$. During the fracture toughness tests the crack opening displacements were measured with a clip-gauge attached to the side of the samples. The monotonic loading rate was 5.08 mm per minute. For all loading angels the critical load values in the calculation of K_I and K_{II} values were determined by 5% offset technique as described by ASTM E-399. Final fatigue crack lengths were calculated as the averages of the six readings along the thickness of the samples from the fracture surfaces.

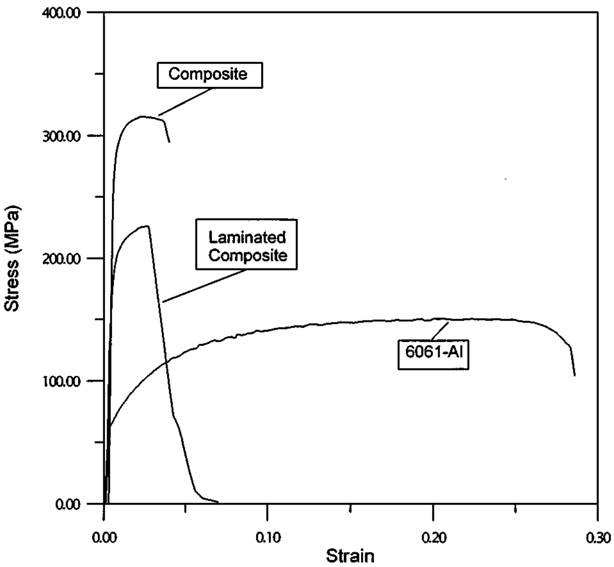

Figure 4 Tensile behavior of the laminated composite and its constituent layers.

3. Results and discussion

The tensile behavior of the laminated composite is compared with its constituent layers in Fig. 4. The tensile specimens used in these tests were 25.4 mm in uniform gauge length and 7 mm in width. The loading rate was again 5.08 mm per minute. As can be seen from the figure, the ultimate strength of the laminated composite was lower than the one observed for the metal matrix composite alone, due to presence of relatively lower strength of 6061-aluminum layers. Although, the failure of the laminated composite after achieving ultimate

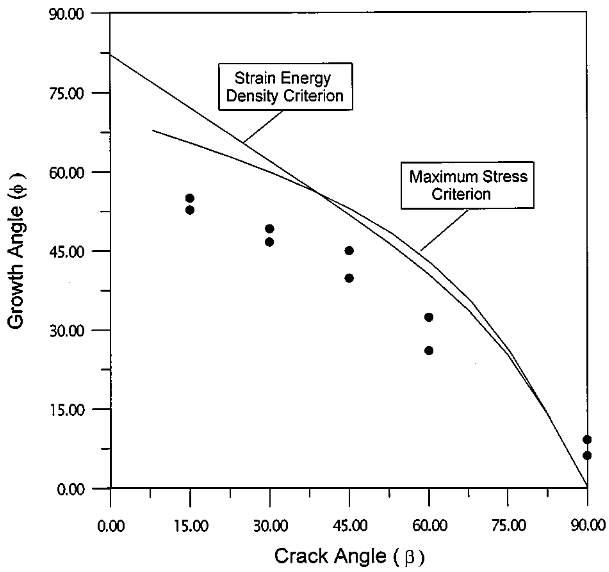

Figure 6 Comparison of the observed growth angles of the cracks from the initial fatigue crack tip with the theoretical predictions. In the figure crack angle (β) represents the orientation of the fatigue crack plane respect to the loading angle. ($\beta = 0.0$ corresponds to pure mode-II and $\beta = 90.0$ corresponds pure mode-I loading).

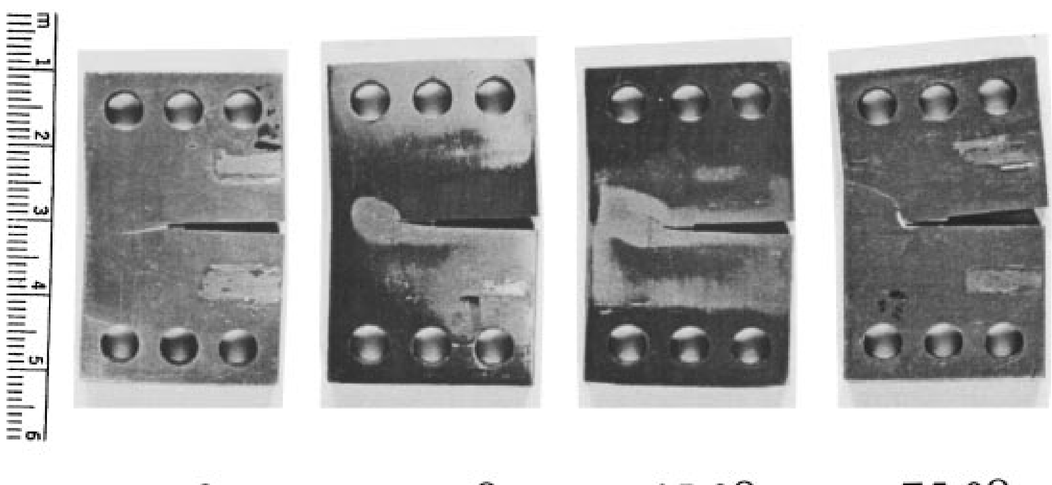

Figure 5 General appearance of the samples after testing under different mixed-mode loading conditions. The angles given under the figures were the loading angles during the tests. (i.e. 0.0 degree corresponds to pure mode-I and 90 degree corresponds pure mode-II).

strength was not as sudden as for the metal matrix composite, the final failure strain of the laminate was not significantly different when it was compared to one observed for the metal matrix composite.

The general appearance of the fracture samples and crack extensions under monotonic loading with different load-mixities are shown in Fig. 5. The observed crack growth directions from the initial fatigue crack under different load-mixities are compared with the predictions based on the strain energy density criterion [10] and maximum stress criterion [11] in Fig. 6. As can be seen from the figure, even though the material was in the laminated form, the observed crack growth directions correlate well with predictions based on isotropic material properties.

For different mode-mixities the observed $K_{\text{effective}}$ values for both the metal matrix composite and the laminated composite are summarized in Fig. 7. As can be seen from the figure, the mixed-mode loading did not significantly change the fracture behavior of the metal matrix composite, and the observed fracture toughness values were nearly constant for all the loading angles. The introduction of the relatively ductile 6061-aluminum layers in the form of laminate into metal matrix composite almost double the fracture toughness value of metal matrix composite for pure mode-I loading ($\alpha = 0°$). However, as can be seen from Fig. 7, this observed improvement for pure mode-I was significantly diminished for the tests carried out under larger load-mixities.

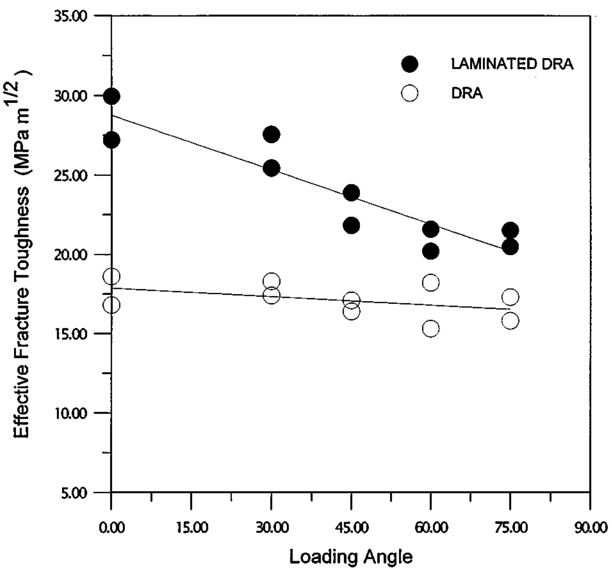

Figure 7 Variation of the effective fracture toughness values with loading angle (0.0 degree corresponds to pure mode-I and 90 degree corresponds pure mode-II).

The general appearance of the fracture surfaces, as the two limiting cases, for the laminated composites tested pure mode-I ($\alpha = 0°$) and tested under mixed-mode loading with ($\alpha = 75°$) are shown in Figs 8 and 9. In these figures, final fatigue crack tip is highlighted with black lines. The most important feature in the figures is the response of the interfaces between the metal matrix composite and the 6061-aluminum layers to the mixed-mode loading conditions. In mode-I condition, both in the fatigue crack growth and fast fracture regions the interface was very sharp and there was no specific damage formation. With increasing mode-mixity the evolution of the large voids at the interface regions, as indicated by the arrows, leading to the limited amount of delamination (not full separation) can be can be depicted from the figures. The void growth behavior in laminated ductile layers as function of delamination behavior has been numerically investigated in detail in [12]. It was shown there that for very small delamination lengths, even under mode-I loading condition, the void growth can be significantly enhanced in the ductile layers due to formation of intense shear bands leading to smaller resistance to the crack extension.

The reduction seen in the fracture toughness values with increasing load mixites in Fig. 7 is the result of the interfacial behavior to the mixed-mode loading. The results also demonstrate that the toughening observed under mode-I by introduction of the ductile layers into more brittle composites in the form of laminated

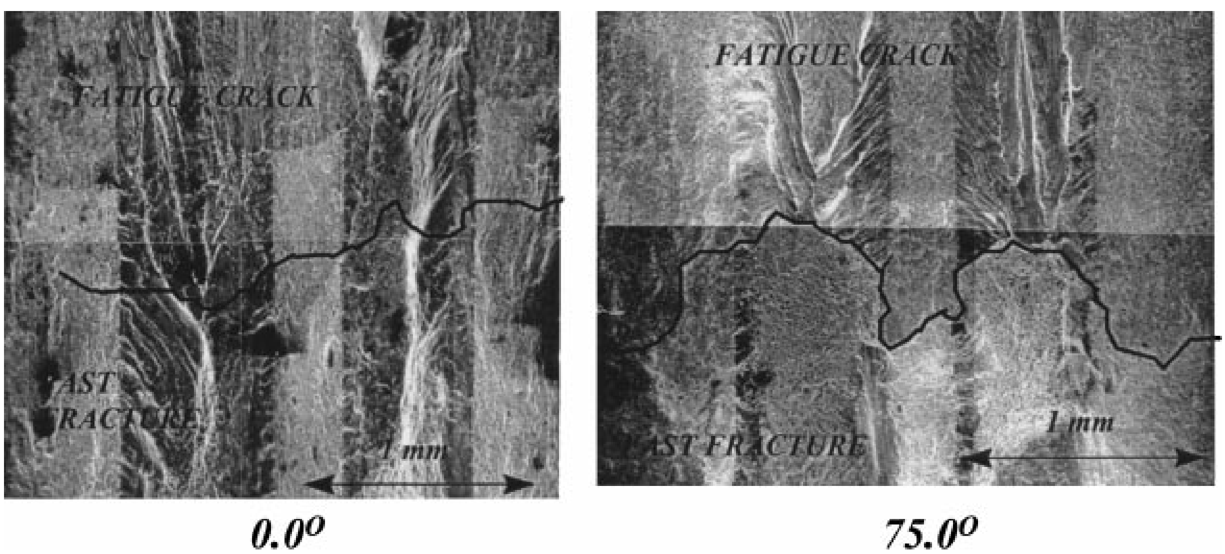

Figure 8 General appearance of the fracture surface tested at 0.0 degree (pure mode-I) and 75 degree (mixed-mode) loading angles. The dark lines indicate the fatigue crack tips.

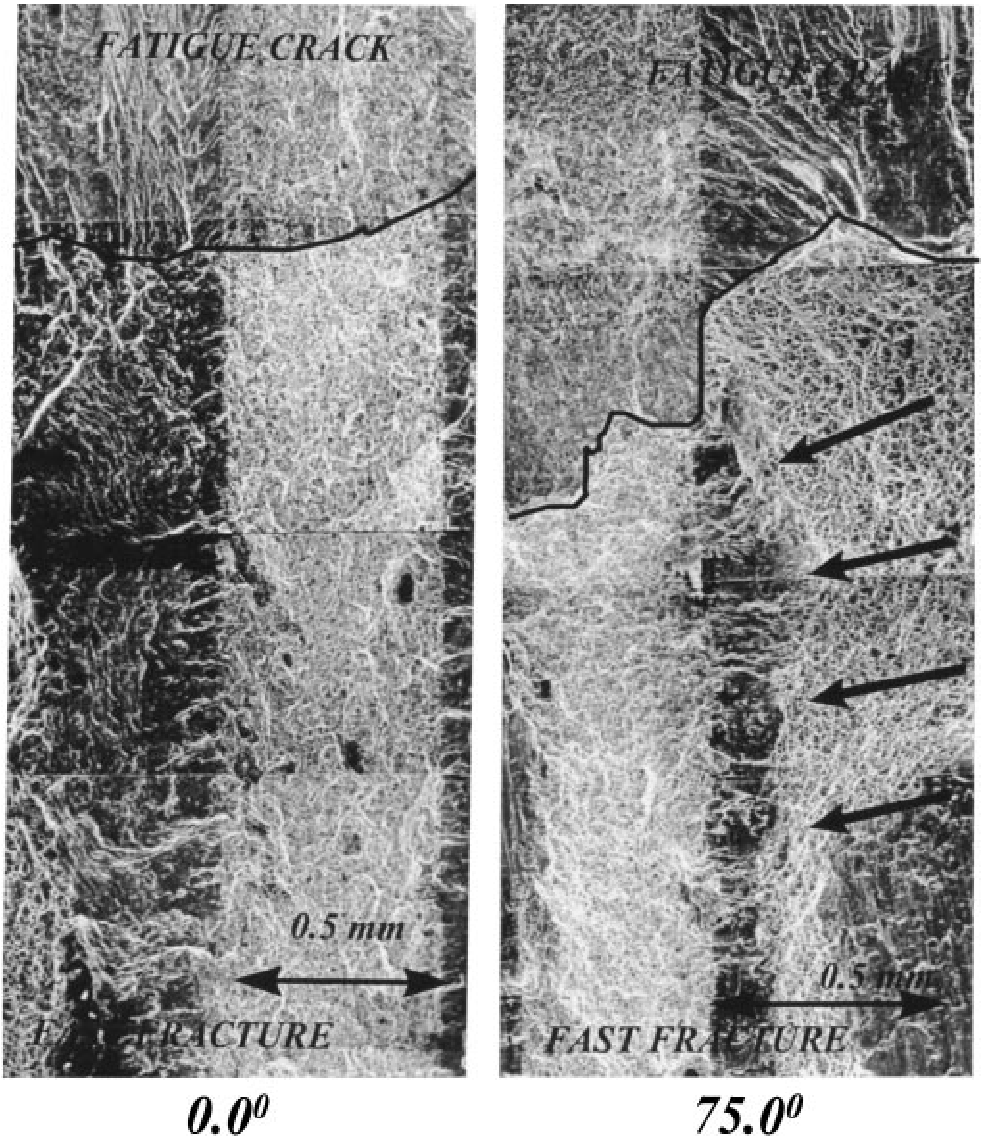

Figure 9 The interfacial behavior of the layers to the mixed-mode loading. The arrows indicate the evolution of large voids at the interface for the fracture tests carried at 75 degree mixed-mode loading angle.

composites could significantly deteriorate under multi-axial loading conditions.

4. Conclusions

In this study, the fracture behavior of a laminated composite, compose of metal matrix composite having 20 vol% particulate SiC and 2014-aluminum matrix and 6061-aluminum as the ductile layers, was investigated under mixed-mode loading. The results indicate that:

1. The increase in the fracture toughness of the metal matrix composite due to lamination with more ductile 6061-aluminum under pure mode-I loading condition diminishes significantly with increasing load-mixity.
2. The interfacial behavior of the layers is shown to be the reason for this reduction in the fracture toughness values with increasing load-mixity.
3. The predicted growth directions of the cracks during fast fracture agree reasonable well with experimental observations, in spite of the laminated miscrostructure of the composite.

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