Fracture toughness of Sicp/2124Al metal matrix composite

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ABSTRACT

An experimental study was conducted to evaluate fracture toughness of metal matrix composite (MMC). The material was a 12,10,7.5 mm thick extrusion of 2124 aluminum alloy with 10 % Sic partillicates. Specimen configuration and test procedure conformed to ASTM E399 Standard for compact specimens. It was found that special procedures were necessary to obtain fatigue cracks of controlled lengths in the preparation of precracked specimens for the MMC material. Fatigue loading with both minimum and maximum loads in compression was used to start the precrack. The initial precracking would stop by self-arrest. Afterwards, the precrack could be safely extended to the desired length by additional cyclic tensile loading. Test results meet practically all the E399 criteria for the calculation of plane strain fracture toughness of the material. A valid $K_{1c}$ value of the Sicp/Al composite was established as $K_{1c} = 25.19\text{MPa}$. The threshold stress intensity under which crack would cause to grow in the material was estimated as $\Delta K_{1c} = 2 \text{MPa} \cdot \sqrt{\text{m}}$ using the fatigue precracking data. Fractographic examinations show that failure occurred by the micromechanisms involving with plastic deformation although the specimens broke by brittle fracture. The effect of precracking by cyclic loading in compression on fracture toughness is included in the discussion.

Key words: Fracture toughness, metal matrix composite, fatigue, cracks.

INTRODUCTION

Silicon carbide reinforced aluminum (Sicp/Al) metal matrix composites are attractive because of their superior properties such as high strength and stiffness. The major limitation, however, is their propensity to brittle fracture. Hence, evaluation of fracture toughness is essential for the reliable use of these materials for structural parts and components. The results of such an investigation on a Sicp/2124 Al composite are reported in this paper.

EXPERIMENTAL

Material

In the present study, the material tested was a 2124 aluminum metal matrix composite (MMC) with 10 volume percent silicon carbide particulates. Particle size of the particulates was approximately 3-5 µm. The composite was manufactured using a Squeeze casting process by Regional Research Laboratory, Trivendram; followed by hot pressing 250*350*40 to 350*450*13mm. It is an rotor alloy as much as possible we compress the alloy then only we get maximum mechanical properties. Hear maximum mechanical properties are obtained when it is compres up to 13 mm from the thickness of 40mm.

Specimen preparation

Nine blanks of 50*50*7.5, 50*50*10.50*50*12mm were cut from the extrusion at Annamalai University. And the blanks were further machined to final dimensions of the Compact Specimens as specified in ASTM Standard E399. The specimens are 7.5, 10.12mm thick and notched in the L-T orientation. It was found that special procedures were necessary to precrack the specimens with fatigue cracks of controlled lengths. Initial effort failed
to produce the precrack by conventional methods using cyclic tensile loading because once the fatigue crack started it would instantly propagate through the whole specimen. To avoid the precracking problem, fatigue loading with both minimum and maximum loads in compression was used at first to start the precrack. Then, the initial precracking would stop by self-arrest. Afterwards, the precrack could be safely extended to the desired length by additional fatigue loading in tension. Nine specimens were successfully precracked in this manner with cyclic loading of -920.0 and - 5.4 kg in compression. When crack self-arrest occurred the loads were changed to 261.0 and 27.6 kg in tension to complete the precracking process. In all cases the cyclic frequency was 6 Hz.

**Tests**

Fracture mechanics tests were performed on an Instron servo hydraulic testing machine. Attachable knife edges were used to mount the crack opening displacement (COD) gage to the crack starter notch mouth. The loading rate was 40 MPa. Load versus COD was recorded with an X-Y plotter during testing.

**RESULTS AND DISCUSSION**

**Fracture Toughness**

All nine specimens failed in the tests by brittle fracture. In each test the load-displacement curve was linear up to the point of maximum load. Also, the fracture appearance of the specimens was vertical. Apparently, the specimens broke without yielding. However, in order to formally establish the validity of plane strain fracture toughness, $K_{IC}$, values calculated from the test results, several criteria should be examined according to ASTM E399. These criteria include specimen thickness, crack length, crack width, and the ratio of $P_{max}$ to $PQ$. A check of the test records revealed that all of the above criteria were satisfied. ASTM E399 requires that the difference between any two of the three specified measurements at the crack front shall not exceed 10 percent of the average. But the

<table>
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<th>S. No</th>
<th>Crack Length (a)</th>
<th>Specimen Thickness (B)</th>
<th>Crack Width (w)</th>
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Microstructures
Optical microscope observation

Fig. 1: Best condition (first specimen)

Fig. 2: Best condition (first specimen)

Fig. 3: Worst condition (ninth specimen)

Fig. 4: Un heat treated (first specimen)

Tensile test sem result

Fig. 5(a): Best condition (first specimen)

Fig. 5(b): Best condition (H.T.) (first specimen)
Fig. 5(c): Worst condition (ninth specimen)

Fig. 5(d): Worst condition (H.T.) (ninth specimen)

Fracture sem result best condition

Fig. 6: (First specimen) best condition (200µm)

Fig. 7: (First specimen) best condition (500µm)

Fig. 8: (First specimen) best condition (1000µm)
Fracture sem result worst condition

Fig. 9: (Ninth specimen) worst condition (200µm)

Fig. 10: (Ninth specimen) worst condition (500µm)

Fig. 11: Worst condition (1000µm) (Ninth specimen)

differences for the nine specimens range from 10 to 30 percent. It should be noted, however, that control of the fatigue crack front shape is extremely difficult, and that deviations from this requirements are very common in experimental practice. Therefore, the fracture toughness results obtained from the present tests are considered as valid KIC values. The plane strain fracture toughness results of the nine specimens are determined as follows:

Specimen 1 to 9 Thus, the optimized fracture toughness of the tested Sicp/Al composite is $K_{1c} = 25.17\text{MPa}\cdot\text{m}$. Fracture toughness values depends upon the homogeneous distribution of the Sicp and grain size of sicp

Comparison of data

David\textsuperscript{13} conducted the tensile and fracture toughness tests on 2014 Al alloy/SiC composite
consisting of 15 vol. % SiC particulates. Overall tensile elongations values ranged from 1.6 to 2.4% and fracture toughness values from 18.7 to 29.5 MPa. He observed that tensile ductility and fracture toughness were controlled by two factors namely; deformation characteristics of the matrix and SiC particles distribution. He discovered that the best method for increasing fracture toughness of composites is dispersing uniformly the particles and by increasing ductility of matrix.

McDanel's evaluated the mechanical properties and stress-strain behavior for several types of discontinuous SiC/Al composites, containing SiC-whiskers, nodules and particulate reinforcement. He studied the effects of type of reinforcement, matrix alloy, and reinforcement content by analyzing the stress-strain curves. The elastic modulus of the composites was found to be isotropic, and independent of type of reinforcement and matrix alloy; it depends only on the vol. % of SiC reinforcement and there was 50-100% increase over the modulus of unreinforced Al alloy. Yield/Ultimate tensile strengths were controlled mainly by matrix alloy, temper conditions and by reinforcement content. The yield and tensile strengths showed 60% increase over those of unreinforced Al alloy. Ductility was dependent upon percent reinforcement and matrix alloy. It increased with increased homogeneity in particle distribution. The tensile ductility or plastic strain to failure, for this material is estimated as 1/2 percent by McDanel's data. It can be seen that the present result fits very well into the curve for the particulate composites. The implication is that the present result compares well with other data, and that fracture toughness of composites with different amounts of particulate content can be correlated in terms of tensile ductility. When Sicp/2124 Al composites are made with high strength properties, their tensile ductility may be reduced to about 1 percent or less. Under such conditions, the minimum fracture toughness of the composites may be conservatively estimated at zero ductility as \( K_{1c} = 25.17 \text{ MPa} \sqrt{m} \) is apparently applicable to the MMC extrusion tested in the present investigation.

Fatigue crack growth

During fatigue precracking, the crack length was measured on the specimen surface and recorded with the corresponding number of loading cycles. Hear the load levels had to be sufficiently low for the precracking process; the data available are limited only in the lower range of crack growth rate. The linear curve in the log-log plot, and that the crack would still tend to grow at a \( \Delta K = 2 \text{ MPa} \sqrt{m} \) . However, at this \( \Delta K \) level it would take one million cycles to extend the crack by only about 1.7mm. Therefore, with such a slow crack growth rate, the threshold stress intensity of the tested material may be arbitrarily assumed as a \( \Delta K = 2 \text{ MPa} \sqrt{m} \) the present loading condition of \( R = 0.09 \). Harrison's has studied the fatigue data on 14 materials, including an aluminum alloy. He concluded that the crack would not propagate under the following condition

\[
\frac{\Delta K}{E} < \left( \frac{1}{2} \right) \left( \frac{1}{R} \right) 
\]

In this formula, the Young's modulus, \( E \), is expressed in psi. According to Mohn and Vukobratovich (6), Sic/6061-T6 composites with 10 volume percent of particulates have a value of \( E = 21 \times 10^6 \text{ psi} \) (145GPa). Substituting this value in the equation, the threshold stress intensity under which crack would cease to grow in the tested material would be \( a\Delta K = 2.1 \text{ ksi} \) (2.3 MPa) In a previous study, Longston have determined a threshold value of \( \Delta K = 1.5 \text{ ksi} \) (1.7 MPa 6) or 25 v/o Sic/Al composites. The present data compare closely with these results. It seems that Harrison's formula might be applicable to MMC materials. This formula indicates that a material with increased Young's modulus should also have increased threshold stress intensity, If so, the use of MMC materials would have an additional advantage of improved resistance to fatigue crack growth, at least near the threshold a \( \Delta K \) level, since the composites have greater modulus values than conventional metals and alloys.

Fracture Surfaces

Fractographic examination was performed on broken specimens using a scanning electron microscope (SEM). Fig. 6,7,8 shows the fractographic examination in specimen I. Compressive fatigue of the specimen resulted in a precrack extension of approximately 2 mm before crack self-arrest, and the fracture surface in this region
Fig. 6,7,8) shows that crack propagated in the material with plastic deformation. The subsequent tensile fatigue also produced plastic deformation with essentially similar features (Fig. 5a,5b). The region of fast fracture due to tensile overloading exhibits even more extensive plastic deformation with fine dimples, which indicate that fracture occurred by the ductile mechanism of void coalescence. and material have shown that removal of the far field compressive loads during cycling results in a reversal of the stress state at the crack tip from compression to tension; and it is such residual tensile stresses that are responsible for crack growth when the specimen is subjected to compressive cyclic loading. Thus, the basic mechanisms of crack growth should be the same for fatigue in tension and in compression. This may explain the similarity in fracture morphology in the two regions of precrack produced by tensile and compressive fatigue. The SEM micrographs indicate that the failure mechanism for fatigue cracking and fast fracture in the tested extrusion was ductile in nature characterized by plastic deformation on the microscopic scale. The ductile crack propagates after a certain amount of damage in the form of discontinuous micro cracks is accumulated ahead of the crack tip. The sites of void or micro cracks nucleation are not well defined. Crack propagates when these micro cracks are connected by micro voids coalescence which explains the dimpled appearance of the fracture surface. The dense reinforcement prevents the formation of fatigue striations.

As stated before, of the 18 specimens prepared, the first two broke during precracking under tensile fatigue loading. Remaining Specimen was then used to determine, by trial and error, the proper load levels for compressive fatigue precracking. Thus, for this particular specimen, the initial maximum load was increased in several steps to higher magnitudes during precracking while the minimum load was fixed at - 4.5 kg. Consequently, the specimen received a significant number of compression cycles at low and intermediate loads (e.g., approximately 200,000 cycles at P < - 350 kg). A precrack of 1.6 mm was eventually measured after 60,000 cycles at P = - 680 kg. The precracking process stopped at this point without any use of tensile fatigue. Specimen was then tested to determine fracture toughness at a loading rate of 130 MPa  Ön. It was found that the specimen apparently experienced considerable yielding before fracture as seen by the deviation from linearity in the load versus COD record .The ASTM requirement that the ratio Pmax/PQ , 1.10 satisfied, and therefore a valid K value can be established by the results of this specimen. The K values calculated from Pmax and PQ, are K = 5MPa Ön and KQ = 4.593 MPa Ön Specimen 9 was quite different from the other eight in fracture behavior. But detailed metallographic examinations revealed no differences in specimen 9 in orientation, size and distribution of Sic particulates in the aluminum matrix compared to all the other specimens. Perhaps extensive compression cycling in the precracking process created near the crack tip a plastic zone which could induce yielding in the specimen during fracture testing. It is also possible that the residual tensile stresses due to compressive fatigue precracking and the relatively fast loading rate might account for the lower K values for specimen 9. (The loading rates used in this work were within ASTM E399 recommendation of 33 to 165 MPa) Apparently, precracking only by compressive fatigue could have exerted some influence on the fracture behavior of this specimen.

Summary

The plane strain fracture toughness of the tested Sicp/2124- A1 composite extrusion has been determined as K1c = 25.17 MPa by testing Compact Specimens according to ASTM E399 Standard. Threshold stress intensity under which crack ceases to grow in the material is estimated as a K = 2 MPa Cm. These results compare well with data on other similar composites reported in the open literature. Although the specimens failed by brittle fracture in the K1c tests, the failure...
mechanism of the material involved plastic deformation as seen in the Fractography. There were no fatigue striations in the fracture morphology in areas of fatigue precrack. Such “anomalies” can be attributed to the complicated nature of other composites as indicated by the uncertainty in defining the sites of void nucleation and the appearance of the “damage zone” type fracture process”1. Fracture mechanics specimens of MMC materials can be successfully precracked with controlled crack lengths by increasing with compressive fatigue only may influence the test results. It means of compressive fatigue loading to initiate the crack followed by tensile fatigue to complete the process. precracking with the compressive fatigue only may influence the test results.

REFERENCES