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PREFACE

An experimental study was conducted to evaluate fracture toughness of SiC/Al metal matrix composite (MMC). The material was a 12.7 mm thick extrusion of 6061-T6 aluminum alloy with 40 v/o SiC particulates. 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 met practically all the E399 criteria for the calculation of plane strain fracture toughness of the material. A valid K_{IC} value of the SiC/Al composite was established as $K_{IC} = 8.9 \text{ MPa} \sqrt{m}$. The threshold stress intensity under which crack would cease to grow in the material was estimated as $\Delta K_{th} = 2 \text{ MPa} \sqrt{m}$ for $R = 0.09$ using the fatigue precracking data. Fractographic examinations show that failure occurred by the micromechanism involved 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.

1. INTRODUCTION

Silicon carbide reinforced aluminum (SiC/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 SiC/6061 Al composite are reported in this paper.

2. EXPERIMENTAL PROCEDURE

2.1 Material

In the present study, the material tested was a 6061-T6 aluminum metal matrix composite (MMC) with 40 volume percent silicon carbide particulates. Particle size of the particulates was approximately 3–5 μm. The composite was manufactured using a power metallurgical process by Arco Co. in Greer, S.C. It was made in the form of a 12.7 × 127 × 2540 mm extrusion. Figure 1 is a three dimensional photomicrograph which shows the uniformity of particulate distribution in the composite. There are no indications of pronounced directionality effects or clusters of SiC with respect to orientation of the extrusion.

2.2 Specimen Preparation

Six blanks of 12.7 × 63.5 × 63.5 mm were cut from the extrusion by the Space Systems Division, General Electric Co. in Valley Forge, PA. They were supplied to NASA Goddard Space Flight Center, where the blanks were further machined to final dimensions of the Compact Specimens as specified in ASTM Standard E399–83(1). The specimens were 12.7 mm thick and notched in the L–T orientation (Figure 2).

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. Four specimens were successfully precracked in this manner with cyclic loading of −818.0 and −4.5 kg in compression. When crack self-arrest occurred the loads were changed to 241.0 and 22.7 kg in tension to complete the precracking process. In all cases the cyclic frequency was 5 Hz. The method of initiating a precrack by means of compressive fatigue loading was based on the work of Suresh and his co-workers(2).

2.3 Tests

Fracture mechanics tests were performed on an Instron servohydraulic 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 $\sqrt{\mathrm{m}}$/min. Load versus COD was recorded with an X–Y plotter during testing.

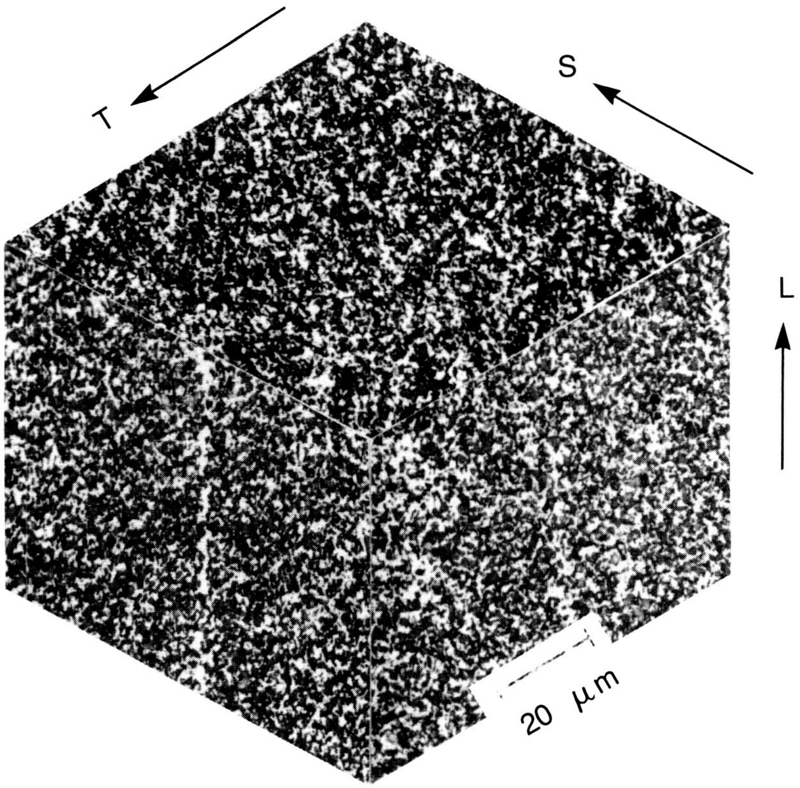

Figure 1. Photomicrograph of 40 v/o SiC/6061-T6 Aluminum Composite Extrusion.

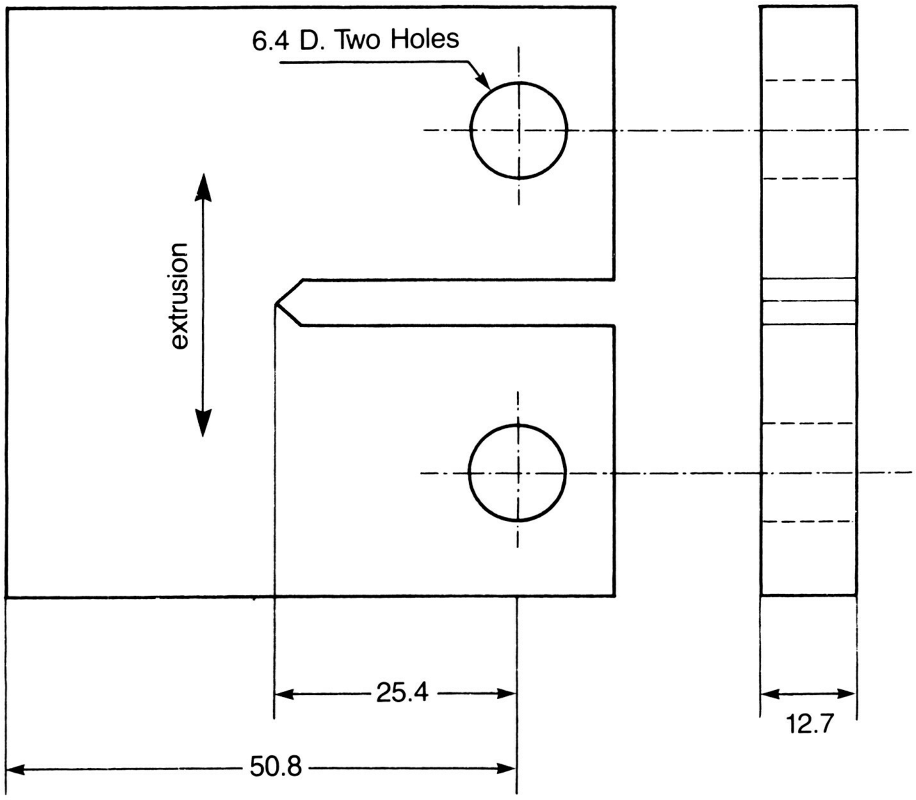

Figure 2. Schematic View of the Compact Specimen. (all dimensions in mm)

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3. RESULTS AND DISCUSSION

3.1 Fracture Toughness

All four specimens failed in the tests by brittle fracture. In each test the load-displacement curve was linear up to the point of maximum load (Figure 3). Also, the fracture appearance of the specimens was completely flat. 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 front shape, and the ratio of P_{max} to P_Q.

A check of the test records revealed that all of the above criteria were satisfied except the crack front shape. 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 differences for the four specimens range from 19 to 29 percent. An example of the shape of the precrack is shown in Figure 4. 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 K_{IC} values.

The plane strain fracture toughness results of the four specimens are determined as follows:

Specimen #	III	IV	V	VI
K_{IC} (MPa $\sqrt{m}$)	8.9	9.0	8.8	8.8

Thus, the average fracture toughness of the tested SiC/Al composite is $K_{IC} = 8.9$ MPa $\sqrt{m}$. It is interesting to note that the MMC extrusion has rather consistent fracture toughness values as evidenced by the small scatter of data listed above. This may be atributed to the benefit of a homogeneous distribution of the SiC reinforcement in the material (see Figure 1).

3.2 Comparison of Data

A search in the open literature failed to find any fracture toughness data on MMC materials similar to the extrusion tested in this work. However, Crowe and Gray(3) have compiled some K_{IC} data on SiC/6061 Al composites which are reinforced with 20 percent of whiskers and 25 percent of particulates (Figure 5). The fracture toughness result of $K_{IC} = 8.9$ MPa $\sqrt{m}$ for the SiC/6061 Al composite with 40 percent of particulates is included in Figure 5 as a solid square data point. The tensile ductility, or plastic strain to failure, for this material is estimated as 1/2 percent by McDanels' data.(4) 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 SiC/Al composites with different amounts of particulate content can be correlated in terms of tensile ductility.

Also, since the two curves by Crowe and Gray are linear, they can be extended by a short extrapolation to reach the vertical axis. This is shown as the dashed portions of the curves in Figure 5. The intercepts have some technical significance. When SiC/6061 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

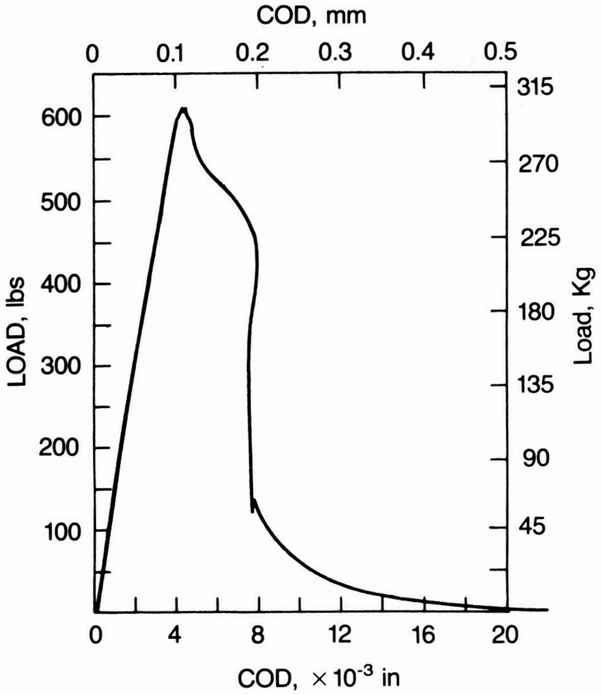
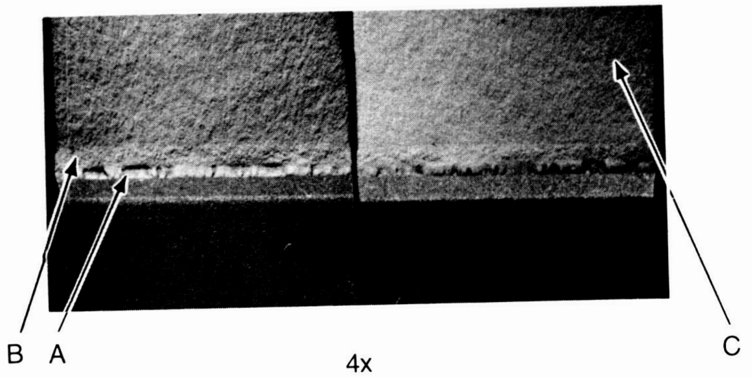


Figure 3. Load-COD Record of Specimen #3 Which Failed by Brittle Fracture.



A. Compressive Fatigue
B. Tensile Fatigue
C. Tensile Overload

Figure 4. Optical Photograph of the Crack Front Shape of a Tested Specimen.

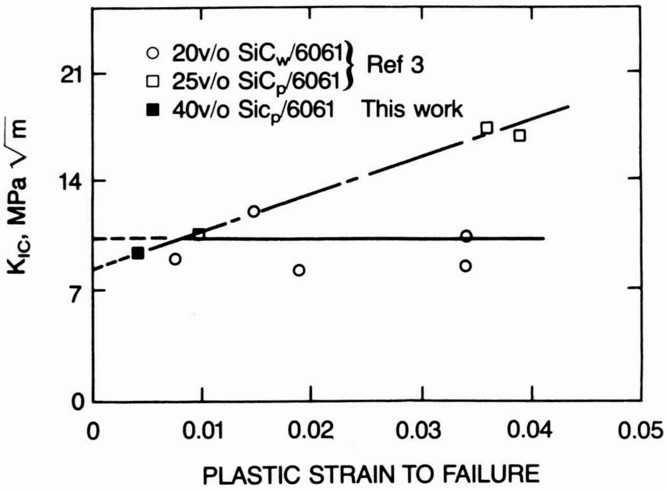


Figure 5. Fracture Toughness as a Function of Tensile Plastic Strain to Failure in SiC_d/6061 Al Composites. (From Ref. 3)

be conservatively estimated at zero ductility as $K_{IC} = 8$ MPa $\sqrt{m}$. It is apparently applicable to the MMC extrusion tested in the present investigation.

3.3 Fatigue Crack Growth

During fatigue precracking, the crack length was measured on the specimen surface and recorded with the corresponding number of loading cycles. The data obtained under tensile fatigue loading of one specimen are presented in Figure 6 in a conventional plot of crack growth rate versus stress intensity range (Da/DN vs ΔK). Since 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. It is interesting to note that the data points can be faired with a linear curve in the log-log plot, and that the crack would still tend to grow at $\Delta K = 2$ MPa $\sqrt{m}$. However, at this ΔK level it would take one million cycles to extend the crack by only about 0.025 mm. Therefore, with such a slow crack growth rate, the threshold stress intensity of the tested material may be arbitrarily assumed as $\Delta K_{th} = 2$ MPa $\sqrt{m}$ for the present loading condition of $R = 0.09$.

Harrison⁽⁵⁾ has studied the fatigue data on 14 materials, including an aluminum alloy. He concluded that the crack would not propagate under the following condition:

$$\Delta K/E < 10^{-4} \sqrt{in.} \text{ for } R = 0.$$

In this formula, the Young's modulus, E, is expressed in psi. According to Mohn and Vukobratovich⁽⁶⁾, SiC/6061-T6 composites with 40 volume percent of particulates have a value of $E = 21 \times 10^6$ psi (145 GPa). Substituting this value in the above equation, the threshold stress intensity under which crack would cease to grow in the tested material would be $\Delta K = 2.1$ ksi $\sqrt{in}$ (2.3 MPa $\sqrt{m}$). In a previous study, Longston and Liaw⁽⁷⁾ have determined a threshold value of $\Delta K = 1.5$ ksi $\sqrt{in}$ (1.7 MPa $\sqrt{m}$) for 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 an increased threshold stress intesity, ΔK_{th}, value. If so, the use of MMC materials would have an additional advantage of improved resistance to fatigue crack growth, at least near the threshold ΔK_{th} level, since the composites have greater modulus values than conventional metals and alloys.

3.4 Fracture Surfaces

Fractographic examination was performed on broken specimens using a scanning electron microscope (SEM). Figure 7 shows the fracture surface morphology in specimen VI. Compressive fatigue of the specimen resulted in a precrack extension of approximately 1 mm before crack self-arrest, and the fracture surface in this region (Figure 7a) shows that crack propagated in the material with plastic deformation. The subsequent tensile fatigue also produced plastic deformation with essentially similar features (Figure 7b). 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 (Figure 7c).

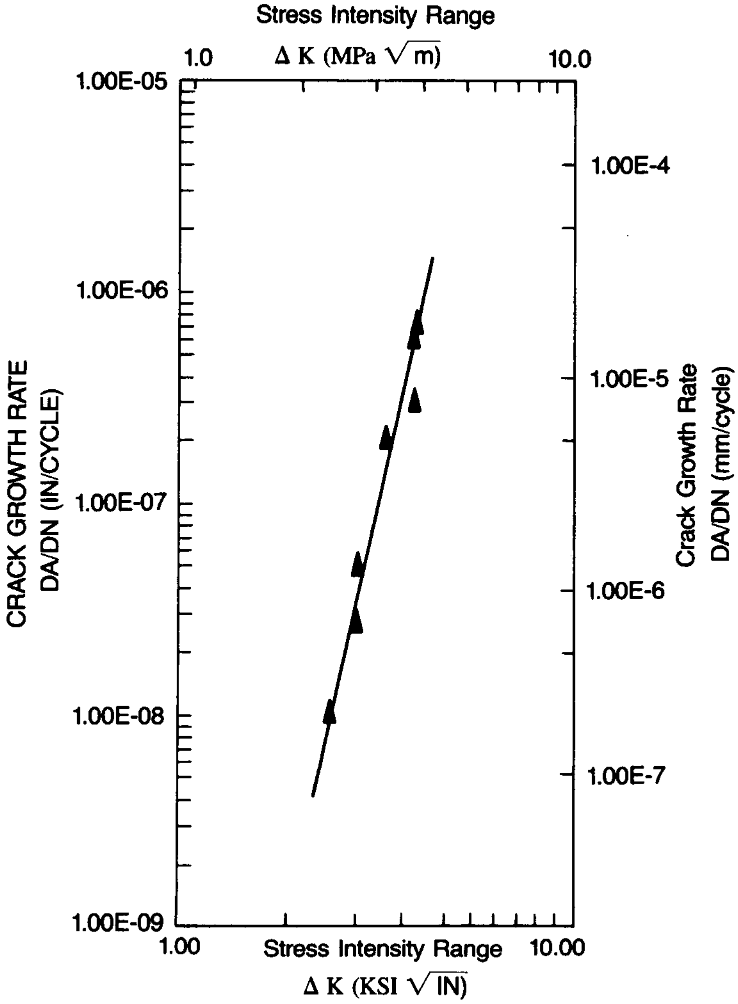


Figure 6. Crack Growth Rates for Tension (R = 0.09) Cycling.

Suresh and others[8] 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 fracture is rather characteristic to 6061-T6 aluminum alloy which is a fairly tough material[9]. Yet, on the macroscopic scale, the specimens failed completely by brittle fracture in the K_{IC} tests. What is more unusual is that the fracture morphology does not show any fatigue striations, commonly seen in metals failed by cyclic loading, in the regions of precrack (see Figures 7a and 7b).

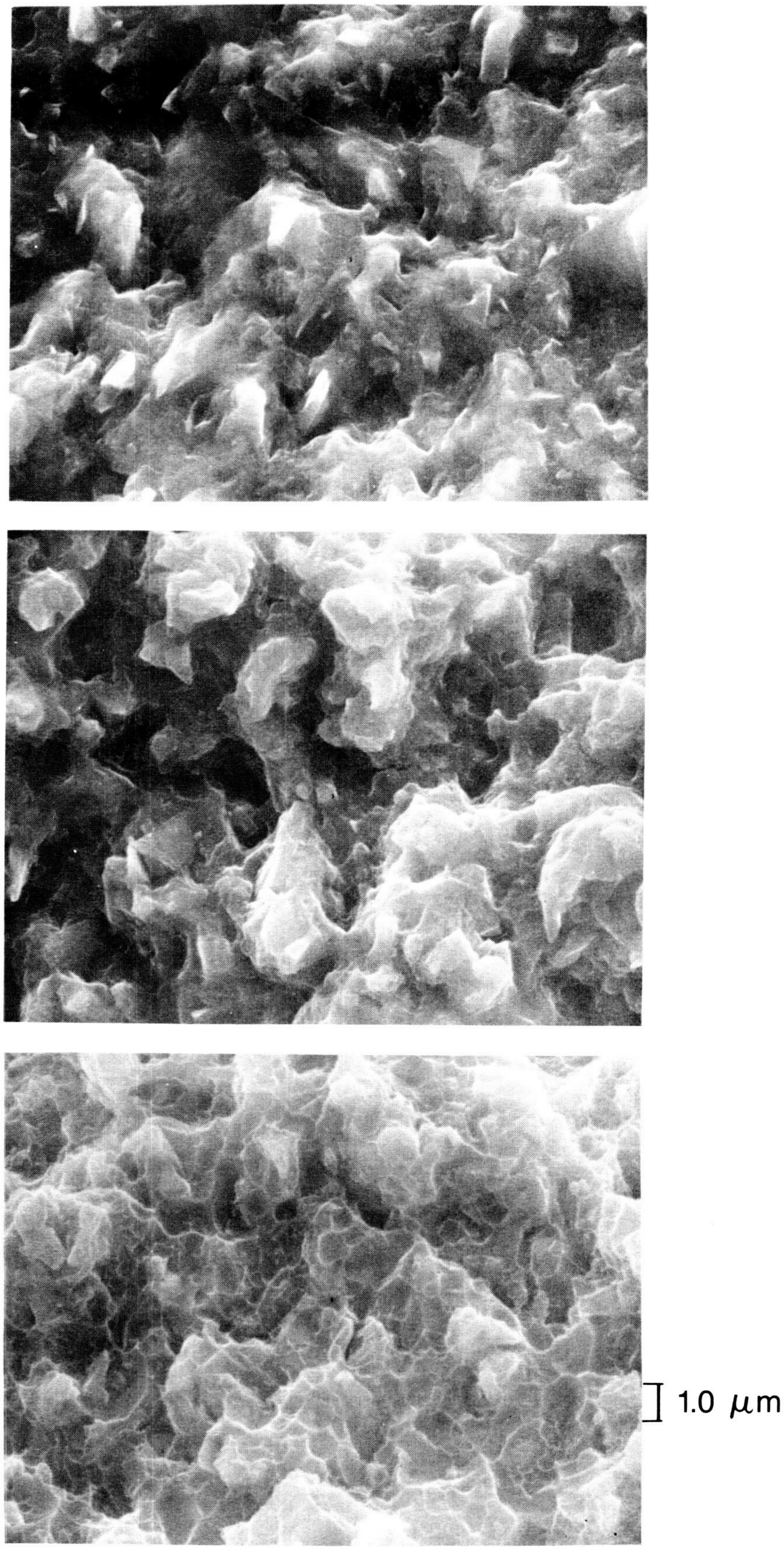
These "anomalies" reflect a complicated nature of discountinuous SiC/Al composites noted in previous reports[10-12]. The lack of strong evidence of debonding of SiC particles from matrix observed in the present investigation speaks in favor of the "damage zone" type fracture suggested earlier[11]. Crack extension takes place after a certain amount of damage in the form of discontinuous microcracks is accumulated ahead of the crack tip. The sites of void or microcrack nucleation are not well defined. Crack propagates when these microcracks are connected by microvoid coalescence which explains the dimpled appearance of the fracture surface. The dense reinforcement prevents the formation of fatigue striations.

3.5 Experimental Observations

As stated before, of the six specimens prepared, the first one broke during precracking under tensile fatigue loading. Specimen #2 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 $P_{max} < -350$ kg). A precrack of 1.1 mm was eventually measured after 60,000 cycles at $P_{max} = -680$ kg. The precracking process stopped at this point without any use of tensile fatigue.

Specimen #2 was then tested to determine fracture toughness at a loading rate of 130 MPa $\sqrt{m}$/min. 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 (Figure 8). The ASTM requirement that the ratio P_{max}/P_Q shall not exceed 1.10 is not satisfied, and therefore a valid K_{IC} value can not be established by the results of this specimen. The K values calculated from P_{max} and P_Q are $K_{max} = 6.6$ MPa $\sqrt{m}$ and $K_Q = 5.6$ MPa $\sqrt{m}$.

Specimen #2 was quite different from the other four in fracture behavior. But detailed metallographic examinations revealed no differences in specimen #2 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



(a) Compressive Fatigue

(b) Tensile Fatigue

(c) Tensile Overloading

Figure 7. Fractographs of Specimen #VI

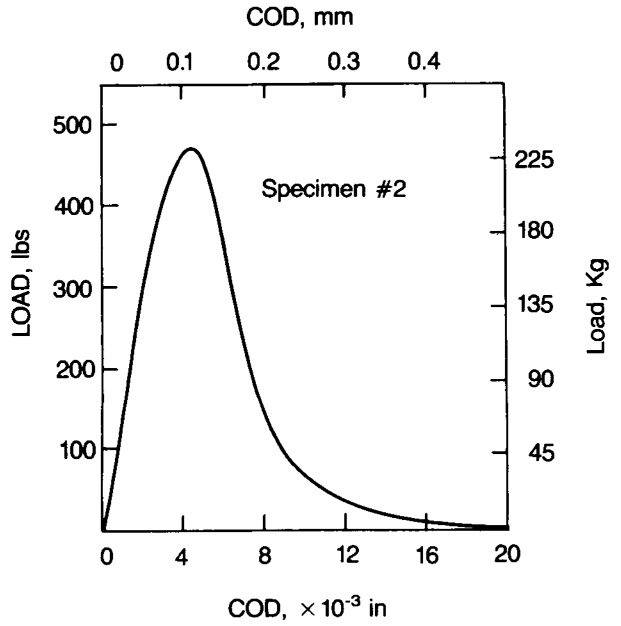


Figure 8. Load-COD Record of Specimen #2 which does not meet ASTM E399 P_{max}/P_Q Requirement.

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 #2. (The loading rates used in this work were within ASTM E399 recommendation of 33 to 165 MPa $\sqrt{\text{m}}$/min.) Apparently, precracking only by compressive fatigue could have exerted some influence on the fracture behavior of this specimen.

4. SUMMARY

The plane strain fracture toughness of the tested SiC/6061-T6 Al composite extrusion has been determined as $K_{IC} = 8.9\ \text{MPa}\ \sqrt{m}$ by testing Compact Specimens according to ASTM E399 Standard. Threshold stress instensity under which crack ceases to grow in the material is estimated as $\Delta\ K_{th} = 2\ \text{MPa}\ \sqrt{m}$. These results compare well with data on other similar composites reported in the open literature.

Although the specimens failed by brittle fracture in the K_{IC} tests, the failure mechanism of the material involved plastic deformation as seen in the fractographs. There were no fatigue striations in the fracture morphology in areas of fatigue precrack. Such "anomalies" can be attributed to the complicated nature of SiC/Al composites as indicated by the uncertainty in defining the sites of void nucleation and the appearance of the "damage zone" type fracture process(11).

Fracture mechanics specimens of MMC materials can be successfully precracked with controlled crack lengths by means of compressive fatigue loading to initiate the crack followed by tensile fatigue to complete the process. Precracking with compressive fatigue only may influence the test results.

5. ACKNOWLEDGMENT

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16. Abstract

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17. Key Words (Suggested by Author(s))
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