Fracture of Silicon Carbide Whisker Reinforced Aluminum[1]

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ABSTRACT

This paper discusses the results of an investigation into the validity of using standard fracture toughness testing procedures (developed for metals) for whisker reinforced metal matrix composites. Results of tests of ten and twenty volume percent silicon carbide whisker reinforced 2124 aluminum extruded plate are presented. Test coupons in the form of compact-tension, center-notched, and edge-notched specimens were used, with the loading direction either parallel or perpendicular to the extrusion direction. Testing was in the as-extruded condition.

None of the tests were found to give a valid fracture toughness (K_{IC}) according to the criteria of the ASTM Standard E-399. For an extrusion direction aligned with the loading, the compact-tension, plane-strain coupon, did not even produce self-similar fatigue pre-crack growth. The center-notched coupon gave the most consistent results and was indicated to be useful in comparing different materials or to quantify improvements made in a material by changes in processing. Linear elastic fracture mechanics did not correlate the fracture behavior for these materials and tests. Even when the fiber direction was held constant the measured fracture toughness values obtained from the different coupons differed by as much as a factor of two.

KEY WORDS

Fracture, MMC, composites, whisker reinforced, silicon carbide.

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[1] Supported by NASA-Langley Research Center under NASA Grant NSG-1-724, Grant Monitors W.S. Johnson and W.D. Brewer.

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INTRODUCTION

In the development of discontinuously reinforced metal matrix composites (MMC), it has been found to be relatively easy to make significant improvements in the unnotched strength and the stiffness over that of the unreinforced matrix. Also, it is possible to determine well defined material property values for strength and stiffness. Unfortunately, it is considerably more difficult to decrease the notch sensitivity (or increase the fracture toughness). Indeed, in almost all cases the fracture toughness, or at least the ultimate load at which a notched coupon will fail, decreases. There are, however, no standard procedures available for determining consistent fracture toughness properties. It is, in fact, not at all clear what is meant by "the fracture toughness" of MMC, although at the present time most of the toughness values reported in the literature are obtained using standard test methods developed for metals.

For most isotropic metals a plane-strain, mode I (K_{IC}), fracture toughness obtained by following the test procedures outlined in ASTM E-399 (1983) has essentially the same validity as other material properties such as the extensional modulus. The same degree of consistency does not appear to exist for some MMC systems, and while particular difficulties have been discussed in the literature (Hayes and Knight, 1987; Crowe and Gray, 1985; Hasson *et al.*, 1985) to the authors' knowledge no comprehensive comparative study has been presented. The primary purpose of the investigation reported here was to provide a detailed record of the fracture behavior of the whisker reinforced material when tested using E-399 guidelines.

It is reasonable to expect the fracture toughness for the MMC to change with fiber orientation just as the stiffness does. It is not as clear that test specimen geometry should make a significant difference. Some studies though (Hayes and Knight, 1987; Crowe and Gray, 1985) for example, have indicated that this is the case and it has been suggested that a compact-tension test specimen is not as "good" as a center-notched coupon. While it is possible to use only center-notched coupons in the laboratory, edge cracks do form in structures. Questions that must be asked then are: do the standard linear elastic fracture mechanics (LEFM) test methods work for this material, even if we accept different behavior depending on fiber direction, and how do we obtain fracture data to use in design?

One of the fundamental precepts of LEFM is that the stress field in the near vicinity of the crack tip controls the fracture behavior. In particular, the stresses have a square-root singular form and this singular term alone is sufficient to predict fracture. Under a pure opening (mode I) stress field the three test specimens used in this study, compact-tension, center-notched and edge-notched, have an explicit relationship between the coefficients of this singular stress term (i.e. the stress intensity factor). For many metals one can accurately predict fracture for all of the specimens by testing only one geometry.

If the whisker reinforced composite is viewed as an orthotropic continuum, the stresses are also square-root singular (Paris and Sih, 1965) and the coefficient of the singular term for an edge-notch is directly related to the corresponding coefficient in a center-notched panel. In fact, the mode I stress intensity factor is the same as for the isotropic case. If LEFM is applicable for this orthotropic material, the test results should also be consistent with the analytical stress intensity factors.

Some early work by Reedy (1980) using continuous fiber unidirectional boron/aluminum MMC laminates pointed out the inability of LEFM to predict the fracture toughness of the continuous system. Reedy found that drastically different values of fracture toughness could be obtained in those composites through variations in test specimen geometry. This paper extends Reedy's work to give a similar comparison of the crack growth and fracture behavior for a whisker reinforced material.

A parallel study is also underway (Goree and Rack, 1988) to consider a more complete fracture criterion. It has been shown by Sih (1973) that mixed mode fracture for isotropic materials can be predicted by a strain energy criterion. A related strain energy criterion is being investigated and will be compared with the present experimental results. In addition to this mechanics based research, a materials phase (Goree and Rack, 1988) is being considered under the direction of Professor Rack. The results of that effort will be reported elsewhere.

EXPERIMENTAL PROCEDURE

The material used in this study was 2124 aluminum reinforced with 10 and 20 volume percent F-9 SiC whiskers. The fabrication was a powder metallurgy process as described by Rack (in press). The material was produced in billets and then extruded into 127 mm wide by 12.7 mm thick plates. The extrusion ratio was 11.5:1, resulting in a very uniform alignment of the SiC whiskers in the extrusion direction, both with respect to width and thickness. A detailed description of the fiber distribution will be given in the final report (Goree and Rack, 1988). The material was tested in the as-extruded (F) temper.

For metals, the compact-tension specimen is an accepted design used to determine the mode I, plane strain, fracture toughness, K_{IC}. Very specific guidelines and test procedures are given in E-399. The center-notched and edge-notched coupons are not covered in the ASTM standard, but the same procedures were used for those specimens. That is, the criteria for "valid" fracture toughness results were applied to all three specimens.

Figure 1 shows the test coupon geometries with the compact-tension (CT) specimen designed according to ASTM E-399. The CT coupons were tested with thicknesses of 12.7 mm (plane-strain) and 2.54 mm (plane-stress). The thin specimens were obtained by machining both sides of the 12.7 mm stock. As indicated above, work by Rack (Goree and Rack, 1988) found the fiber distribution to be very uniform through the thickness. The 2.54 mm coupons were then essentially the same material as the plane-strain coupons. The center-notched (CCT) and edge-notched (SENT) coupons were only tested in 12.7 mm thickness. All specimens had straight-through starter notches.

The fatigue loading during pre-cracking was done at between 20 and 40 cycles per second, starting with a maximum load equal to 50 percent of the estimated fracture load. The loads were gradually increased, maintaining a load ratio of minimum to maximum value of 0.1, until crack initiation was detected. Crack growth was monitored with a traveling microscope and a COD gage. A strobe light was used to assist in following the fatigue precrack as they were extremely tight, especially at short lengths. In general, all specimens were much more difficult to pre-crack than an all-aluminum coupon. The difference between the maximum load (or K) required to initiate a fatigue crack and the load giving unstable growth (fracture) was very small. That is, the da/dn vs ΔK curve was steep. All tests were run under load control and a load reduction procedure was used during fatigue pre-cracking. Most of the testing was done using an MTS-880 servo-hydraulic machine; however, some of the 20 volume percent CCT coupons were tested in an Instron 800 machine.

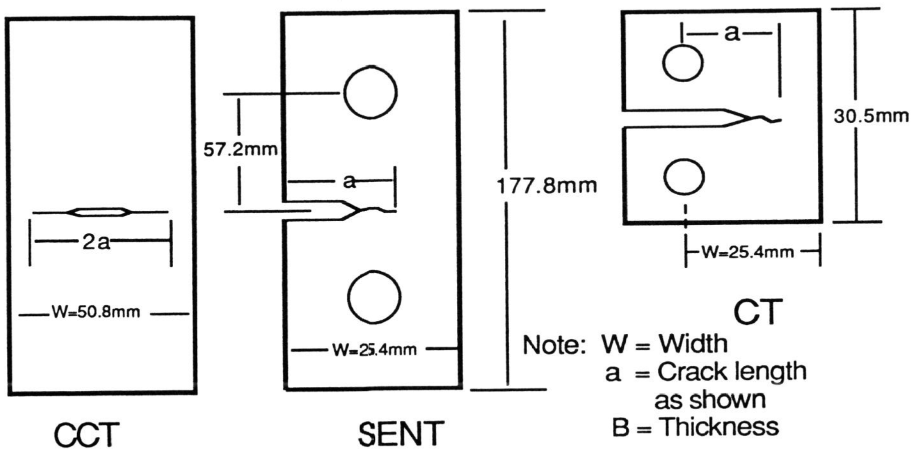

Fig. 1. Specimen Geometries

The detailed procedures of E-399 were followed in all tests and those requirements on the size of the specimen and manner of testing were all met. In order for the tests to give a valid fracture toughness measure, specific requirements were imposed on the results. The most fundamental of these are listed below, and will be compared to the test results.

1) Self-similar crack growth (8.2.4 of E-399).

2) The crack front at the end of the fatigue pre-crack stage should be relatively flat. The difference between surface crack length and the average crack length should be no more than 15% of the average, with $0.45W<a<0.55W$. (8.2.2 of E-399).

3) The maximum value of the mode I stress intensity factor, K, during the terminal fatigue crack growth stage must be less than 60% of K at fracture. (A.2.4 of E-399).

4) From the test record of the load vs COD results, the 95% tangent line (i.e. having 95% the slope of the tangent to the initial linear part of the curve) must intersect the curve at a point P_Q such that $P_{max}/P_Q \leq 1.10$. (9.1.1 and 9.1.2 of E-399).

The equations used to calculate K, the mode I stress intensity factor, for the three different specimen geometries, are given in the following references. For the CT specimen the equations in section A4.5 of E-399 (1983) were used. The equation for the CCT coupon with clamped ends and a free length-to-width ratio of 1.5 was taken from Isida (1971) and is accurate for $2a/W<0.6$. The appropriate equation for the SENT coupon is given by Brown and Srawley (1966) and is accurate for $a/W<0.6$. These equations are

for isotropic materials but, as discussed above, the mode I stress intensity factors are the same in an orthotropic material. In all cases the stress intensity factor K is of the form $K=PF(a,W)$. Values of K corresponding to P_Q and P_{max} were obtained from the appropriate equations and are designated K_Q and K_M respectively. For a metal, if all the criteria are met, the conditional value K_Q is denoted by K_{IC} and is called the plane-strain factor toughness.

RESULTS

The test program with resulting values of K_Q and K_M is given in Table 1, where the L-T designation indicates that the loading was in the extrusion direction and the machined notch in the transverse direction. The T-L designation corresponds to loading perpendicular to the extrusion direction with the initial notch being parallel to the extrusion direction. The coupons designated CT (CCT) were special compact-tension coupons that were cut from pre-cracked center-notched coupons. Material property values are given in Table 2.

TABLE 1. Testing Program and Results

All specimens were 2124 aluminum reinforced with either 10 or 20 volume percent SiC whiskers, and were tested in the as-extruded, F-temper. The results are the average of 2 or 3 replicate tests in most cases.

No.	Geometry	Thickness	Orientation	%Fiber	$K_Q(MPa\sqrt{m})$	$K_M(MPa\sqrt{m})$
1	CT	12.7 mm	L-T	10	13.7[1]	19.6[1]
2	CT	12.7 mm	T-L	10	12.7	17.9
3	CT	12.7 mm	L-T	20	17.1[1]	18.2[1]
4	CT	12.7 mm	T-L	20	15.8	17.7
5	CT	2.54 mm	L-T	10	12.5	22.9
6	CT	2.54 mm	T-L	10	12.7	17.9
7	CT	2.54 mm	L-T	20	15.9	22.2
8	CT	2.54 mm	T-L	20	14.7	20.5
9	CT(CCT)	12.7 mm	L-T	10	15.3[1]	21.2[1]
10	CT(CCT)	12.7 mm	L-T	20	17.0[1]	17.0[1]
11	CCT	12.7 mm	L-T	10	17.9	20.9
12	CCT	12.7 mm	T-L	10	20.3	20.3
13	CCT	12.7 mm	L-T	20	17.3	18.2
14	CCT	12.7 mm	T-L	20	13.0	16.2
15	SENT	12.7 mm	L-T	10	20.0	26.3

[1] In these specimens the fatigue crack turned, K was computed using the horizontal projection of the crack length

TABLE 2. Material Properties

% fiber	E_1 (GPa)	E_2 (GPa)	σ_{ys} (MPa)	$K_{IC}(MPa\sqrt{m})$
0%	73	73	300	≈40
10%	95	73	≈350	?, see Table 1
20%	128	101	≈390	?, see Table 1

All specimens tested had self-similar fatigue pre-crack growth except the plane strain, compact-tension coupons with L-T orientation, (i.e. tests 1,3,9, and 10). In these four coupons the fatigue crack initiated at the end of the notch and grew at an angle with respect to the transverse direction. In none of these four cases was there any transverse growth. Note that specimens 1 and 3 had machined notches while in 9 and 10 the machined notch had been extended as a sharp self-similar crack by first fatiguing a center-notched coupon and cutting the CT specimen from it. The sharpness of the notch had no measureable influence, and the cracks initiated at a 45° angle in the 10% material and at a 70° angle in the 20% material. Several 20% CT(L-T) coupons with chevron starter notches were also tested and the fatigue crack still turned. It was much more difficult to observe the crack so the remaining tests had straight-through starter notches. A photograph of a failed 20% CT(L-T) coupon is shown in Fig. 2. Having these results, it was very interesting that when the thickness of the CT coupon was reduced (by machining) to 2.54 mm the crack did not turn. Also note that the SENT coupon gave self-similar crack growth. The SENT coupon is similar to a CT coupon except that the location of the pin loaded holes gives different contributions of stress due to bending and axial loading. For the geometry of Fig. 1, the bending moment about the center-line of the net-section ligament is Pa/2 for the SENT coupon and P(W + a)/2 for the CT geometry. The CCT specimen has no net bending moment.

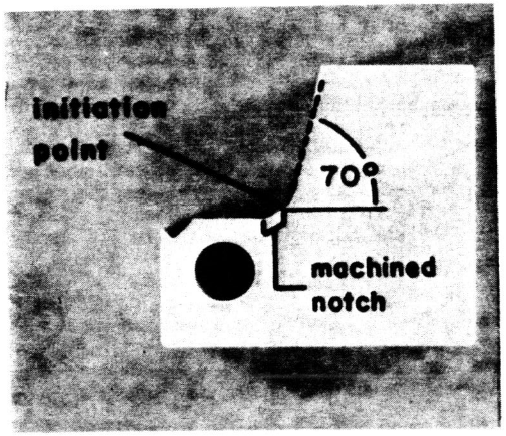

Fig. 2. Crack Deflection in a 20% L-T, Plane Strain Specimen.

None of the compact-tension specimens met the second condition. The crack front was very uniformly rounded, (nearly a circular arc) with the surface crack length differing from the average length by about 20%. The CCT and SENT coupons were fatigued to give a longer crack length in order to be able to fracture the specimens and the percent difference was about 10%, but the crack front was essentially the same shape as the CT coupons.

The third criteria was marginal (i.e. on the order of 65%) in most cases, when the requirement was based on the maximum value of K, i.e. K_M in Table 1. In those cases of considerable non-linearity in the load-COD record the value of K maximum during the final fatigue cycle was frequently as large as K_Q.

The fourth critera imposes a limitation on the degree of non-linearity in the load-COD results. Only tests 3,10,12 and 13 satisfied this condition of $K_M/K_Q \leq 1.1$, and in tests 3 and 10 the fatigue crack was not self-similar. A typical load-COD curve is given in Fig. 3.

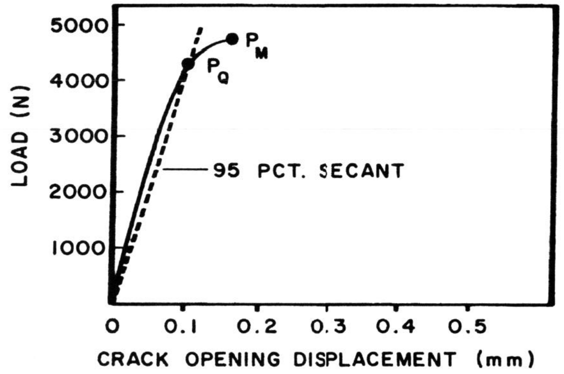

Fig. 3. Load-COD Curve for a 20% CT, T-L Specimen.

The difference in behavior (crack branching) observed between the thick and thin CT coupons and between the thick CT and SENT specimens is the most significant difficulty in attempting to use these tests to develop fracture data. The observed response is apparently due to the influence of the different stress states: plane strain vs. plane stress and the stress gradient due to the different bending components. A series of tests using a SENT coupon with different pinhole locations are now underway to investigate this behavior.

The variation in the averaged values given in Table 1 (with fiber orientation and specimen geometry) covers a range of K_Q or K_M of over 20%. These results were the average of several tests for each particular specimen configuration. The variation within a given series was also on the order of 25%, giving a large scatter in the full set of data. For example, for a 10% T-L material the minimum value of K_Q recorded was 11.8 Mpa$\sqrt{m}$ for a CT specimen, and a maximum value of 21.6 Mpa$\sqrt{m}$ was obtained from a CCT coupon. This was typical of all the tests, with the CT coupon giving the lowest value of toughness, the CCT next, and the SENT the highest. As indicated however, it appears that the SENT results depend on the pin location.

CONCLUSIONS

Following the E-399 guidelines, it must be concluded that none of the tests gave a valid K_{IC}.

There is no real reason to feel that the above criteria must be applied to the composite. If the results were such that a consistent value of K (either K_Q or K_M) emerged, then there would be some justification for using it as a material property in design. Unfortunately, the results do not show such consistency.

It seems that the best one can say for these testing methods is that the center-notched coupon is the most consistent and is the most suitable specimen to use to compare different materials or to quantify improvements made in a material by changes in processing. These tests do not indicate that an increased K value using a CCT test will necessarily correspond to the same improvement in a different specimen geometry.

The singular crack-tip stress field (stress intensity factor) and the standard application of LEFM does not represent the fracture behavior of these materials. No single value of toughness was found, even when the fiber orientation was fixed.

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