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CHARACTERIZATION OF SHORT FATIGUE CRACKS AT NOTCHES IN SiC PARTICULATE ALUMINUM COMPOSITE

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S.B. BINER

Ames Laboratory
Iowa State University
Ames, IA 50011

Abstract

The initiation and growth of cracks emanating from blunt notches in 6061-Al alloy reinforced with 25% particulate SiC metal matrix composite was investigated. To elucidate the role of aging condition of the matrix on the fatigue behavior, the studies were carried out at T6 and overaged conditions. The results indicate that the initiation of fatigue cracks are insensitive to the notch severity and to the aging condition of the matrix. The overaging heat treatment resulted in slower fatigue crack growth rates. The failure of the SiC particles during the fatigue process is given as the reason for the both observed initiation and crack growth characteristics. It is also shown that the growth rate of short cracks emanating from blunt notches can be accurately described by an effective stress intensity factor range ΔK_{eff}. This could provide an adequate engineering method for design against fatigue failure from various stress concentrations for this composite system.

Introduction

Discontinuous fiber or particulate reinforced metal matrix composites (MMC), apart from their high strength and stiffness, also have distinct advantages of being both machinable and producible by conventional metallurgical processes. Therefore, there is ever increasing potential in the use of MMCs in several engineering applications. In structural applications intended for these composite materials, resistance to fatigue failure is of significant importance. Experimental data on fatigue crack growth and fracture behavior have been reported recently (1-7). However, the role of geometric discontinuities (e.g. notches, holes, sharp corners, etc...) on fatigue crack initiation and growth of short cracks emanating from stress concentrations have not been studied in detail.

Geometric discontinuities are preferred sites for damage formation and crack initiation. In initiation-controlled design approaches; it is often assumed that the stress concentration factor K_t will be a reasonable parameter to estimate the stress level at the notch. Under this assumption usually the notch-free specimen fatigue limit $\Delta\sigma_f$, is divided by K_t (i.e. $\Delta\sigma_f/K_t$). However, in practice it is found that the actual notch fatigue limit is higher than that predicted. Also, there is a considerable "hole size effect " (e.g. at the same K_t a larger notch has a lower notch fatigue limit) (8). To overcome these difficulties, Smith and Miller (9), Tanaka et.al. (10) and others (11-19), suggested models to establish a fatigue threshold for notches.

An accurate prediction of the growth rate of small cracks emanating from notches is particularly important for the MMCs. This is due to their inherently low fracture toughness (20,21) which yields very small fatigue crack growth for a critical crack length at which unstable fracture does occur. In general fatigue cracks in a notched specimen grow faster than cracks in a notch-free specimen subjected to the same nominal stress intensity factor range. It is attractive to predict growth behavior of short cracks using a stress intensity factor, since it accounts for changes in geometry and loading conditions.

In this study, the fatigue crack initiation and growth characteristics of short cracks emanating from blunt notches in a particulate SiC reinforced aluminum MMC are investigated. The correlation of crack initiation and growth of short cracks with fracture mechanics parameters, and the role of aging treatment on the fatigue behavior, are discussed.

Experimental Studies and Results

The MMC consisting of 25% SiC particulate in 6061-Al alloy in T6 condition in the form of 1.9mm thick sheet was received from DWA Inc. The material was produced by a P/M technique and the tensile properties after final mechanical processing are summarized in Table I. The material was tested in two metallurgical conditions, at T6 (as-received) and an overaged condition. The overaging heat treatment was carried out by heating the as-received material at 177°C for 100 hours. The variation in matrix hardness was measured with a diamond pyramid intenter under 5 gf load. After overaging heat treatment the hardness level was reduced from 118 to 84 (Vickers Dph) indicating a considerable loss in the matrix strength. The accelerated aging effect of MMCs due to the high dislocation density around the particles resulting from the differences in the thermal expansion coefficients of the particles and matrix was reported (6).

Table I Tensile properties of the as-received (T6 condition) metal matrix composite.

Orientation	E (GNm^{-2})	0.2% σ_{ys} (MNm^{-2})	σ_{uts} (MNm^{-2})	$\%\epsilon_f$
L	110.0	416.4	512.6	5.02
T	107.0	412.6	510.9	4.88

The single edge notch specimens (SEN) of 22mm width and 140mm in length were machined parallel to the rolling direction. During the studies, the fatigue crack initiation from five different notch geometries was investigated. The notches had essentially a deep hyperbolic shape with zero flank angle and were introduced perpendicular to the rolling direction by grinding. The dimension of the notches and resulting stress concentration factors are summarized in Table II. The fatigue tests were carried out under constant load amplitude. The load ratio was kept at about 0.3, and the loads were applied sinusoidally at a frequency of 15 Hz.

Table II Dimensions of the notches and resulting stress concentration factors for isotropic materials(28).

Notch Type	Notch Depth (mm)	Root Radius (mm)	K_t
I	5.0	0.15	9.59
II	5.0	0.30	6.80
III	5.0	0.70	4.48
IV	10.0	1.50	2.65
V	10.0	3.00	1.98

Initiation and propagation of fatigue cracks were monitored by measuring the potential difference across the notch faces. The other details of the experimental procedure and full results can be found in Ref. 22.

In Fig. 1, the fatigue crack initiation life for the T6 and the overaged conditions are presented. In this figure, the number of cycles to initiate fatigue crack are correlated with $K_t\Delta\sigma$.

The correlation of the crack growth rates with stress intensity factor range ΔK is given in Fig. 2. In this figure only the results obtained from specimens containing notches I-III were included. In specimens having notch types IV and V, immediately after crack nucleation fast fracture took place due to the deep notch depths. After crack initiation, an initial fast growth with small increase in the crack lengths can be seen from the figure. However, as the crack lengths become long enough, the growth rates varied linearly with ΔK. The crack growth data for long cracks can be presented using the Paris-Erdogan (16) law as:

$$da/dN = C\,(\Delta K)^n \qquad (1)$$

The parameters for this equation for the materials tested are:

	C $mm/(N/mm^{3/2})^n$ cycle	n
T6 Condition..........	9.121×10^{-17}	5.055
Overaged Condition.....	8.669×10^{-20}	5.944

Although the slope of the da/dN curve is slightly higher for the overaged material, overall crack growth rates for given ΔK values are lower than the T6 condition, as can be seen from Fig. 2.

To predict the crack growth rates over the entire range of fatigue crack lengths, effective crack lengths, δ, were calculated from the equation given below (19).

$$\delta = a\,(1.0-\exp(-4.0\,(c/\sqrt{a\rho})(1.0+a/\sqrt{a\rho}))) + c \qquad (2)$$

where a is the notch depth, ρ is the notch radius and c is the length of the fatigue crack emanating from the notch. These effective crack lengths were used to calculate the stress intensity factor ranges in the usual manner. Calculated stress intensity factor ranges were designated as ΔK_{eff} in order to distinguish them from the standard ΔK. Then, the material parameters that had been determined previously for the long crack growth data (C and n values) were used together with ΔK_{eff} values in the Paris-Erdogan law (Eq. 1) to determine the da/dN values. These predicted crack growth rates are compared with the experimental values. The examples of such comparisons are presented in Figs. 3-5. As can be seen, the agreement is reasonably good for the all three notch geometries.

The growing cracks from the notches remained relatively straight and planar on a macro scale. On the other hand, examinations and high magnifications as given in Fig. 6 indicated that crack paths are quite irregular on a micro scale. The decohered or broken SiC particles associated with the crack path can be seen. Also, it may be seen that the crack path was often through regions of the matrix having an absence of visible particles. Measurements of volume % of the SiC particles associated with the crack paths gave, on average, a slightly higher volume % of the particles than the measurements that were made on other areas. Crack deflection and crack bridging from the decohered or fractured particles were often observed.

Discussion

It is well known in the fatigue literature that the notch tip plasticity plays an important role in dictating crack initiation. One might assume that the thickness of the specimens (1.9mm) could be too small to maintain a plane-strain condition. Therefore, there is an intrinsic thickness effect in the data presented. However, as can be seen from Table I and Fig. 2, during the entire fatigue crack growth, K_{max} values were much lower than the ASTM E-399 limit of $0.45\sigma_{ys}\sqrt{W}$ for valid plane-strain conditions. Also the fatigue fracture surface remained flat and shear type fracture was only observed during the unstable fracture.

The fatigue crack initiation data observed in Fig. 1 are considerably different from those commonly seen for the matrix alloy. Although the stress concentration factors varied from 9.59 to 1.98, there is almost no influence of the notch geometry on the crack initiation. Also, the metallurgical condition of the matrix alloy did not have a significant effect on the crack initiation life. No direct observation could be made; however, the test results and metallographic data presented earlier suggest that the nucleation of the fatigue cracks are associated with SiC particles. The nucleation event could take place by either the failure of the interface between the particles and matrix or the failure of the SiC particles at the notch stress field. For monotonic loading it is now well established that failure mechanisms of carbide particles resulting from dislocation pile-up are essentially maximum principle stress controlled. The strength of the particles is inversely proportional to the square root of their dimension (23-25). Considering the inhomogenous size of particles, the probability of finding a crack nucleating particle increases with increasing sampling volume ahead of a stress riser. As the notch severity decreases, an increase in the number of cycles to nucleate a fatigue crack is usually expected. In the case of MMCs, it appears that the reduction in the stress concentration in blunt notches is compensated by the other competing factor which is the large sampling of particles (statistically an increase in possible nucleation sites).

The crack initiation data presented here clearly indicate that, during the design or selection of these materials for components containing stress risers, the division of the fatigue strength obtained from smooth specimens by a stress concentration factor (i.e. $\Delta\sigma_f/K_t$) can be considerably in error and very misleading.

In Figs. 2-5 the observed crack growth rates for short cracks emanating from the notches are in the order of 10^{-4} to 10^{-5} mm/cycle. These values are higher than the values usually measured for the matrix alloy at threshold values(10^{-6} to 10^{-8} mm/cycle)(26,27). Also in the overaged composite, the growth rate of fatigue cracks for entire crack lengths are slower than the T6 condition. In the 2xxx and 7xxx Al alloys produced by powder metallurgy (P/M), due to the very small grain size, insignificant effects from crack closure and deflection on fatigue crack growth for a wide range of aging conditions have been reported (26,27). Although the composite system studied in this work was produced by a P/M technique, the observed different behavior from the typical fatigue characteristics of the matrix alloy is assumed to be associated with the interaction of the SiC particles and discussed in detail in Ref. 22.

The procedure described predicts the growth rate of short cracks from notches within a reasonable accuracy, despite the microstructural inhomogeneity in MMCs. As mentioned earlier an accurate predictions of short crack behavior emanating from notches is particularly important for MMCs because of their inherently low fracture toughness values. The results indicate that the procedure outlined here could be an adequate engineering method for designing against fatigue failure from a range of stress concentrations for this composite system.

Conclusions

The initiation and growth rate of cracks emanating from blunt notches in a metal matrix composite consisting of 6061-Al alloy and 25% particulate SiC were studied for two aging conditions. The results indicate that

1. The initiation of the fatigue cracks is insensitive to the notch severity and to the aging condition of the matrix alloy.
2. The growth rate of fatigue cracks is found to be sensitive to the matrix aging condition in this composite system.
3. Growth rates of short cracks emanating from notches can be accurately described for this material by an effective stress intensity factor range ΔK_{eff}.

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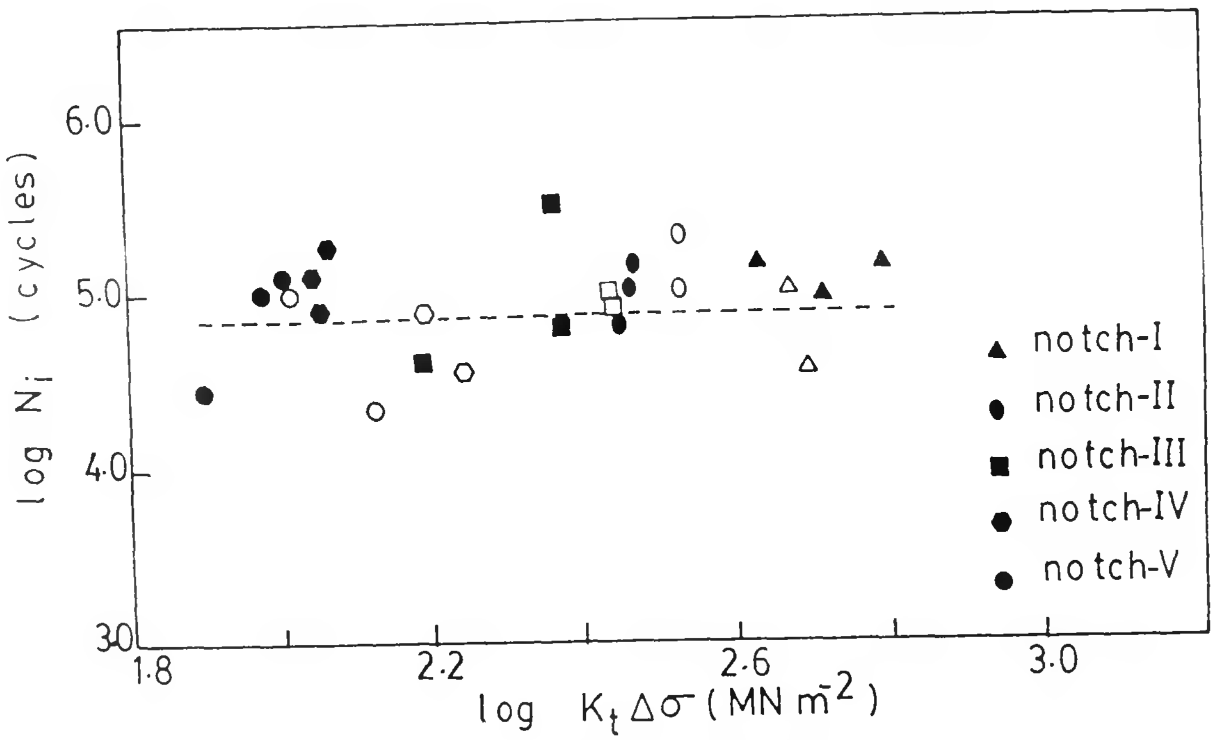

Fig. 1 - Correlation of crack initiation data with stress concentration factor and net section stress. Open symbols are for overaged and solid symbols for T6 condition.

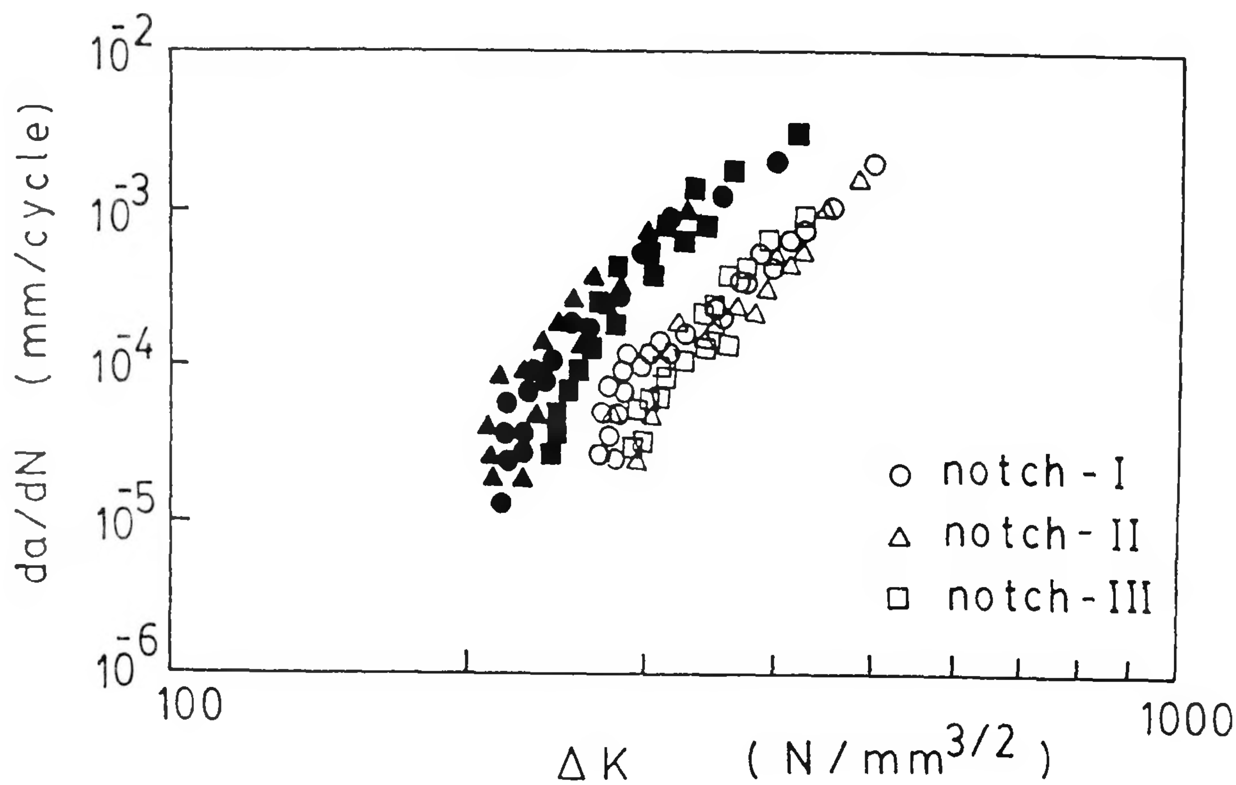

Fig. 2 - Correlation of fatigue crack growth data with stress intensity factor range. Open symbols are for overages and solid symbols are for T6 condition.

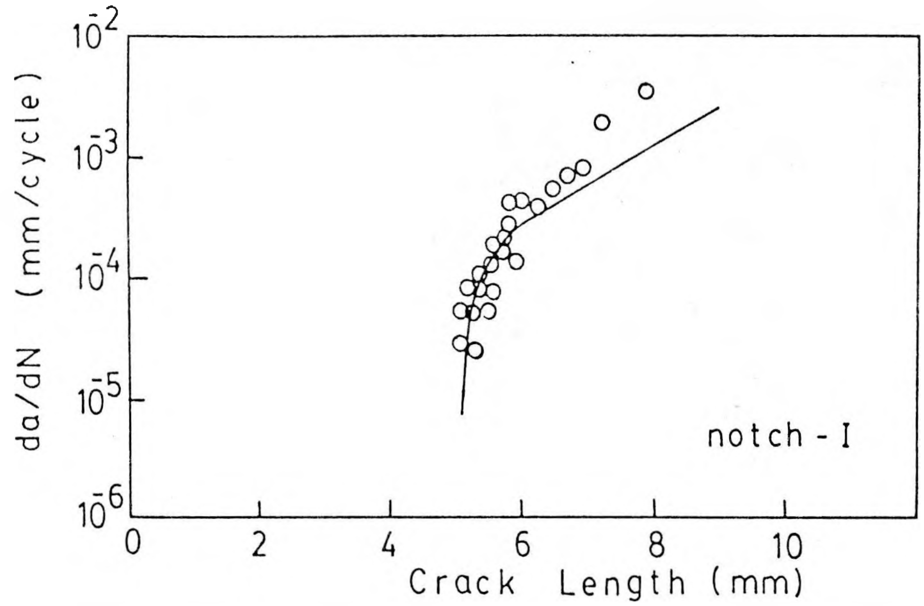

Fig. 3 - Comparison of the predicted (solid line) and the observed crack growth rates. Notch depth 5 mm and Root radii 0.15 mm.

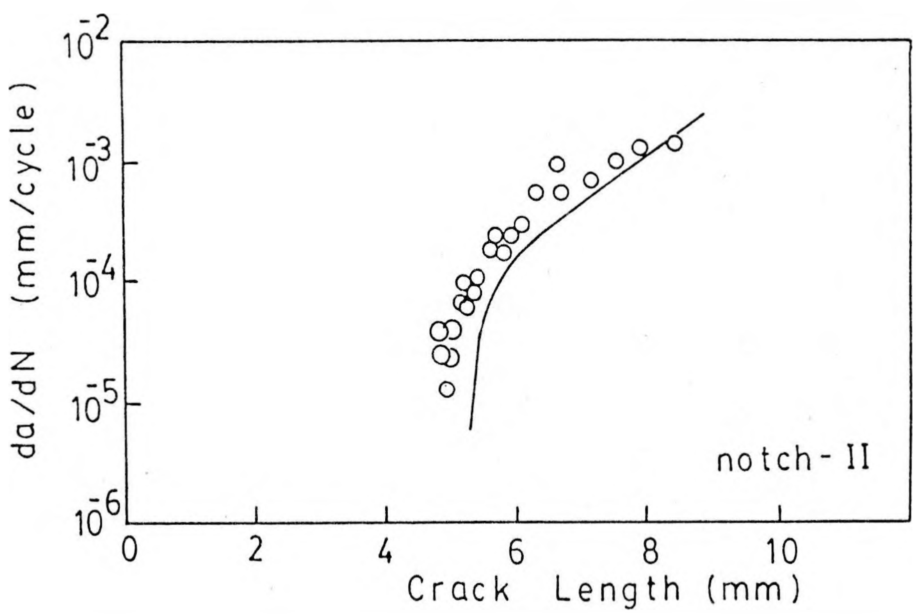

Fig. 4 - Comparison of the predicted (solid line) and the observed crack growth rates. Notch depth 5 mm and Root radii 0.30 mm.

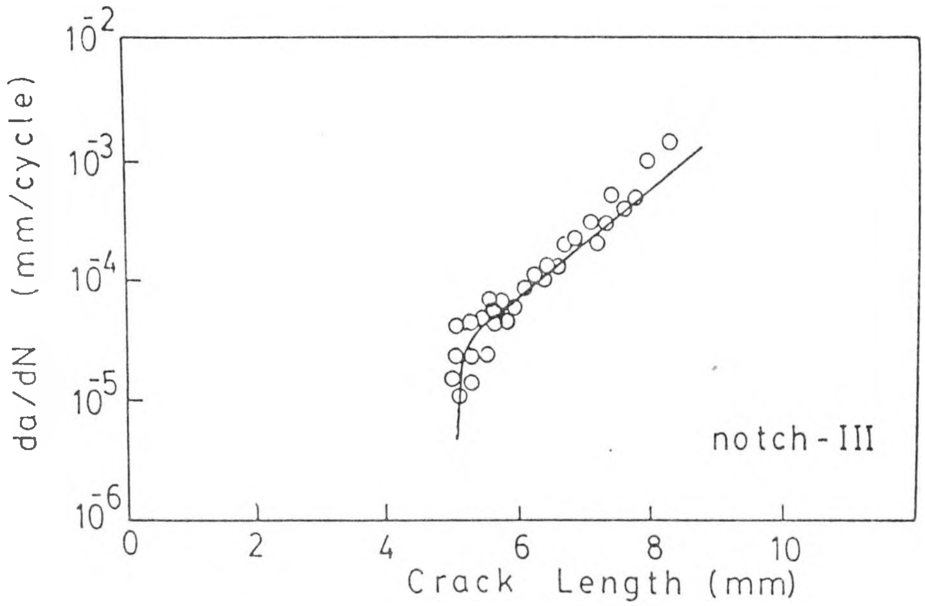

Fig. 5 - Comparison of the predicted (solid line) and the observed crack growth rates. Notch depth 5 mm and root radii 0.30 mm.

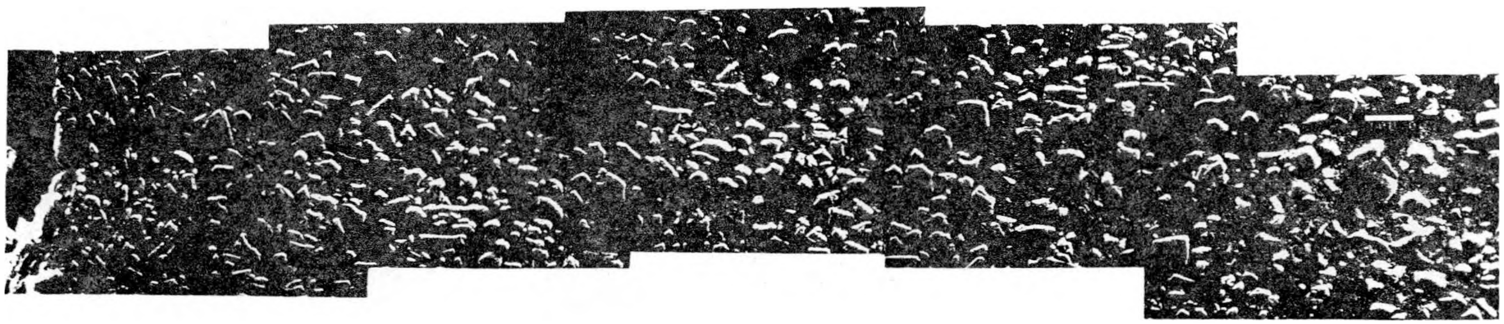

Fig. 6 - Appearance of the fatigue crack path. The crack deflection from SiC particles and crack bridging can clearly be seen.