DAMAGE EVOLUTION IN CERAMIC MATRIX COMPOSITES

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The evolution of the matrix cracking spacing in a 0/90 cross ply CAS/SiC ceramic matrix composite has been studied using an interrupted four-point bend test, taking replicas of the tensile surface at several stresses until the saturation cracking stress was reached. A precise strain measurement was simultaneously obtained from a strain gauge fixed on the sample's tensile surface. The interfacial frictional shear resistance to sliding is derived from this data using the ACK model for matrix crack evolution. This is compared with frictional shear stress measurements made by fibre push-down tests, using nanoindentation techniques.

INTRODUCTION

Ceramic Matrix Composites (CMCs) have higher toughness than monolithic ceramics because of their ability to redistribute stresses around the stress concentration zones. There are two basic mechanisms of stress redistribution: matrix cracking and fibre pullout. Nevertheless these phenomena occur only for interfaces between the fibre and the matrix that are weak enough to allow debonding and fibre sliding. Damage in these materials initiates with matrix cracking. By using four point bend and replication techniques, the evolution of damage in a CMC can be measured. The Ceramic Matrix Composite selected for this study is a cross-ply $[(0/90)_3]_s$ calcium-aluminium silicate glass matrix (CAS) reinforced with continuous Nicalon® fibres, provided by Rolls-Royce plc (U.K.).

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EXPERIMENTAL PROCEDURE

The evolution of the matrix cracking density with tensile strain has been measured using interrupted four point bending tests, with an outer span of 40 mm and an inner span of 20 mm, on 4x2.5x45 mm beams. The specimens were set with the plies perpendicular to the tensile surface. The actuator was stopped every 10 MPa and the matrix cracking density measured in all the plies of the tensile surface using acetate film replicas. Simultaneously the strain in this surface was measured with a strain gauge positioned as shown in Fig. 1.

RESULTS

Figures 2 to 4 show the matrix cracking evolution in an area of the tensile surface comprising the double 90° central ply, another 90° ply and three 0° plies. It is noticeable that the damage initiates in the central ply and at higher strains cracks appear in the other 90° plies and propagate towards the 0° plies. Saturation in 90° plies occurs for lower stresses than in 0° plies.

Figure 5 is a plot of the average crack densities in 0° and 90° plies and in the central ply for each tensile surface replica versus the strain measured by the gauge in this surface. Again, it is noticed, as in Fig. 2, that damage initiates in 90° plies, with the first cracks appearing in the central ply. For a strain between 0.16% and 0.18% the crack density in 0° plies becomes higher than in 90° plies, with the lowest values corresponding to the central ply. This trend is maintained up to saturation. The stresses and the strains in the tensile surface at matrix cracking initiation, σ_{mc} and ε_{mc}, at matrix cracking saturation, σ_s and ε_s, and the matrix cracking saturation density, ρ_s, for plies at 90°, at 0° and for the central ply are gathered in Table 1.

TABLE 1– Characteristic values of matrix cracking initiation and saturation.

Plies	σ_{mc} MPa	ε_{mc} %	σ_s MPa	ε_s %	ρ_s cr/mm
central	51	0.04	180	0.29	6.19
90°	61	0.05	191	0.32	7.46
0°	61	0.05	191	0.32	10.25

The stress-strain behaviour of the tensile surface during the interrupted four point bending test, together with matrix cracking densities in 0° plies, are shown in Fig. 6. Also illustrated in Fig. 6 and Table 1, matrix cracking initiates at approximately 61 MPa in 0° and 90° plies. This compares well with previous work (Sánchez et al. (1)) on tensile testing of the same material, where the matrix cracking stress was measured as 62.2 MPa.

From fibre push-down tests, the interfacial shear stress τ was determined as $\tau=16 \pm 2$ MPa (Daniel et al. (2)). Push-through tests (from (2)) give $\tau = 13\pm3$ MPa.

DISCUSSION

The ACK model (3) is the original model that predicts the crack spacing in unidirectional long fibre reinforced composites. Pryce and Smith (4) state that this model reasonably predicts the cracking initiation and the cracking spacing in 0° plies in cross ply composites. The minimum matrix cracking spacing at saturation, x', is given by the following expression:

$$x' = \frac{V_m}{V_f}\frac{\sigma_{mu} r}{2\tau} \qquad (1)$$

where σ_{mu} is the breaking strength of the matrix, V_m and V_f are the matrix and fibre volume fraction, respectively, r is the fibre radius and τ the interfacial frictional shear stress. Puente et al. (5) measured V_m, V_f and r for the cross-ply CAS/SiC, at 61.3 %, 38.7 % and 7.1 μm respectively.

The breaking stress of the matrix is derived from the composite matrix cracking stress as in Cao et al. (6), that accounts for the residual stresses present in the matrix. For this matrix, σ_{mu} = 135 MPa. The crack density in 0° plies, once saturation is reached, is 10.25 cr/mm (Table 1), i.e. average spacing, l_s = 97.5 μm. As l_s=1.34x' (Kimber and Keer (7)), x'=72.8 μm.

By substituting these parameters in Eq. (1), an interfacial frictional stress of τ=10.4 MPa is obtained. This result is within the lower bound of the standard deviation of measurements made by push-through tests.

CONCLUSIONS

The onset and evolution of matrix cracking in the cross-ply layers of a ceramic matrix composite, have been measured using an interrupted four point bend test, tensile surface replication, and strain gauge measurement.

The measured matrix cracking stress was used to determine the interfacial frictional shear stress for the composite and found to compare well with the same property measured by other, individual fibre push-down, experiments. Thus, the experimentally measured macroscopic behaviour of the material has been used to determine a micromechanical property that compares well with alternative micromechanical measurements.

ACKNOWLEDGEMENTS

The authors acknowledge Rolls-Royce plc for the financial support. The funding received from the Spanish “Comisión Interministerial de Ciencia y Tecnología” (CICYT) and from the “Viceconsejería de Educación, Universidades e Investigación” of the Basque Government made possible the purchase of the nanoindentation equipment. M.R.E., I.P. and A.M.D. are grateful to the Spanish Ministry of Education and Science, to the Department of Education, Universities and Research of the Basque Government, and to the Commission of the European Union, for the grants received.

REFERENCES

(1) Sánchez, J.M., Puente, I., Elizalde, M.R., Martín, A., Martínez, J.M., Daniel, A.M., Fuentes, M. and Beesley, C.P., ASTM STP 1309, Jenkins, M.G., Gonczy, S.T., Lara-Curzio, E., Ashbaurgh, N.E., and Zawada, L.P. (Eds), 1996, in press.

(2) Daniel, A.M., Elizalde M.R., Martínez-Esnaola, J.M. and Janczak, J., Ceram. Eng. Sci. Proc., Vol. 17, No 4-5, 1996, in press.

(3) Aveston, J., Cooper, G.A. and Kelly, A., Proc. Nat. Phys. Lab., 1971, pp. 15-25.

(4) Pryce, A.W. and Smith, P.A., J. Mat. Sci., Vol. 27, 1992, pp. 2695-2704.

(5) Puente, I., Sánchez, J.M., García-Alonso, S., Martín, A., Fuentes, M. and Beesley, C.P., Anales de Mecánica de la Fractura, Vol. 11, 1994, pp. 354-359.

(6) Cao, H.C., Bischoff, E., Sbaizero, O., Ruhle, M., Evans, A.G., Marshall, D.B. and Brennan, J.J, J. Am. Ceram. Soc., Vol. 73, 1990, pp. 1691-99.

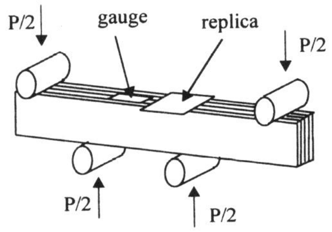

Figure 1. Interrupted bending test. Scheme.

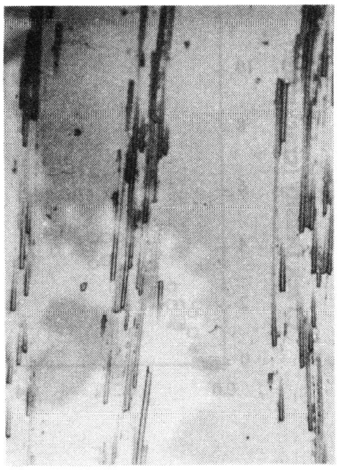

Figure 2. Replica micrograph for a strain of 0.06 %.

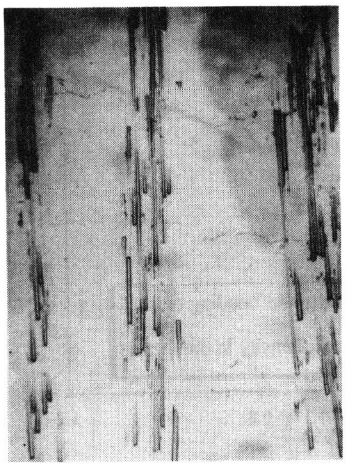

Figure 3. Replica micrograph for a strain of 0.14 %.

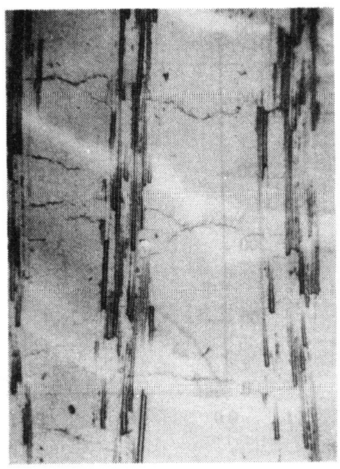

Figure 4. Replica micrograph for a strain of 0.2 %.

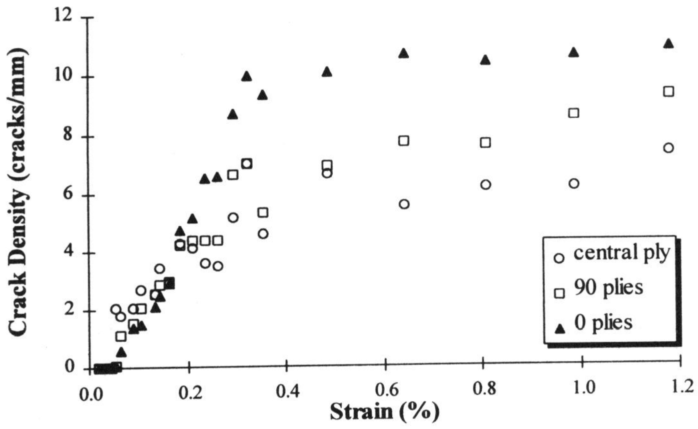

Figure 5. Matrix cracking density versus strain for the central ply, the other 90° plies and the 0° plies.

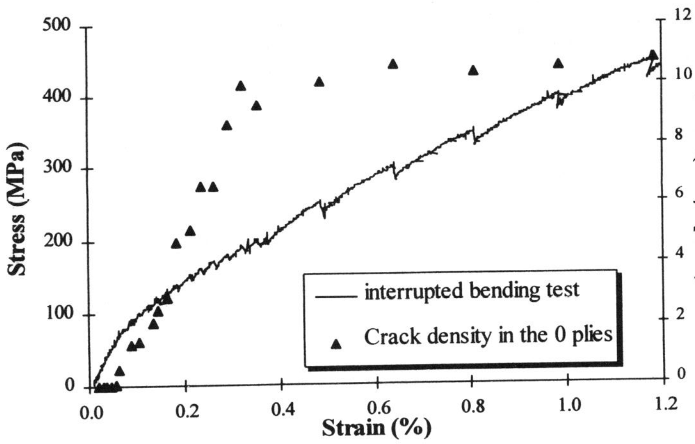

Figure 6. Matrix cracking density in the 0° plies and stress versus strain in the tensile surface of a bending four point test.