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High Temperature Fracture and Fatigue of Ceramics

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1.0 Introduction

This report covers work done in the final year of our contract "High Temperature Fracture and Fatigue of Ceramics" that commenced in August, 1994 as a follow-on from our prior contract "Mechanisms of Mechanical Fatigue in Ceramics." We focused in this period on developing constitutive models for multiple cracks bridged by creeping fibers; experimental observations of mechanisms and crack growth rates at high temperatures; and scaling results in the problem of a crack growing in the presence of a viscous fluid.

2.0 Experiments

Slow crack growth tests have been performed on 2D woven SiC-SiC compact tension specimens in order to develop a complete understanding of bridging mechanisms and crack growth at elevated temperatures. The extent of creep crack growth is accurately monitored using stereographic analysis of *in situ* images. Images were typically taken at 32 times magnification. It has been demonstrated that photographs of this type can be used to differentiate crack openings of less than 0.5 μm by stereoscopy [1]. This procedure allows identification of open cracks even when the crack is not visible on a single image. The time dependence of crack path, length, and opening along the length can be recorded. These are essential data for model formulation and validation.

Figure 1 shows the crack path of a sample tested at 1000 N and 1000°C. Only one crack was observed although it branched as shown in the figure. The crack grew to approximately 9.7 mm from the notch (8.7 mm longer than the initial fatigue crack). Following each branching, one offshoot became dominant while the other stopped growing. At the first split, the lower branch in the figure was the first to propagate in the plane of the notch. The upper branch then propagated past the lower branch and was the only branch to continue to grow. Stereoscopy reveals that the stalled branch does not continue to open. This single branch dominance is different from what has been observed at room temperature during monotonic loading. In this case parallel cracks were seen to open and extend concurrently.

In order to confirm that the cracks observed on the sample surface by stereoscopy were in fact through-thickness cracks and to check for cracks outside the field of view during testing, specimens were polished down to reveal crack paths in the interior. A number of observations can be made. First, fiber bridging in crept samples is evident from the notch to the crack tip validating the use of the crack openings measured for calculating fiber bridging laws. Second, cracks observed by stereoscopy did persist through the thickness of the samples. Third, more cracks were observed on the polished samples than were observed *in situ* requiring future experiments to be conducted with a wider field of view, although the additional cracks are probably small enough to be consistent with the hypothesis of a single dominant crack for large crack lengths. Fourth, cracks tend to

travel through the regions of high porosity in the corners between fiber tows. Fifth, there appear to be a greater number of cracks in the interior of the specimen (where there is greater porosity) than on the surface. We continue to probe the implications of these observations by viewing these detailed observations in light of micromechanical models.

Continued investigation of creep crack growth is taking place on two fronts. The width of the field of view for stereoscopy is being increased to approximately 6.5 mm from the current 2.8 mm. This will allow *in situ* observation of all of the cracks seen on the polished samples and a thorough test of the hypothesis of a single dominant crack. In addition, a novel real time crack length monitoring technique has been developed. It consists of a thin film high temperature crack gauge that allows continuous, accurate readings of crack length. This is a major development in experimentation, since widely used compliance based techniques have proven to be inaccurate.

Figure 1: Creep crack growth path in SiC-SiC at 1000°C and 1000 N.

3.0 Constitutive Law for Cracks Bridged by Creeping Fibers

It has been observed experimentally in some CMCs that when the temperature is raised enough to cause fiber creeping, one single crack grows across the specimen, at the expense of other cracks [1,2]. This is in contrast with what is often observed at room temperature, where multiple cracks grow. We believe that this is caused by the reduction of the matrix stresses next to the prevailing crack, which shields other matrix crack tips from the applied load.

The determination of the size and progression of the shielding zone is essential to predicting the existence of a dominant crack. We believe the phenomenon may be related to fiber creep, since the constant volume deformation of creep produces a large contraction of the fiber. In the elastic case, the fiber loses contact with the matrix when Poisson's contraction exceeds the initial strain mismatch that produced residual radial stresses along the interface. Constant volume creep deformation adds to Poisson's

contraction, augmenting the size of the shielding zone and making its length time dependent.

In our model, the fiber/matrix interface is divided in three zones. The first zone, the closest to the crack plane, is the noncontact region where no shear stress is transmitted across the fiber-matrix interface. The next region is modeled using a shear-lag model assuming that the sliding along the interface is resisted by a uniform shear stress. It has been shown that this simple model produces very good approximations for many experiments [3]. The transition from the noncontact region to the frictional region is controlled by the radial stresses, which are negative (compressive) in the frictional zone and zero (loss of contact) in the noncontact zone. Far away from the crack plane the composite is intact and there is no sliding along the interface. The transition from the intact zone to the frictional zone is controlled by the fracture mechanics of a mode II crack running along the interface. We consider the case where an arbitrary residual stress exists in both radial and axial directions, thus controlling the residual stresses and so the extent of each of the interface zones. With the basic model described above, we are able to determine, in closed form, the stress and strain states of the composite. The bridging law is then determined and can be used to predict the shielding effects. We expect to be able to predict the onset of the changing from a multiple crack configuration in low temperature to a single dominant crack in high temperature. This work continues.

4.0 Computational Modeling of CMC Failure

We developed a custom finite element model called the Binary Model under other funding to study failure in textile composites [4]. The Binary Model represents all tows in a representative volume of material (usually several cubic cm) and predicts the distribution of local stresses among tows and interstitial matrix during the evolution of damage events. The constitutive laws required for tow or matrix elements are derived by micromechanical modeling from experimental observations of failure mechanisms. The Binary Model has hitherto been applied exclusively to problems in polymer composites, where the degree of anisotropy is very high. We are now interested in adapting it to study problems in textile CMCs, since we believe that textile architectures are a very promising solution (and perhaps the only solution) to the severe delamination problem in CMCs. But CMCs have much milder elastic anisotropy than polymer composites, so the formulation of the model had to be modified somewhat. Partly to demonstrate the correctness of the new formulation for CMCs, we have completed successful simulations of the stochastic rupture process in a unidirectional CMC composite [5]. The simulations include realistic calculations of the 3D-stress redistribution around broken fibers and matrix cracks. Analytic solutions due to Curtin and others are reproduced in appropriate limits, while solutions are also obtained for more general conditions of interface strength and elastic mismatch between fibers and matrix, where the analytical solutions are in

error. We are now confident that the Binary Model will be an accurate and efficient analytical method for CMC textile composites.

5.0 Models of Rate Dependent Crack Processes

In collaboration with Professor Reiner Dauskardt of Stanford University, we are modeling cracks containing viscous fluids, using glass and water as a model system, but with very similar mechanics expected for ceramics containing glassy phases at high temperature. The model is built on an adaptation of our bridged crack codes, which solve a powerful integral equation formulation of quite general bridged crack problems.

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6.0 Collaborations and Other Activities

Key collaborations over this period were as follows.

1. With Professor Bob McMeeking on applications of the Binary Model to the basic analysis of failure in CMCs with various nonlinearities. Ph.D. students advised on this topic: Mr. Mike McGlockton and Mr. Chad Landis.
2. With Professor Reiner Dauskardt of Stanford University. His Ph. D. student Keith Yi has used our bridged crack codes to analyze crack growth in the presence of a viscous crack-filling fluid.
3. We continue to test SiC/SiC material supplied by Professor Nasr Ghoniem of UCLA.
4. We have begun to exchange test data and information with the group at PNL, including Drs. Chuck Henager and Charles Lewinson.
5. We received some free samples of 3D angle interlock woven SiC/SiC composite through DoE from a previous materials development program at Dow Corning (Andy Szweda). Specimens are currently being cut from these for delamination crack growth studies.

Invited papers on our work were presented at the annual American Ceramic Society meeting in Cincinnati and at ICF9 in Sydney, Australia.

7.0 Cumulative List of Publications under This Contract

1. B.N. Cox and D.B. Marshall, "The Determination of Crack Bridging Forces," *Int. J. Fracture* **49**, 159-76 (1991).
2. B.N. Cox and D.B. Marshall, "Stable and Unstable Solutions for Bridged Cracks in Various Specimens," *Acta Met. Mater.* **39**, 579-89 (1991).
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17. R. M. McMeeking, M. R. Begley, and B. N. Cox, "A Model for Creep Rupture in Ceramic Matrix Composites," *Anales de Mecanica da Fractura - 3^as Jornados Ibericas de Fractura*, 1996.

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21. C. Argento, "Bridging Law for Cracks Bridged by Creeping Fibers with Loss of Fiber/Matrix Contact," to be submitted to *Acta Materialia*.
22. K. S. Yi, B. N. Cox, and R. H. Dauskardt, "Fatigue Crack-Growth Behaviour of Materials in Viscous Fluid Environments," submitted to *J. Mech. Physics Solids*.

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8.0 Papers Published or in Preparation in this Reporting Period.

1. M. A. McGlockton, R. M. McMeeking, and B. N. Cox, "A 3D Finite Element Model for Assessing Unidirectional CMC Strength," to be submitted to *J. Mech. Phys. Solids*.
- 2.* R. M. McMeeking, M. A. McGlockton, and B. N. Cox, "Rupture Simulations for Unidirectional Ceramic Matrix Fiber Composites," in *Advances in Fracture Research, Proc. Ninth Int. Conf. Fracture*, Sydney, Australia, 1997, ed. B. Kharihaloo, Y.-W. Mai, M. I Ripley, and R. O. Ritchie, Pergamon, Amsterdam, 1997. Vol. 2, pp. 751-8.
- 3.* C. Argento, "Bridging Law for Cracks Bridged by Creeping Fibers with Loss of Fiber/Matrix Contact," to be submitted to *Acta Materialia*.

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- 4.* K. S. Yi, B. N. Cox, and R. H. Dauskardt, "Fatigue Crack-Growth Behaviour of Materials in Viscous Fluid Environments," to be submitted to *Acta Materialia*.

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