High Temperature Fracture and Fatigue of Ceramics

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1.0 Introduction

This report covers work done in the second year of the phase 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 computational models of stress redistribution effects in CMCs, high temperature experiments, and analytical models of rate dependent crack growth, including creeping fiber effects and the effects of a viscous fluid.

2.0 Experiments

We are now generating remarkably detailed *in situ* observations of cracking in woven SiC/SiC laminates at 1150°C [1]. In conjunction with high temperature fracture data from other laboratories (e.g., [2]), we are forming a consistent picture for the first time of the failure sequence under creep conditions. In SiC/SiC, the first nonlinearity to set in as temperature rises in an inert environment is fiber creep. At the temperature of our tests, the matrix remains essentially elastic; and, since the fiber creep rate is strongly stress dependent, fiber creep occurs mainly in fibers that bridge matrix cracks and therefore have unusually high loads. The experiments show subcritical matrix crack growth at fixed load, with one matrix becoming dominant. We believe this crack growth results from loss of crack tip shielding as the bridging fibers creep. Cracks that would remain arrested and benign (in many applications) in a rate independent material grow subcritically to become through cracks. Through cracks are often fatal in themselves; and their presence also accelerates fiber failure.

3.0 Theory of High Temperature Failure

The experiments are confirming the validity of our modeling approach, which out of our impatience had moved a little ahead of experiment! Our bridged crack codes have been adapted to the problem of creeping fibers (rate dependent bridging tractions). The subcritical crack growth problem has been analyzed in detail by a combination of numerical and analytical methods; regimes of stable and unstable crack growth have been mapped out (stable growth usually being preferred for damage tolerant design); and some important transitions in failure mode have been predicted [3,4]. We have solved the problem of a dominant matrix crack emanating from a notch in a standard specimen as well as the problem of natural crack initiation in a typical 0/90° laminate [4].

One of the essential results of our experimental and theoretical work is that the steady state matrix cracking stress, first derived by Aveston, Cooper, and Kelly and a key material design parameter at room temperature, is no longer a safe limiting stress at elevated temperature. Subcritical crack growth will allow failure at much lower stresses, given sufficient time. In engineering practice, there will be a new material parameter,

which will probably take the form of a single rate constant associated with the softening of bridging tractions due to fiber creep, which will lead to predictions of time to failure as a function of load. This has so far been demonstrated only for SiC/SiC, but it is likely to be a general result for all composites in which the fibers are polycrystalline: polycrystalline fibers must be fine-grained to be strong; and fine-grained fibers will creep.

We have also begun to acquire evidence of the interaction of mechanical fatigue loading and ultimate failure after subcritical crack growth. Cyclic fatigue predisposes fibers to fail on the matrix crack plane. This has very important consequences for toughness and high temperature failure mechanisms. Our next phase of work will include studies of the interaction of high temperature and cyclic loading effects.

4.0 Computational Modeling of CMC Failure

In the prior reporting period, we began a collaboration with Professor Bob McMeeking of UCSB and a jointly supervised student Mike McGlockton on a fundamental study of how the brittleness of a unidirectional CMC is affected by the statistics of flaws and the redistribution of load around fiber failures [5]. In the current reporting, work continued on this topic, but its conclusion has been delayed by Professor McMeeking's absence on sabbatical. We will report more fully in the next annual report.

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.

References

1. D.R. Mumm, W.L. Morris, M.S. Dadkhah, and B.N. Cox, "Subcritical Crack Growth in Ceramic Composites at High Temperature Measured Using Digital Image Correlation," in *Thermal and Mechanical Test Methods and Behavior of Continuous-Fiber Ceramic Composites*, ASTM STP 1309, ed. M. G. Jenkins, S. T. Gonczy, E. Lara-Curzio, N. E. Ashbaugh, and L. P. Zawada (ASTM, Philadelphia, 1996).
2. C.H. Henager and R.H. Jones, "High-Temperature Plasticity Effects in Bridged Cracks and Subcritical Crack Growth in Ceramic Composites," *Mater. Sci. Engng A166*, 211 (1993).

3. 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.
4. B.N. Cox and D.B. Marshall, "Crack Initiation in Fiber Reinforced Brittle Laminates," *J. Amer. Ceram. Soc.*, in press.
5. M.A. McGlockton, R.M. McMeeking, and B. N. Cox, "The Tensile Failure of a Unidirectional Ceramic Matrix Composite," submitted to *Acta Mater.*

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 is currently using our bridged crack codes to analyze crack growth in the presence of a viscous crack-filling fluid.
3. We continued a small collaboration with Professor Nasr Ghoniem and Dr. Anter El Azab of UCLA on damage in CMCs at high temperature. Professor Ghoniem supplied us with the SiC/SiC sample we have been testing.

Invited papers on our work were presented at American Ceramic Society meetings in New Orleans and Indianapolis.

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).
3. B.N. Cox, "Extrinsic Factors in the Mechanics of Bridged Cracks," *Acta Met. Mater.* **39**, 1189-1201 (1991).
4. B.N. Cox and D.B. Marshall, "Crack Bridging in the Fatigue of Fibrous Composites," *Fatigue Fract. Enging. Mater. Struct.* **14**, 847-61 (1991).

5. B.N. Cox and C.S. Lo, "Load Ratio, Notch, and Scale Effects for Bridged Cracks in Fibrous Composites," *Acta Met. Mater.* **40**, 69-80 (1992).
6. B.N. Cox, "Fatigue and Fracture of Brittle Fibrous Composites," invited paper in *Fatigue of Advanced Materials*, ed. R.O. Ritchie, B.N. Cox, and R.H. Dauskardt (MCE Publ., Birmingham, England, 1991).
7. R.H. Dauskardt, R.O. Ritchie, and B.N. Cox, "Fatigue of Advanced Materials: Part I," *Advanced Materials and Processes*, Number 7 (1993) pp. 26-31.
8. R.H. Dauskardt, R.O. Ritchie, and B.N. Cox, "Fatigue of Advanced Materials: Part II," *Advanced Materials and Processes*, Number 8 (1993) pp. 30-35.
9. B.N. Cox and D.B. Marshall, "Concepts for Bridged Cracks in Fracture and Fatigue," Overview No. 111, *Acta Metall. Mater.*, **42** (1994) 341-63.
10. B.N. Cox and L.R.F. Rose, "Time or Cycle Dependent Crack Bridging," *Mechanics of Materials*, **19** (1994) 39-57.
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12. B.N. Cox, "Life Prediction for Bridged Fatigue Cracks," in *Life Prediction for Titanium Matrix Composites*, ASTM STP 1253, ed. W.S. Johnson, J. Larsen, and B.N. Cox (ASTM, Philadelphia, Pennsylvania, 1996) pp. 552-72.
13. M.R. Begley, B.N. Cox, and R.M. McMeeking, "Time Dependent Crack Growth in Ceramic Matrix Composites with Creeping Fibers," *Acta Metallurgica et Materialia* **43**[11], 3927-36 (1995).
14. B.N. Cox, "Scaling for Bridged Cracks," *Mechanics of Materials*, **15** (1993) 87-98.
15. B.N. Cox and L.R.F. Rose, "A Self-Consistent Approximation for Crack Bridging by Elastic/Perfectly Plastic Ligaments," *Mechanics of Materials* **22**, 249-63 (1996).
16. D.R. Mumm, W.L. Morris, M.S. Dadkhah, and B.N. Cox, "Subcritical Crack Growth in Ceramic Composites at High Temperature Measured Using Digital Image Correlation," in *Thermal and Mechanical Test Methods and Behavior of Continuous-Fiber Ceramic Composites*, ASTM STP 1309, ed. M.G. Jenkins, S.T. Gonczy, E. Lara-Curzio, N.E. Ashbaugh, and L.P. Zawada (ASTM, Philadelphia, 1996).

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.
18. B.N. Cox and D.B. Marshall, "Crack Initiation in Fiber Reinforced Brittle Laminates" *J. Amer. Ceram. Soc.* **79**[5], 1181-8 (1996).
19. 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*.

Edited book:

Fatigue of Advanced Materials, ed. R.O. Ritchie, R.H. Dauskardt, and B.N. Cox, Proc. Engng Foundation Int. Conf., Santa Barbara, January 1991 (MCE Publishing, Birmingham, UK, 1991).

8.0 Papers Published or in Preparation in this Reporting Period.

- 1.* B.N. Cox, "Life Prediction for Bridged Fatigue Cracks," in *Life Prediction for Titanium Matrix Composites*, ASTM STP 1253, ed. W. S. Johnson, J. Larsen, and B. N. Cox (ASTM, Philadelphia, Pennsylvania, 1996) pp. 552-72. Reprint*
- 2.* M.R. Begley, B.N. Cox, and R.M. McMeeking, "Time Dependent Crack Growth in Ceramic Matrix Composites with Creeping Fibers," *Acta Metallurgica et Materialia* **43**[11], 3927-36 (1995). Reprint*
- 3.* B.N. Cox and L.R.F. Rose, "A Self-Consistent Approximation for Crack Bridging by Elastic/Perfectly Plastic Ligaments," *Mechanics of Materials* **22**, 249-63 (1996). Reprint*
- 4.* D.R. Mumm, W.L. Morris, M.S. Dadkhah, and B.N. Cox, "Subcritical Crack Growth in Ceramic Composites at High Temperature Measured Using Digital Image Correlation," in *Thermal and Mechanical Test Methods and Behavior of Continuous-Fiber Ceramic Composites*, ASTM STP 1309, ed. M.G. Jenkins, S.T. Gonczy, E. Lara-Curzio, N.E. Ashbaugh, and L.P. Zawada (ASTM, Philadelphia, 1996). Reprint*
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- 6.* B.N. Cox and D.B. Marshall, "Crack Initiation in Fiber Reinforced Brittle Laminates" *J. Amer. Ceram. Soc.* **79**[5], 1181-8 (1996). Reprint*

* Pulled for separate processing.

7. 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*.

*Copies appended.