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High Temperature Fracture and Fatigue of Ceramics

Final Technical Report

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ABSTRACT

This program has supported basic research into the mechanisms and mechanics of failure of ceramic matrix composites at high temperature and under cyclic loads. Specialist experiments have been developed to assess mechanisms by in situ observations of specimens under load at temperature. Extensive models have been formulated based on observed mechanisms. A central theme has been the theory of bridged cracks, which appear as a universal mechanism in CMC failure. Fundamentals of bridged cracks have been elucidated, including length scales and important asymptotic limits. Both experiments and models have studied rate dependent problems, for example, cracking at high temperature in the presence of fiber creep in composites.

1.0 Introduction

This report covers work done over the eight year life of our contract "Mechanisms of Mechanical Fatigue in Ceramics" spanning from August 14, 1989 through August 14, 1997. 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.

All our work has been reported in annual reports throughout this period and in journal articles. Here we provide a brief summary of areas of primary activity and a list of the publications.

The focus of our work has been high temperature failure of ceramic matrix composites and the theory of bridged cracks, which are the essential observed failure mechanism.

2.0 Experiments

We have developed apparatus for observing microscopic damage manifestations in situ in CMC specimens under load at temperature. High quality images are analyzed using our unique strain imaging apparatus, HASMAP, to reveal displacement fields and crack displacements. These quantitative measurements are the foundation of all our modeling work.

Our experimental methods have been applied to various materials, including carbon/SiC and SiC/SiC fibrous composites, multi-phase phase metal/ceramic materials, and monolithic ceramics. We have determined failure mechanisms in fatigue, monotonic loading, and creep conditions. Bridged cracks have been shown to be the central phenomenon in failure of CMCs. We have contributed substantially to understanding of crack initiation, single/multiple crack transitions, and rate effects (fatigue and creep).

3.0 Analytical Modeling

We have contributed many papers on models of bridged cracks. We have emphasized fundamental concepts, including the definition and roles of length scales, which determine how bridged cracks in widely differing classes of materials adhere to universal patterns of behavior. Length scales and limiting bridged crack configurations are now quite widely used to analyze bridged crack data in CMCs and other materials.

We developed algorithms for solving integral equations for bridged cracks, which are now used by several groups around the world to study diverse problems. The algorithms and analytical results for limiting cases have been extended to rate dependent cracks, which are found, for example, in creep dominated failure.

4.0 Textile Composites

In the last years of the contract, we became especially interested in the mechanics of textile composites. Textile reinforcement is especially relevant to CMCs, because it offers a solution to the vital problem of transverse strength in the presence of a brittle matrix.

We have developed various micromechanical models of the action of 3D reinforcing fiber tows. These models provide a guide to optimal composite design. They also enable quantitative analysis of experiments on textile composites. In a follow-on program, we are extending our models to rate dependent cases required for high temperature applications.

We have also developed a computational model, the Binary Model, of textile CMC composites. We have also used the Binary Model to study stress transfer and statistical failure problems in CMCs.

5.0 Collaborations and Other Activities

Key collaborations during the contract 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. With Professor Nasr Ghoniem of UCLA. On SiC/SiC composites. Ph.D. student involved: Dr. Anter El-Azab.

4. Exchange of test data and information with the group at PNL, including Drs. Chuck Henager and Charles Lewinson.

5. With Dr. Francis Rose of ARL, Melbourne, on the theory of bridged cracks.

6. With Professor Bob McMeeking on analytical models of bridged cracks. Ph.D. students advised on this topic: Dr. Calvin Lo and Dr. Matt Begley.

Invited papers on our work were presented at numerous conferences in the U.S. and elsewhere over the life of the contract.

6.0 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.

11. W. L. Morris, B. N. Cox, D. B. Marshall, R. V. Inman, and M. R. James, "Fatigue Mechanisms in Graphite/SiC Composites at Room and High Temperatures," *J. Amer. Ceram. Soc.*, **77** (1994) 792-800.

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[a]s 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*.

20. 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.

21. C. Argento, "Constitutive Law for Creeping Fibers Bridging a Brittle Crack," to be submitted to *J. Mech. Phys. Solids*.

22. 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*.

<u>Edited book:</u>

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).