High Temperature Fracture and Fatigue of Ceramics

Annual Technical Report No. 7

August 15, 1995 thru August 14, 1996

Grant No. DE-FG03-89ER45400

Prepared for:
U.S. Department of Energy
1333 Broadway
Oakland, CA 94605
Attn: James Solomon

Prepared by:
Brian Cox
Rockwell Science Center
1049 Camino Dos Rios
Thousand Oaks, CA 91360

June 1998

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MASTER
This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER
DISCLAIMER

Portions of this document may be illegible electronic image products. Images are produced from the best available original document.
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


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


Edited book:


8.0 Papers Published or in Preparation in this Reporting Period.


* Pulled for separate processing.

*Copies appended.*