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A NEW APPROACH TO THE EVALUATION OF THE EFFECTS OF STRESS STATE AND INTERFACIAL PROPERTIES ON THE BEHAVIOR OF ADVANCED METAL MATRIX COMPOSITES

FINAL REPORT

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The processing/microstructure/fracture properties relationships in fiber-reinforced Mg-alloy and Al-alloy composites have been characterized using mechanical testing, fractography, and Auger spectroscopy techniques. Fatigue crack growth mechanisms have also been identified, and the crack tip strain field and crack opening displacements measured using a stereoimaging technique. Local conditions for fiber and interface fracture have been determined as a function of fiber orientation. Relevant information of fracture mechanisms and failure criteria have been used to develop a 2D fracture-mechanics-based micromechanical fatigue crack growth model. Applications of the model to fiber-reinforced Mg-alloy and Ti-alloy composites under cyclic loading demonstrate that fatigue crack growth in these materials can be predicted on the basis of the fracture properties of the matrix, fiber, and interface.

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I. Statement of the Problem

The high specific strength and stiffness associated with advanced metal matrix composites offer considerable potential for use of these material systems in several key Army structural components, including portable bridges and helicopter transmission housings. At present, structural design approaches utilizing metal matrix composites require either incorporation of off-axis plies of fiber to reduce deficiencies in the inherent transverse strength of the fiber-reinforced composites and to improve the resistance of the fiber-reinforced composites to multiaxial loading or the use of particle or whisker reinforced material. Although a qualitative appreciation has been developed for the response of metal matrix composites to loads applied at an angle to the fiber axis and the behavior of cross-plied composites, no quantitative connection between microstructural variables and crack propagation behavior exists for these materials. The achievement of such an understanding is required before metal matrix composites can be most effectively utilized for structural components. Furthermore, a general capability for predicting fatigue crack growth in fiber-reinforced metal-matrix composites has not been available. This research program is an attempt to quantitatively relate fracture micromechanisms to interfacial properties and fatigue crack growth behavior of fiber-reinforced MMCs.

II. Summary of Program

The objective of this program was to develop quantitative relationships between crack tip strain fields, matrix microstructure and properties, interfacial strength, and fiber orientation and volume percent for continuous fiber reinforced metal matrix composites. Materials studied in this program were primarily alumina fiber reinforced Mg-alloy and, to a lesser extent, the Al-Li composites. For comparison with a fatigue crack growth model developed in this program, the experimental results of a B_4C-coated boron fiber reinforced Ti-alloy composite from a previous Air Force research program conducted at SwRI were also utilized.

The program goal was achieved using these approaches:

(1) experimental characterization of processing/microstructure/fatigue properties relationships in fiber-reinforced metal-matrix composites via conventional mechanical testing, fractography and Auger spectroscopy techniques [1,2].*

(2) identifying the relevant fracture mechanisms in a SEM equipped with a cyclic loading stage [3]. Important fracture mechanisms observed in the MMCs included fracture of fibers located ahead of the crack tip, propagation of fiber microcracks into the matrix, formation of interface microcracks by decohesion of the fiber/matrix interface, crack deflection at uncracked fibers, and the propagation of the interface cracks.

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* References are listed in Section V.

(3) experimental characterization of the crack-tip strain fields [3], local conditions for fiber fracture and interface decohesion [3], and the local driving force for fatigue crack growth [4] using the stereoimaging technique. This has led to the development of a modulus-normalized ΔK approach for predicting fatigue crack growth rates in fiber-reinforced composites [3]. The driving force for interface fatigue cracks has also been established [4].

(4) developing a 2D fracture-mechanics-based micromechanical model [5], which incorporates most of the relevant fracture mechanisms for predicting fatigue crack growth in fiber reinforced metal-matrix composites [6,7]. The proposed model, dubbed MML/CRK, has been successfully applied for predicting/simulating the fatigue crack behavior of an alumina fiber reinforced ZE41A composite and a B_4C-coated boron fiber Ti-6Al-4V composite as a function of either fiber orientation or interfacial degradation due to thermal exposure.

Important accomplishments in this program are:

1. established processing/microstructure/fracture properties relationships in alumina fiber Mg-alloy and Al-alloy composites.

2. identified the fracture mechanisms in alumina fiber ZE41A composite as a function of fiber orientation.

3. measured the crack-tip strain fields in MMC's leading to fiber fracture and interface fracture.

4. established failure criteria for fiber fracture.

5. quantified both experimentally and theoretically the local driving force for interface fatigue cracks in fiber composites; measured crack tip opening displacements for interface cracks.

6. developed a 2D fracture-mechanics based micromechanical fatigue crack growth model (MMC/CRK model) for fiber reinforced metal-matrix composites.

7. applied the MMC/CRK model to a fiber composite with strong interfaces (alumina fiber reinforced ZE41A composite) and to a composite with weak interfaces (B_4C-coated boron fiber Ti-6A-4V composite).

8. developed a modulus-normalized ΔK approach for relating matrix crack growth behavior to composite crack growth behavior.

9. established the beneficial effects of interfacial strength on fatigue threshold and crack growth rate.

10. identified possible effects of residual stress (from composite manufacturing) on the local crack driving force and the crack-tip opening displacements.

III. List of Publications Under Current Contract

1. "The Effect of Processing Parameters on the Tensile Properties of Alumina Fiber Reinforced Magnesium," by A. McMinn, R. A. Page, and W. Wei, Metallurgical Transactions, 18A, 1987, pp. 273-281.

2. "Relationship of Fatigue and Fracture to Microstructure and Processing in Al_2O_3 Fiber Reinforced Metal Matrix Composites," by R. A. Page and G. R. Leverant, Fifth Int. Conference on Composite Materials, ICCM-V, edited by W. C. Harrigan, Jr., J. Strife, and A. K. Dhingra, TMS, Warrendale, PA, 1985, pp. 867-886.

3. "Micromechanisms of Fatigue Crack Growth in An Alumina Fiber Reinforced Magnesium Alloy Composite," by D. L. Davidson, K. S. Chan, G. R. Leverant, and A. McMinn, Metallurgical Transactions A, 1988 (submitted).

4. "Driving Forces for Composites Interface Fatigue Cracks," by K. S. Chan and D. L. Davidson, Engineering Fracture Mechanics, 1988 (in press).

5. "A Fatigue Crack Growth Model for Fiber-Reinforced Metal-Matrix Composites," by K. S. Chan, Fatigue and Fracture of Engineering Materials and Structures, 1988 (submitted).

6. "Relationships of Fatigue Mechanism and Crack Growth Rate in Fiber-Reinforced Metal-Matrix Composites," by K. S. Chan, D. L. Davidson, and G. R. Leverant, Proceedings of the Seventh International Conference on Fracture, ICF7, Houston, TX, 1989.

7. "Effects of Interfacial Strength on Fatigue Crack Growth in a Fiber Reinforced Titanium-Alloy Composite," by K. S. Chan and D. L. Davidson, Metallurgical Transactions A, 1988 (submitted).

IV. Participating Scientific Personnel

1. Dr. G. R. Leverant (Director, Department of Materials Sciences, Principal Investigator).
2. Dr. D. L. Davidson (Institute Scientist).
3. Dr. K. S. Chan (Principal Engineer).
4. Dr. R. A. Page (Staff Scientist).
5. Dr. W. Wei (Research Engineer).
6. Mr. A. McMinn (Senior Research Engineer).
7. Mr. John B. Campbell (Senior Technician).
8. Mr. James F. Spencer (Senior Technician).

V. References

1. A. McMinn, R. A. Page, and W. Wei, "The Effect of Processing Parameters on the Tensile Properties of Alumina Fiber Reinforced Magnesium," Metallurgical Transactions, 18A, 1987, pp. 273-281.

2. R. A. Page and G. R. Leverant, "Relationship of Fatigue and Fracture to Microstructure and Processing in Al_2O_3 Fiber Reinforced Metal Matrix Composites," Fifth Int. Conference on Composite Materials, ICCM-V, edited by W. C. Harrigan, Jr., J. Strife, and A. K. Dhingra, TMS, Warrendale, PA, 1985, pp. 867-886.

3. D. L. Davidson, K. S. Chan, G. R. Leverant, and A. McMinn, "Micromechanisms of Fatigue Crack Growth in An Alumina Fiber Reinforced Magnesium Alloy Composite," Metallurgical Transactions A, 1988 (submitted).

4. K. S. Chan and D. L. Davidson, "Driving Forces for Composite Interface Fatigue Cracks," Engineering Fracture Mechanics, 1988 (in press).

5. K. S. Chan, "A Fatigue Crack Growth Model for Fiber-Reinforced Metal-Matrix Composites," Fatigue and Fracture of Engineering Materials and Structures, 1988 (submitted).

6. K. S. Chan, D. L. Davidson, and G. R. Leverant, "Relationships of Fatigue Mechanism and Crack Growth Rate in Fiber-Reinforced Metal-Matrix Composites," Proceedings of the Seventh International Conference on Fracture, ICF7, Houston, TX, 1989.

7. K. S. Chan and D. L. Davidson, "Effects of Interfacial Strength on Fatigue Crack Growth in a Fiber Reinforced Titanium-Alloy Composite," Metallurgical Transaction A, 1988 (submitted).