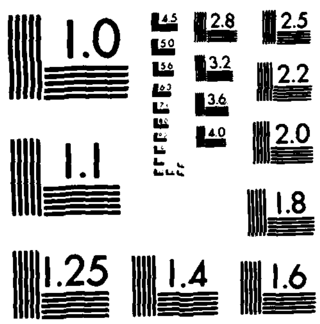
AD-A143 911 EVALUATION OF THE EFFECTS OF STRESS STATE AND INTERFACIAL PROPERTIES ON T..(U) SOUTHWEST RESEARCH INST SAN ANTONIO TX G R LEVERANT ET AL. JUL 84 1/1

UNCLASSIFIED ARO-17207.4-MS DAAG29-81-K-0049 F/G 11/4 NL



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Evaluation of the Effects of Stress State and Interfacial Properties on the Behavior of Advanced Metal Matrix Composites

FINAL REPORT

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July 1984

Contract No. DAAG29-81-K-0049

Southwest Research Institute
San Antonio, Texas

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER: ARO 17207.4-MS
2. GOVT ACCESSION NO.: N/A
3. RECIPIENT'S CATALOG NUMBER: N/A

4. TITLE (and Subtitle)
Evaluation of the Effects of Stress State and Interfacial Properties on the Behavior of Advanced Metal Matrix Composites

5. TYPE OF REPORT & PERIOD COVERED
FINAL REPORT
July 1981 - June 1984

6. PERFORMING ORG. REPORT NUMBER
06-6621

7. AUTHOR(s)
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John E. Hack
Richard A. Page

8. CONTRACT OR GRANT NUMBER(s)
DAAG29-81-K-0049

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Southwest Research Institute
6220 Culebra Road
San Antonio, TX 78284

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
P-17207-MS

11. CONTROLLING OFFICE NAME AND ADDRESS
U. S. Army Research Office
Post Office Box 12211
Research Triangle Park, NC 27709

12. REPORT DATE
July 1984

13. NUMBER OF PAGES

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report)
Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

NA

18. SUPPLEMENTARY NOTES

The view, opinions, and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Metal Matrix Composite
Al_2O_3 Fiber
Magnesium Alloys
Tensile Behavior
Fatigue
Cyclic Cleavage
Fracture Toughness
Thermal Exposure
Processing
Defects

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)
The effects of fiber fraction, fiber orientation and matrix alloy additions on tensile and fatigue behavior were studied in commercially pure magnesium and ZE41A (Mg-4.25Zn-0.5Zr-1.25RE) that were both reinforced with FP alumina fibers. In general, axial properties were found to be dependent on fiber fraction while off-axis properties were not. Off-axis loading resulted in substantial reductions in tensile and fatigue strength in the commercially pure matrix material. Although failure in tensile overload occurred along the weak fiber/matrix interface in off-axis specimens, subcritical fatigue -

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84 07 31 238

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cracks propagated parallel to the fiber direction but through the matrix. The fractographic appearance of these cracks is similar to cyclic cleavage along slip planes. The critical stress intensity for unstable fracture of off-axis material was controlled by a combination of the normal and shear stress components acting on the fiber/matrix interface. The alloying conditions in ZE41A resulted in a slight decrease in axial properties accompanied by a significant improvement in off-axis behavior. These differences were found to be a result of improved matrix and interface strengths and a decrease in fiber strength. The reaction zone product in both materials was determined to be MgO. The only influence of the alloying elements in ZE41A on the reaction zone appears to be a thickening of the zone due to a longer contact time with liquid Mg during solidification of the alloy. Subsequent investigation of reaction zone thickness in commercially pure material which was exposed to temperatures in excess of the melting point of Mg for various times appears to confirm this interpretation.

I. Background

The use of metal matrix composites (MMC) in structures will require design information based on well-developed quantitative relationships between processing history, microstructure and mechanical properties. Based on available information in the literature, the establishment of such relationships in various MMC systems has proven very elusive. Although a great deal of work has been performed on fracture mechanisms in metal matrix composites, the results to date have been quite contradictory in nature. The inconsistencies arise from the complex interaction of the fiber/matrix interfacial region with various applied states of stress. Furthermore, the presence of the fiber/matrix interface in these composites introduces several mechanisms of crack propagation in addition to those observed in monolithic materials. Also, standard metallurgical techniques for modifying the properties of the matrix material (i.e., alloying, heat treatment, deformation processing, etc.) affect the metallurgical structure and properties of the interfacial region as well. Thus, the effects of processing variables on composite behavior through microstructural changes in the matrix are difficult to separate from the effects of those variables on the fiber/matrix interface.

This report summarizes the results of a program which was initiated to overcome these difficulties by developing quantitative relationships between matrix microstructure, composition and properties, fiber orientation and volume percent, and fatigue crack growth behavior in these materials through direct observations of the effects of these variables on the strain field at the tip of a growing crack. The overall program is aimed at determining the local sequence of events at the tip of a fatigue crack (i.e., matrix failure vs. fiber failure vs. interfacial decohesion) and the critical strain accumulation required for these events to occur. However, very little data exist on the relationships between microstructure and fracture behavior in metal matrix composites. Thus, the efforts to date have concentrated on the baseline characterization of the tensile and fatigue behavior of Al_2O_3 fiber reinforced commercially pure Mg (CPMg) and a magnesium alloy (ZE41A). In particular, the influences of fiber fraction, fiber orientation, alloy content and loading conditions were investigated.

II. Summary of Program

The tensile and fatigue properties of CPMg and ZE41A as a function of orientation are shown in Figs. 1 and 2. Of particular note are the reduced monotonic and cyclic axial properties and enhanced off-axis properties for ZE41A compared to CPMg. This behavior is directly related to the size of the MgO reaction zone, Fig. 3, that forms at the fiber (Al_2O_3)/matrix interfaces, as well as the respective matrix strengths.

The manufacturer has indicated that the processing cycle (liquid metal infiltration) is identical for both composites. Since commercially-pure Mg will solidify congruently (i.e., no mushy zone) while ZE41A has a

mushy zone extending over a range of 120°C, this suggested that the reason for the thicker reaction zone and larger MgO particles in the latter were directly related to the time that the fibers were in contact with liquid magnesium. This has been confirmed by heat treating experiments conducted in this program. This result is also consistent with the fact that Auger spectroscopy has shown no preferential segregation of alloying elements in ZE41A to the fiber/matrix interface.

Detailed fractographic analysis of the off-axis CPMg fatigue specimens defined the extent of the subcritical and overload fracture zones. Combining these results with a fracture mechanics analysis, it was shown, Fig. 4, that the critical stress intensity (K_c) is controlled by both the normal and shear stress components acting on the fiber/matrix interface as follows:

$$\left(\frac{K_I}{K_{Ic}}\right)^2 + \left(\frac{K_{III}}{K_{IIIc}}\right)^2 = 1$$

Similar K_{Ic} and K_{IIIc} values were determined for a variety of crack geometries, indicating that K_c for interfacial delamination is geometry independent. Therefore, K_c should be effective as a design parameter. The principal conclusions resulting from this study are as follows:

1. Process defects in the form of large clumps of Al_2O_3 grains and fibers that were broken and lying on their sides were preferential sites for crack initiation for both monotonic and cyclic loading along the fiber axis. However, the presence of the defects was not detrimental to axial properties unless the size of the defect was a significant fraction of the specimen cross section. These defects did not play a role in crack initiation during off-axis loading.

2. For CPMg, a relatively weak fiber/matrix interface resulted in a large reduction in off-axis tensile properties. The reduction in strength is related to a change in the mode of fracture from flat fracture across fibers in the axial orientation to failure along the fiber/matrix interface in off-axis orientations. Interfacial failure occurred between the magnesium matrix and the MgO reaction zone.

3. For CPMg, fatigue crack initiation and propagation occurred primarily in the magnesium matrix for off-axis loading.

4. The critical stress intensity for unstable fracture of off-axis CPMg is controlled by both the normal and shear stress components acting on the fiber/matrix interface.

5. The alloying elements in ZE41A resulted directly in an increased matrix strength and indirectly in an increased fiber/matrix interfacial strength and a decreased fiber strength compared to CPMg.

6. The increased interfacial strength was due to a thicker reaction zone of larger MgO particles and not to segregation of alloying elements to the reaction zone. The size of the reaction zone is controlled by the markedly different solidification characteristics of CPMg compared to ZE41A, resulting in considerably different exposure times of the Al_2O_3 fibers to liquid magnesium.

7. The increased interfacial and matrix strengths combined with the decreased fiber strengths in ZE41A yielded reduced axial and increased off-axis tensile and fatigue properties compared to CPMg. In addition, this change in component strengths delayed the transition from fracture across the fibers to interfacial failure as the angle between the fiber direction and loading axis was increased.

III. List of Publications

1. "Critical Stress Intensity for Off-Axis Fracture of Al_2O_3 Fiber Reinforced Magnesium", by K. S. Chan, J. E. Hack and R. A. Page, Metallurgical Transactions A, Vol. 15A, pp. 756-759, 1984.

2. "Tensile and Fatigue Behavior of Aluminum Oxide Fiber Reinforced Magnesium Composites: Part I. Fiber Fraction and Orientation", by J. E. Hack, R. A. Page and G. R. Leverant, Metallurgical Transactions A, Vol. 15A, pp. 1389-1396, 1984.

3. "Tensile and Fatigue Behavior of Aluminum Oxide Fiber Reinforced Magnesium Composites: Part II. Alloying Effects", by R. A. Page, J. E. Hack, R. Sherman, and G. R. Leverant, Metallurgical Transactions A, Vol. 15A, pp. 1397-1405, 1984.

4. "The Influence of Thermal Exposure on Interfacial Reactions and Strength in Aluminum Oxide Fiber Reinforced Magnesium Alloy Composites", by J. E. Hack, R. A. Page and R. Sherman, Metallurgical Transactions A (submitted).

IV. Participating Scientific Personnel

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2. Mr. John E. Hack
3. Dr. Richard A. Page
4. Dr. Kwai Chan
5. Dr. Robert Sherman

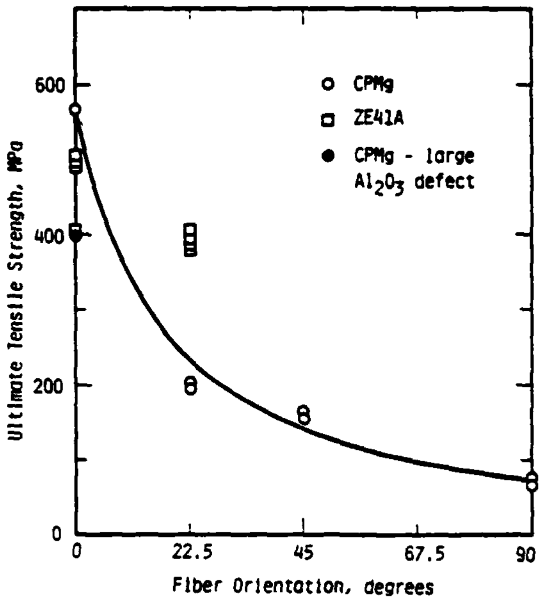

Fig. 1 — Effect of fiber orientation on ultimate tensile strength for both commercially pure magnesium and ZE41A matrix materials.

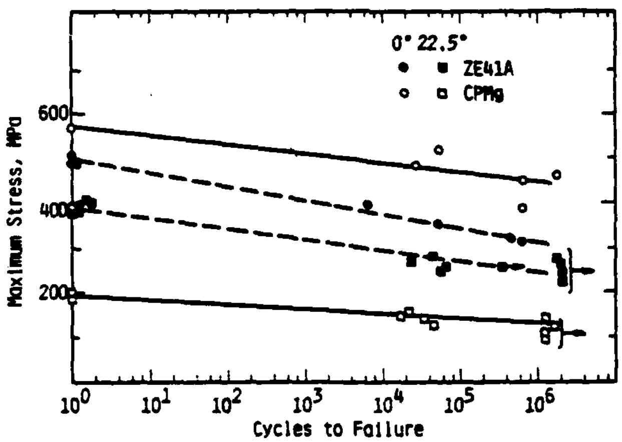

Fig. 2 — Effect of fiber orientation and matrix alloy addition on the fatigue behavior of Al_2O_3 fiber-reinforced magnesium.

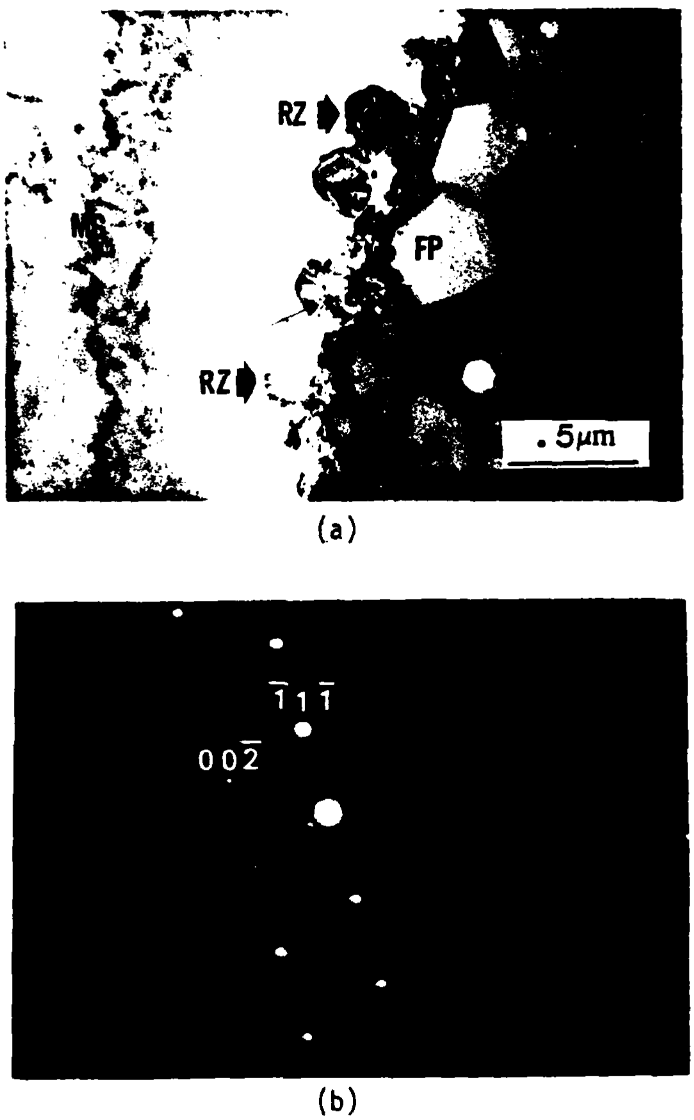

Fig. 3 —Transmission electron micrograph of the fiber/matrix reaction zone in ZE41A (*a*) and a diffraction pattern taken from a typical reaction zone particle (110 Zone) (*b*). The various constituents are indicated by: MG (ZE41A matrix); RZ (reaction zone product); and FP (Al_2O_3 fiber).

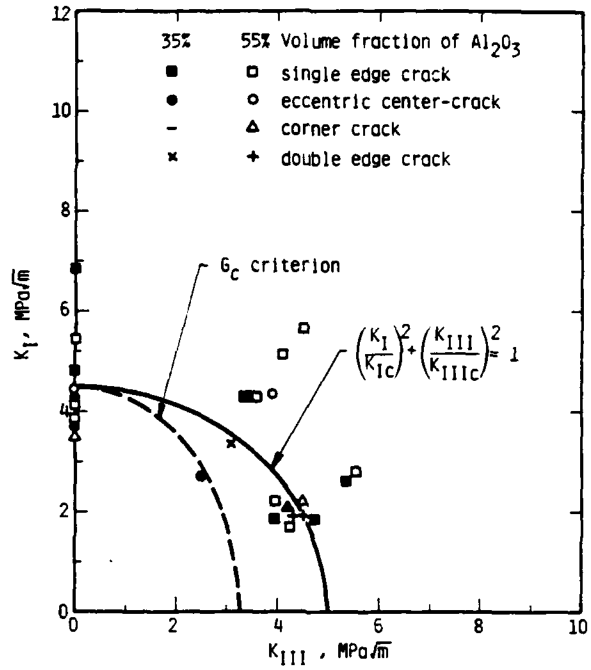

Fig. 4 —Calculated Mode I stress intensity factor, K_I, *vs* calculated Mode III stress intensity factor, K_{III}, for both 35 and 55 vol pct fiber. Solid line is for K_{Ic} = 4.5 MPa$\sqrt{m}$ and K_{IIIc} = 5 MPa$\sqrt{m}$.

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