FRACTURE CRITERIA FOR DISCONTINUOUSLY REINFORCED METAL MATRIX COMPOSITES

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ABSTRACT

This report summarizes the progress achieved during the period November 18, 1986 to November 17, 1987 on NASA Grant NAG-1-724, "Fracture Criteria for Discontinuously Reinforced Metal Matrix Composites". Appended to the report are copies of two manuscripts prepared by the authors under NASA funding during the performance period.

INTRODUCTION

Renewed interest in light-weight, ceramic reinforced metal matrix composites for high performance applications has recently resulted in the development of continuous and discontinuously reinforced silicon carbide reinforced aluminum alloy metal matrix composites (1,2). While these materials offer the potential of achieving outstanding strength and stiffness properties, their successful design application will require development of suitable damage tolerance design criteria. These criteria should also include development of relatively simple and inexpensive mechanical tests that can be used for materials qualification and acceptance.

Historically, damage tolerant design fail-safe design of metallic primary-airframe-structure has evolved from a consideration of whole-life fatigue to assesment of the influence of load spectrum on fatigue crack growth and fracture resistance, the latter utilizing the concepts embodied within linear elastic fracture mechanics (LEFM). The applicability of this approach to fail-safe design of monoque metallic structure has been repeatedly demonstrated through both laboratory and service experience.

One of the fundamental precepts included in the utilization of linear elastic fracture mechanics for airframe fail-safe design is that the description of the critical fracture event depends only on the <u>local</u> stress state in the vicinity of the crack tip, even if the stresses remote from the crack tip are very much different. This approach leads directly to the acceptance of the parameter K_{IC}, the Mode I plane strain fracture toughness, as a material property, similar to the yield strength, whose value does not depend upon specimen configuration. Indeed, determination of K_{IC} has been standardized through use of ASTM E-399 procedures.

However, the rather simple, but classic experiments of Reedy (3), have shown that linear elestic fracture mechanics failure criteria are not appropriate for continuously reinforced unidirectional metal matrix composites. His results showed, for example, that drastically different values of K_{IC} can be obtained in unidirectional boron/aluminum composites through variation in test coupon configuration. For samples oriented so that the pre-crack was perpendicular to the fiber axis, K_{IC} = 77 ksi√in for a center-cracked panel, 59 ksi√in for a three-point bend sample and 34 ksi√in for a compact-tension sample. Microscopic examination further indicated that the mode of crack growth in this material was also sample dependent. Crack growth in the three-point bend and compact-tension samples typically involved crack splitting and branching along the fiber-matrix interface, while crack propagation in the center-cracked samples proceeded across the fibers in a self-similar manner.

Early fracture toughness measurements in whisker reinforced aluminum metal matrix composites suggest that the results may also be specimen dependent. For example, plane strain fracture toughness values between 5 and 30 ksi√in have been reported (4-8) for whisker reinforced 6061 and 2124 aluminum. In addition, these investigators have noted the great difficulty encountered in pre-cracking L-T compact-tension samples. Indeed, almost all data were obtained utilizing L-T center-cracked panels. If confirmed, these observations cast doubt on the general applicability of linear elastic fracture mechanics to discontinuously reinforced whisker metal matrix composites.

The first phase of this investigation, as reported herein, was designed to examine what effect sample configuration has on the details of initial crack propagation in discontinuously whisker reinforced aluminum metal matrix composites. Care was taken to allow direct comparison of fracture toughness values utilizing differing sample configurations and orientations, holding all materials variables constant, e.g., extrusion ratio, heat treatment, chemistry, etc.

EXPERIMENTAL PROCEDURES

2124 reinforced with 5, 10 and 20 volume percent F-9 SiC whiskers is being utilized in this investigation. The 10 and 20 volume percent composites were donated by the Lockheed-Georgia Company and form the basis for this report. These materials were fabricated following the generalized procedures described in Appendices A and B. Essentially this process involves wet blending helium inert gas atomized powder and F-9 SiC whiskers, drying, cold compaction and vacuum hot pressing in the mushy zone to 6 inch diameter billets. Following homogenization, the billets were extruded to 5 inch wide by 0.5 inch thick planks.

Optical micrographs, Figure 1, of the 0.5 inch thick extrusions indicated that the SiC whiskers were relatively evenly distributed throughout the aluminum matrix. Quantitative analysis showed that the 11.5:1 extrusion ratio used in fabricating these composites resulted in a distinct alignment of the SiC whiskers with respect to the extrusion direction in both the transverse (T) and the thru-thickness (S) planes, Figures 2 and 3.

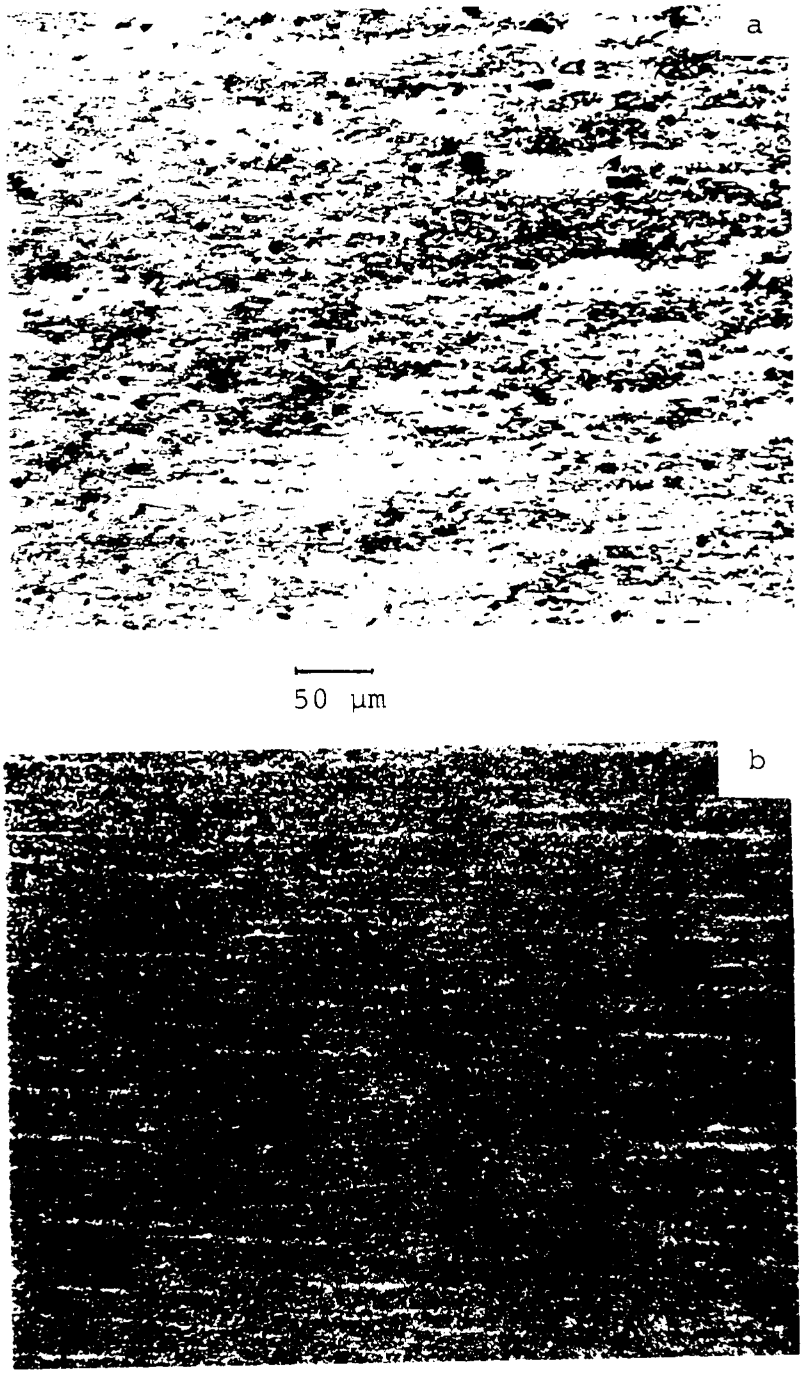

Figure 1 - Optical Micrographs of Extruded 2124 Reinforced with (a) 10 and (b) 20 Volume Percent F-9 SiC Whiskers.

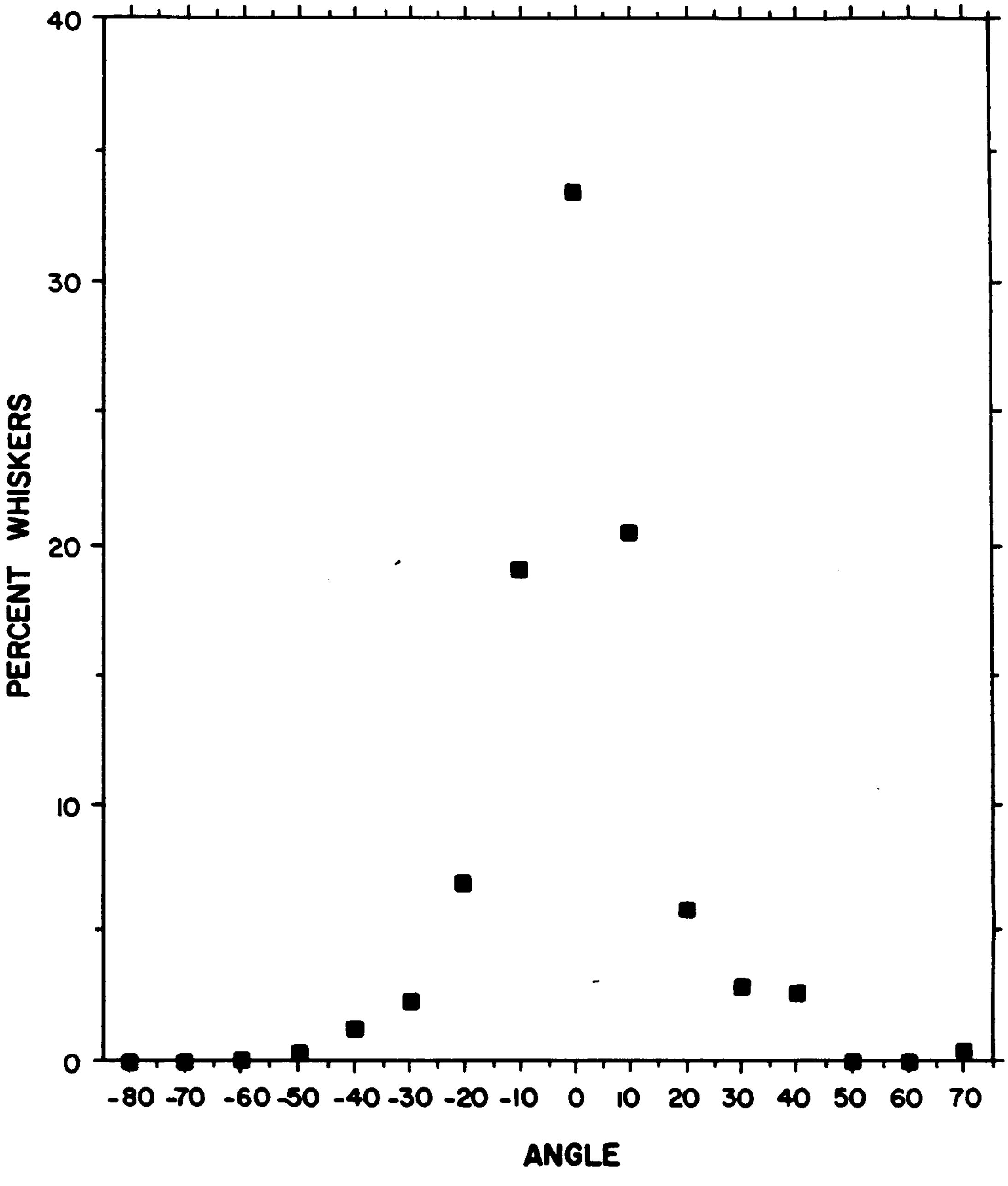

Figure 2 - SiC Whisker Distribution in Extruded 2124 Reinforced Reinforced with 10 Volume Percent F-9 SiC Whiskers. (a) Surface Orientation Plane and (b) Through Thickness Orientation Plane.

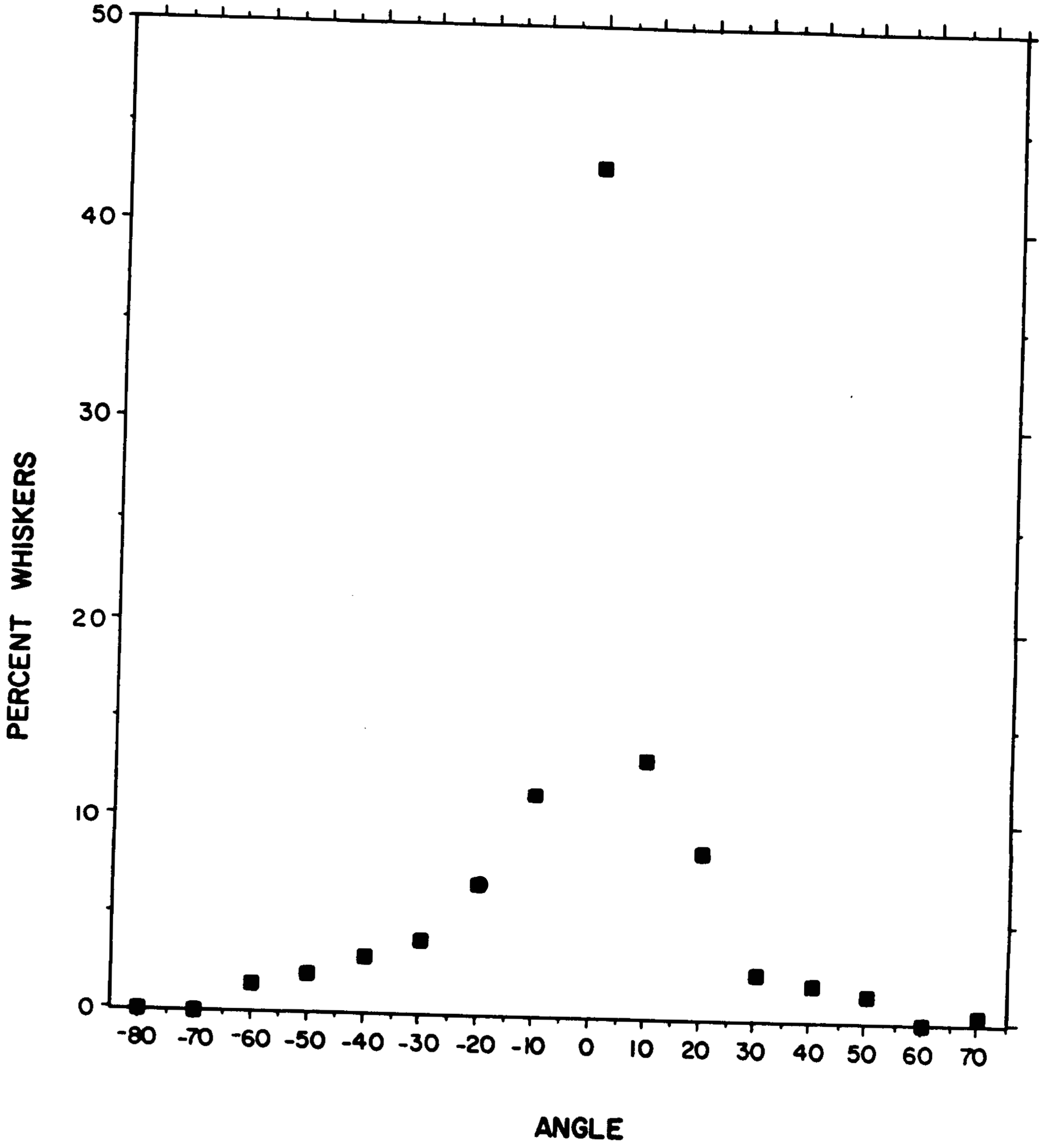

Figure 2(Continued)

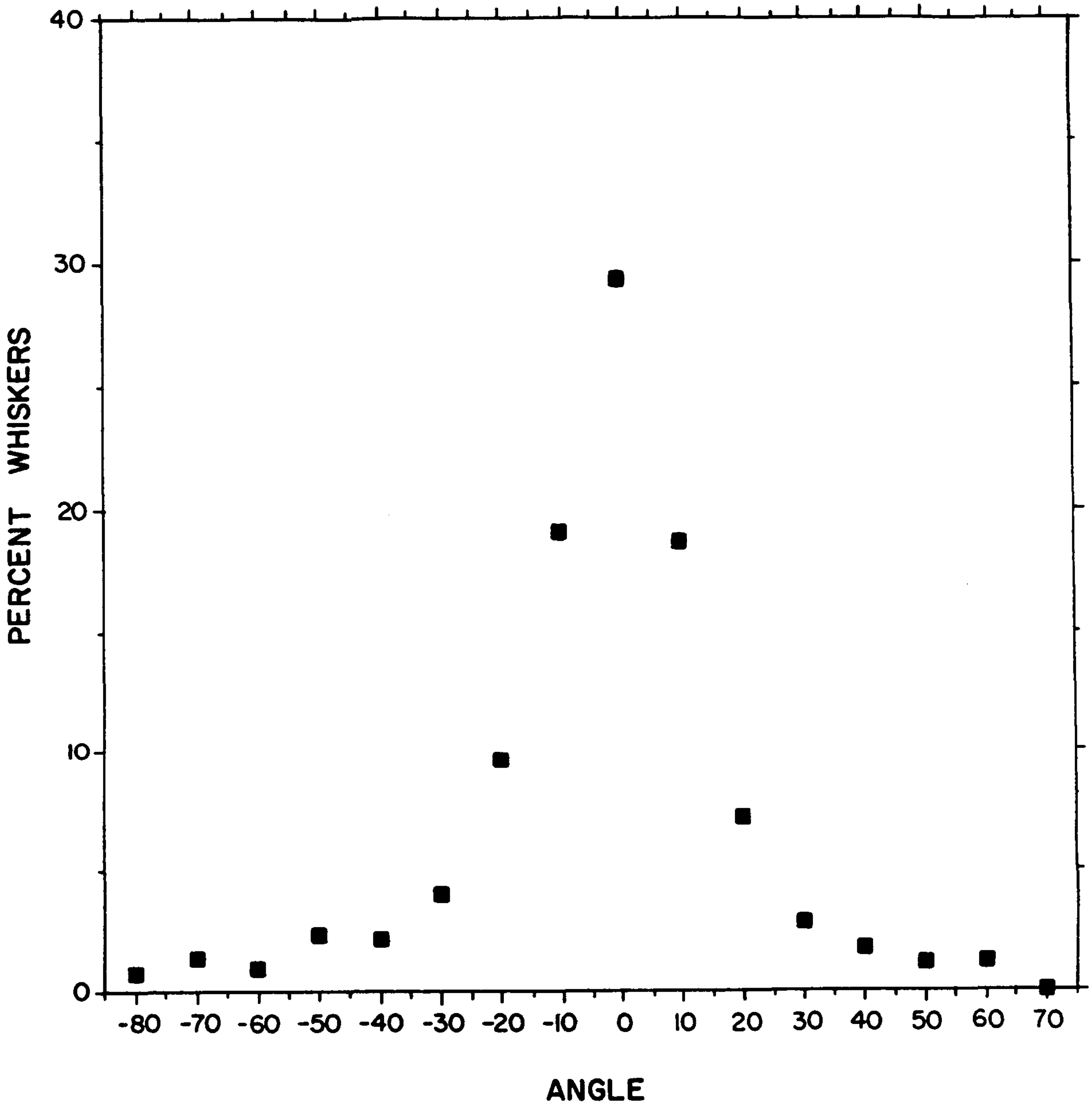

Figure 3 - SiC Whisker Distribution in Extruded 2124 Reinforced with 20 Volume Percent F-9 SiC Whiskers. (a) Surface Orientation Plane and (b) Through Thickness Orientation Plane.

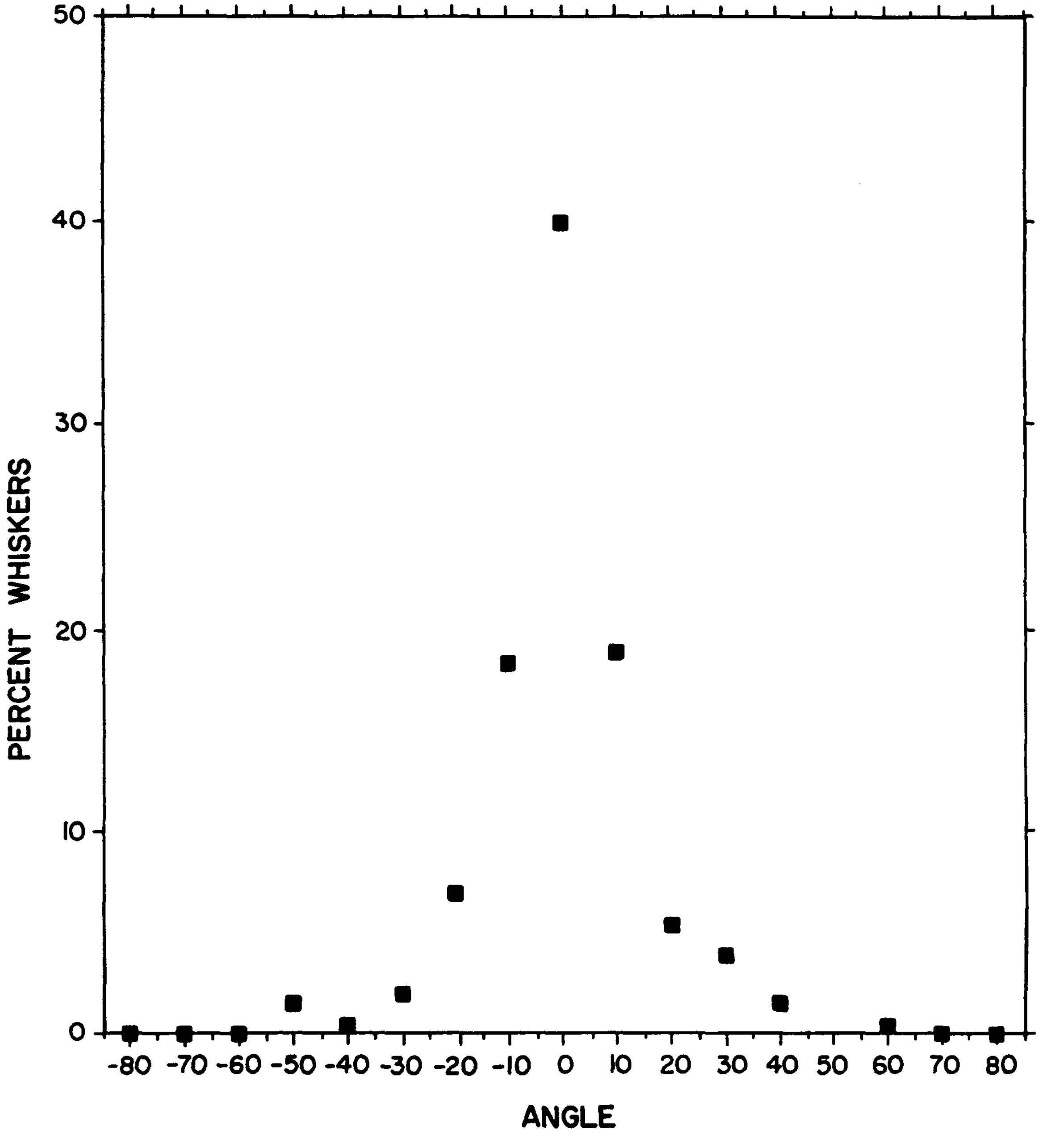

Figure 3(Continued)

Furthermore, the degree of alignment, as depicted by the standard deviation of the whisker orientation with respect to the extrusion direction, was a function of the volume percent SiC, the 20 volume percent reinforced composite exhibiting a higher degree of alignment, particularly in the thru-thickness plane.

All fracture toughness testing conducted during this study utilized the as-extruded (F) temper. Extension of these results to other heat treatment conditions is currently underway.

Figure 4 shows the two fracture toughness sample configurations tested. The first, Figure 4(a), was the standard compact tension (CT) specimen, as defined by ASTM E-399-85. Two thicknesses were examined, i.e., B = 0.1 and 0.5 inches. The second sample configuration was a center-cracked-panel (CCP), Figure 4(b). All center-cracked panels were 2 inches wide x 5 inches long x 0.5 inch thick, the starter notches, 0.04 inch wide x 0.5 inch long, having been cut by electro-discharge machining (EDM). Prior to pre-cracking both the compact tension and center cracked panels were mechanically polished thru 600 grit.

All fatigue loading was done at 40 cycles per second, initially utilizing loads estimated to be slightly below the fatigue crack threshold (9, 10). These loads were gradually increased until crack initiation was observed. Fatigue crack initiation and growth was monitored visually, through the use of a traveling microscope and with a crack opening displacement (COD) gage. Use of the latter techique was particularly important because of the extreme tightness of the fatigue pre-cracks at short lengths.

Pre-cracking of the compact-tension samples was performed on an MTS 880 servo-hydraulic machine operating under load control. Testing of the

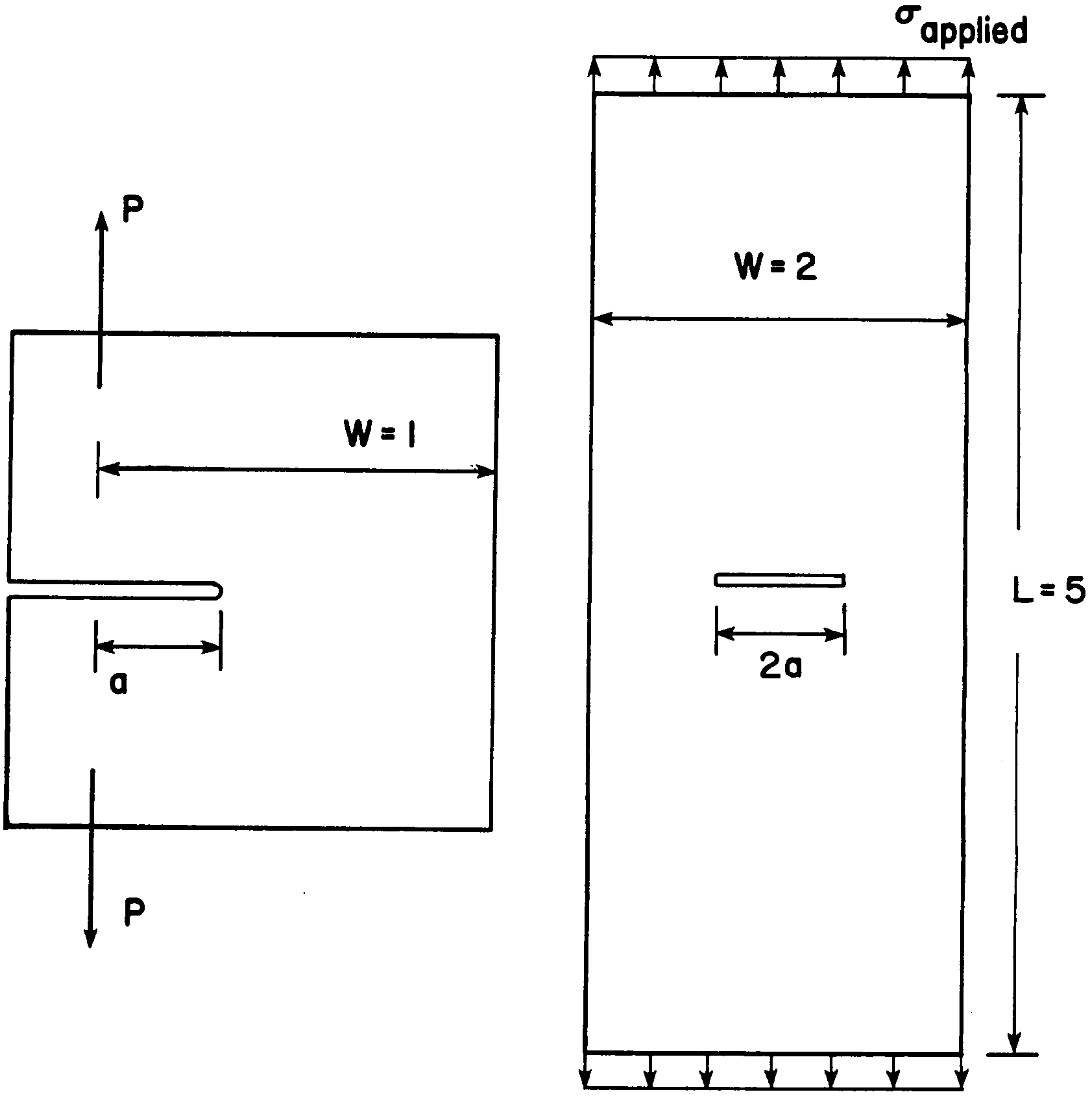

Figure 4 - Fracture Toughness Sample Configurations.
(a) Compact-Tension and (b) Center-Cracked Panel.
Dimensions in Inches.

center-cracked-panels utilized an Instron 800 machine. Figure 5 shows the box grip method of loading required to maintain adequate alignment during testing of the center-cracked-panels. Alignment was achieved by tightening the bolts on the box grip by equal amounts, while continuously monitoring, under slight load, strain gages bonded to opposite sides of each specimen.

Following pre-cracking, fracture toughness tests were performed on both the compact tensile and center-cracked panels utilizing procedures outlined in ASTM E-399-85.

Finally, selected samples are presently being examined after failure utilizing a JEOLCO 848 scanning electron microscope to ascertain the microscopic crack path with respect to the whisker orientation.

EXPERIMENTAL RESULTS AND DISCUSSION

While no difficulty was noted in pre-cracking either 0.1 or 0.5 inch thick T-L compact tension samples, acceptable pre-cracking of 0.5 inch thick L-T compact tension as outlined under ASTM procedures proved extremely difficult. In all cases the pre-crack initiated along a path approximately 70 degrees from the horizontal, Figure 6. Further fatigue loading resulted in a gradual rotation of the crack front, until it was co-linear with the extrusion direction. In contrast, pre-cracking of 0.1 inch thick L-T compact tension samples proceeded without difficulty, the fatigue pre-crack growing in a self-similar manner transverse to the extrusion direction, Figure 7.

No difficulty was encountered in pre-cracking either T-L or L-T oriented 0.5 inch thick center-cracked panels. In all instances, crack growth was self-similar and proceeded perpendicular to the direction of principal far field load application.

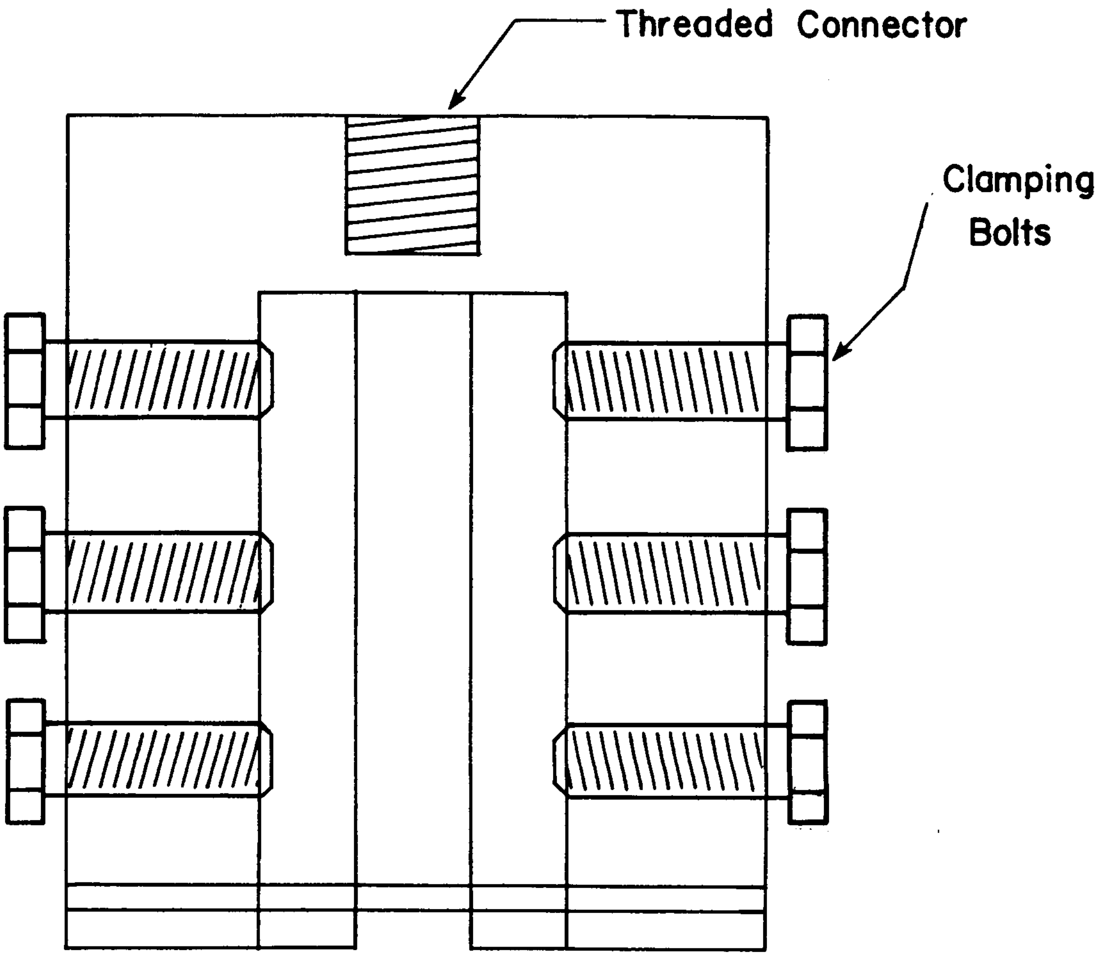

Figure 5 - Box Grip Method for Testing Center-Cracked Panels.

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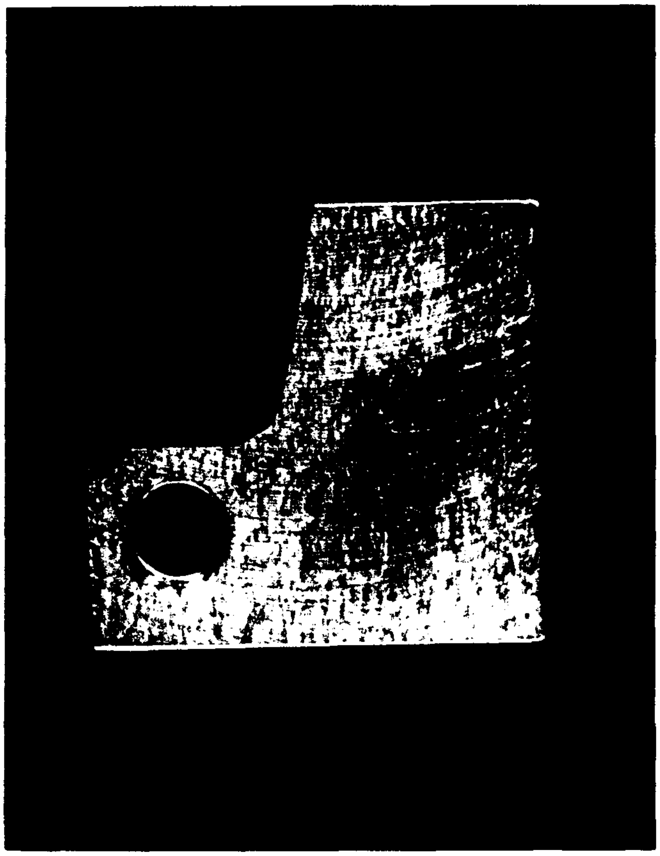

Figure 6 - Macro-photograph of 20 V/O SiC Whisker Reinforced 2124-F 0.5 inch L-T Compact-Tension Sample. Initial Fatigue Crack Propagation Occurs at Approximately 70 Degrees from the Direction of Load Application. Note that the Initial 30 Degree Chevron is Also Shown.

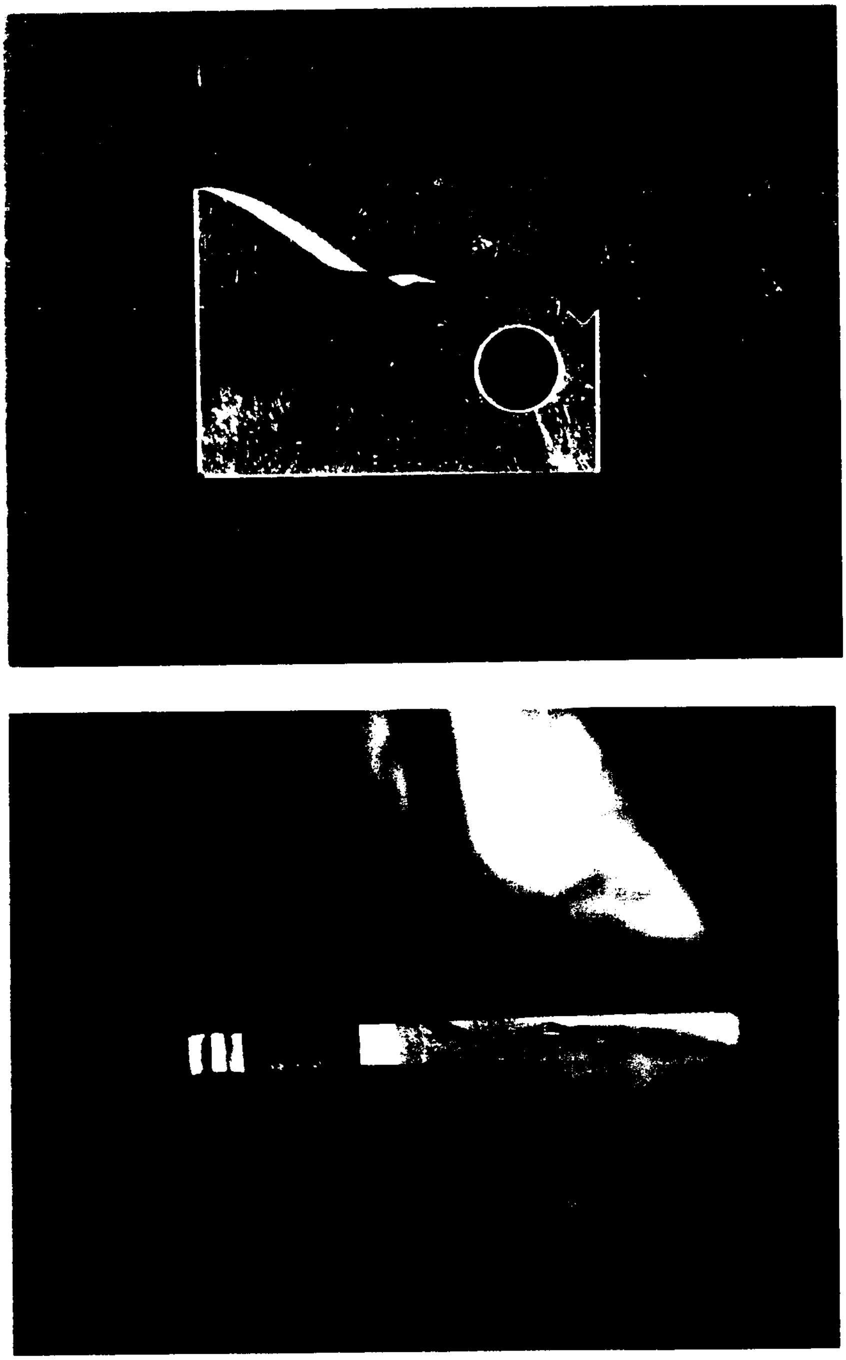

Figure 7 - Macro-photographs of 20 V/O SiC Whisker Reinforced 2124-F 0.1 inch thick L-T Compact-Tension Samples.

Figure 8 shows the general shape of the load-deflection curves recorded from both the T-L compact tension and the L-T/T-L center-cracked panels. In all cases a region of slow crack growth was observed prior to final separation. Table 1 summarizes the fracture toughness results obtained from both the compact tension and center cracked panels. It should be recognized that the "toughness" values reported for the 0.5 inch thick L-T compact tension samples are invalid, as the final crack front was always parallel to the far field load application axis. Other limitations, e.g., excess fatigue pre-crack curvature and high P_{max}/P_Q ratios, are also noted in Table 1.

Notwithstanding the problems encountered in fatigue pre-cracking the SiC reinforced 2124 extrusions, several generalized conclusions may be drawn from the data presented in Table 1. First, the fracture toughness of this material is anisotropic, that is the toughness values obtained from the L-T oriented center cracked panels are approximately 20-25 percent higher than that obtained from T-L oriented center cracked panels.

Second, sample configuration has a drastic effect on the apparent fracture toughness of SiC whisker reinforced 2124 aluminum. Valid toughness values could not be obtained utilizing the L-T compact tension samples, as macroscopic crack branching resulted in the conversion of the main crack from a Mode I to a mixed mode configuration.

Third, self-similar crack growth could be achieved in thin, 0.1 inch thick, compact tension samples. In addition, the fracture toughness values obtained with these samples confirms the enhanced toughness observed in L-T versus T-L orientations.

The importance of sample configuration was confirmed by the following experiment. Two 0.5 inch thick L-T oriented center cracked panels were fatigue pre-cracked to an a/W = 0.5. These samples were then machined into

TABLE 3

FRACTURE TOUGHNESS OF 20 V/O SiC WHISKER REINFORCED 2124-F ALUMINUM

Geometry	Thickness (in.)	Orientation*	K(ksi√in)	Validity
CT	0.5	T-L	14.6	1
	0.5	T-L	16.2	1
CT	0.5	L-T	19.9	NO
	0.5	L-T	21.6	NO
CT	0.1	T-L	16.2	2
	0.1	T-L	15.4	2
	0.1	T-L	13.8	2
CT	0.1	L-T	16.7	2
	0.1	L-T	17.0	2
CCP	0.5	T-L	11.3	2
	0.5	T-L	13.4	1,2
CCP	0.5	L-T	17.5	1
	0.5	L-T	14.8	YES

1. Test invalid crack front curvature excessive

2. $P_{max}/P_Q > 1.1$

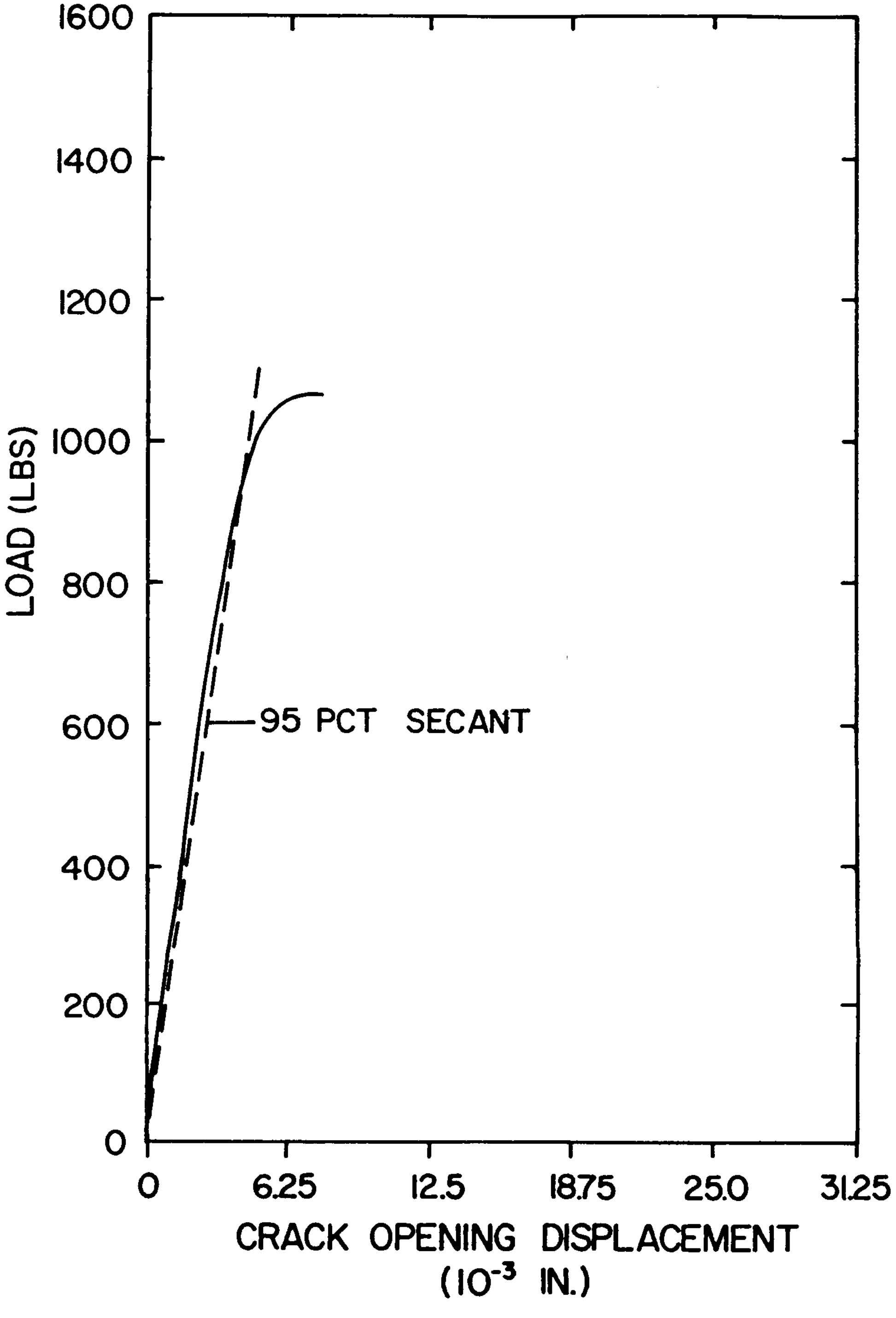

Figure 8 - Load-Deflection Diagram for 20 V/O Whisker Reinforced 2124-F 0.5 inch Thick T-L Compact-Tension Sample.

compact tension samples. One of these samples was then failed in a single load application, catastrophic crack propagation occurring at approximately 40 degrees to the tensile axis, Figure 9. Analysis of the load-deflection curve for this sample yielded a fracture toughness value of 19.8 ksi√in, approximately 10 percent higher than that obtained from L-T oriented center cracked panels.

An unsuccessful attempt was made with the other sample to further extend the fatigue pre-crack by re-initiating fatigue loading. Once again the fatigue pre-crack immediately deveated from a Mode I to a mixed mode configuration.

The preliminary results of the scanning electron microscopy studies are presented in Figures 10 thru 12. Sample orientation and configuration both influenced the microscopic fracture morphology. Orientation effects are most clearly seen by comparing Figures 11 and 12 for L-T and T-L center cracked panels, respectively. The general fracture morphology in the T-L orientation is quite smooth, while in the L-T orientation the fracture is somewhat rougher and undulated. Fatigue crack growth and overload progress either parallel (T-L) or perpendicular (L-T) to the SiC whiskers. In the former, whiskers lie within the plane of crack propagation, while in the latter, crack propagation occurs thru whisker fracture. There appears to be little evidence for appreciable crack deflection along whisker/matrix interfaces during either fatigue crack propagation or final failure in L-T oriented center cracked panels.

This fracture morphology should be contrasted with that observed in compact tension samples, Figure 12. Here crack propagation in the T-L orientation is again quite smooth. However in the L-T orientation, the crack propagation path clearly involves a large amount of localized crack deflection at appropriately oriented SiC whiskers.

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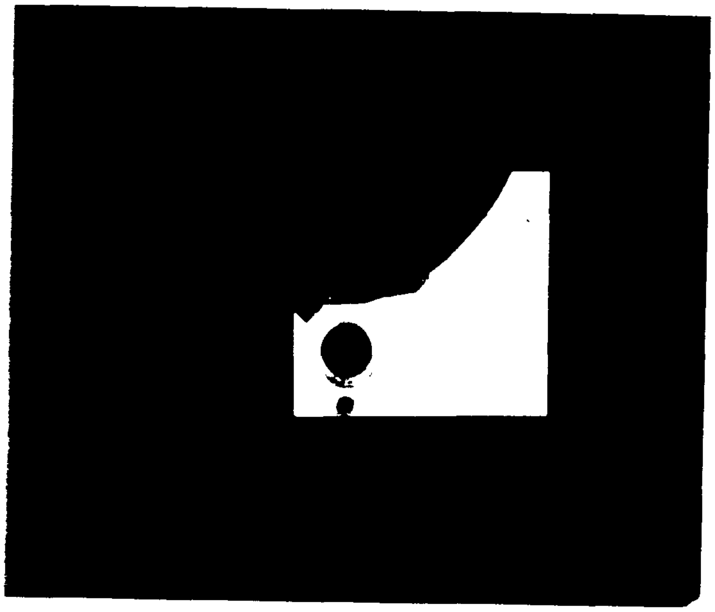

Figure 9 - Macro-photograph of 20 V/O SiC Whisker Reinforced 2124-F 0.5 inch L-T Compact-Tension Sample Having Been Failed in Tension Following Pre-cracking and Machining from Center-Cracked Panel.

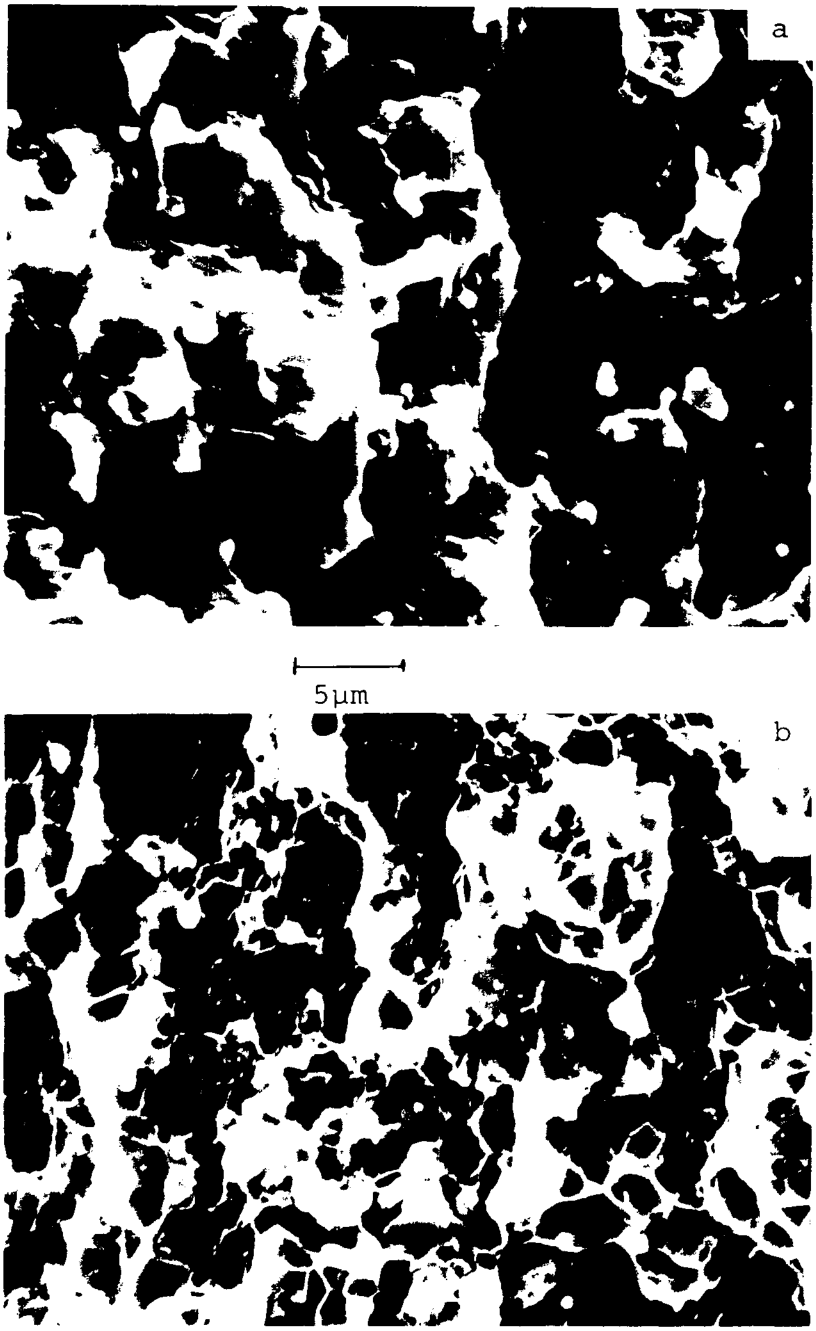

Figure 10 - Scanning Electron Micrographs of 20 V/O Whisker Reinforced 2124-F L-T Oriented 0.5 Inch Center-Cracked Panels. (a) Fatigue Pre-Crack Region, and (b) Overload Region.

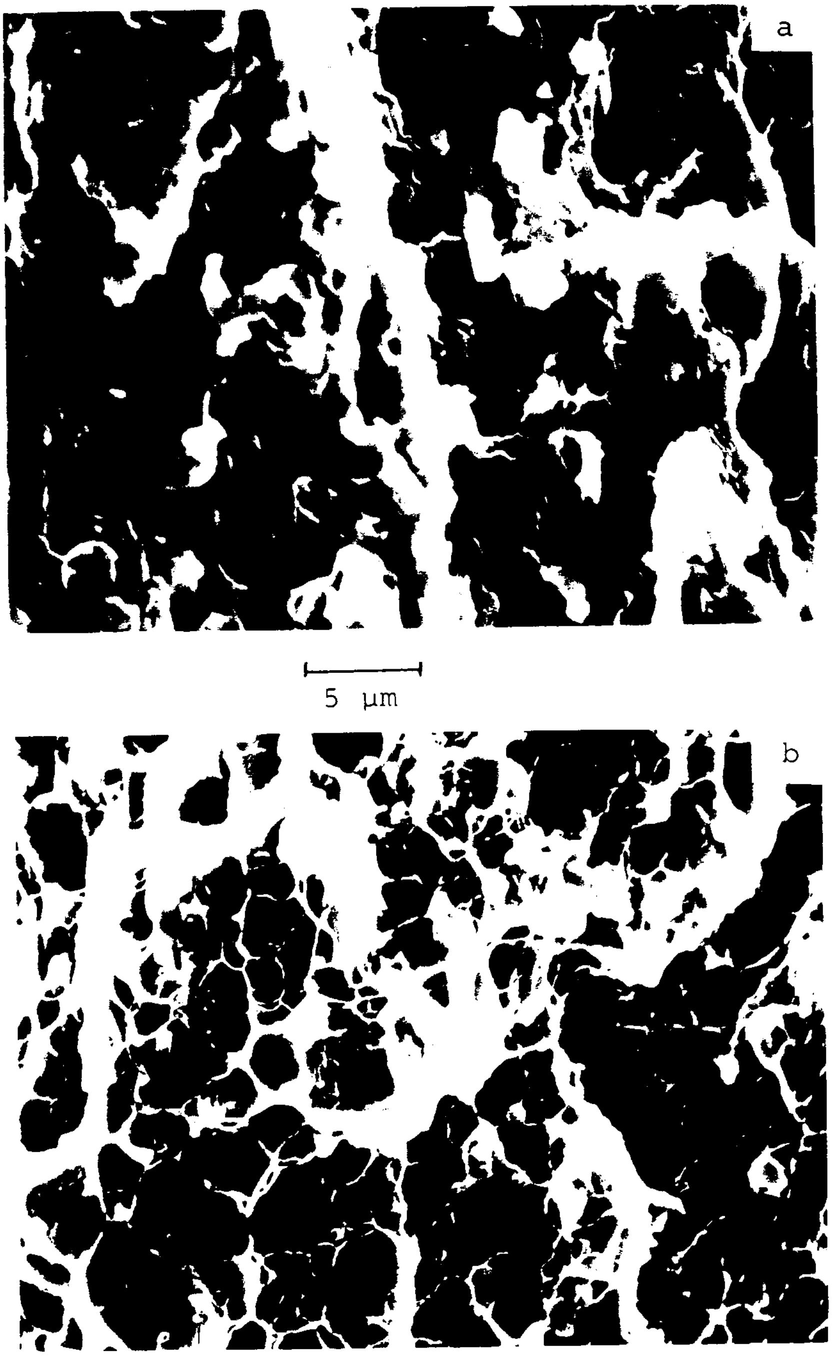

Figure 11 - Scanning Electron Micrographs of 20 V/O SiC Whisker Reinforced 2124-F T-L Oriented 0.5 Inch Center-Cracked Panels. (a) Fatigue Pre-Crack Region, (b) and (c) Overload Region.

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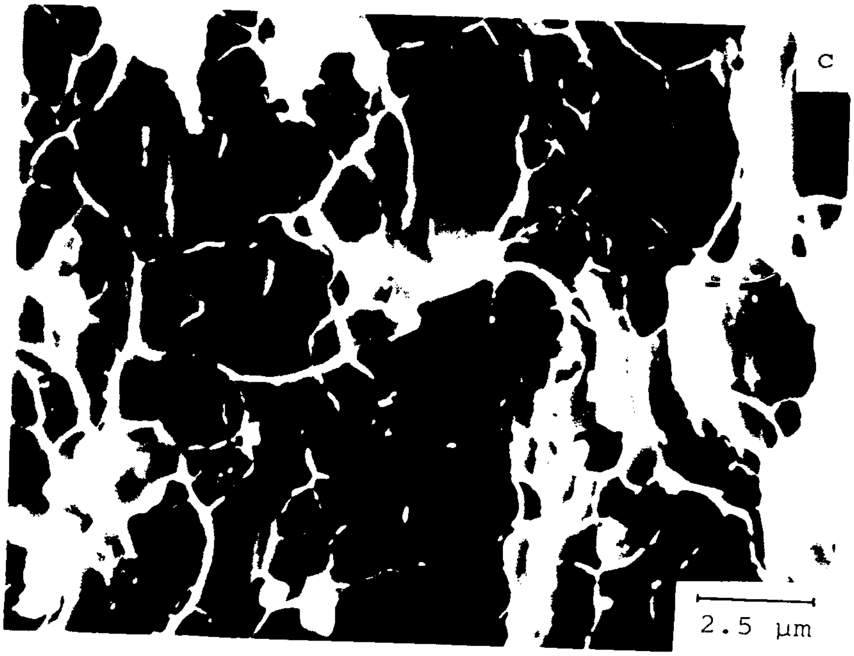

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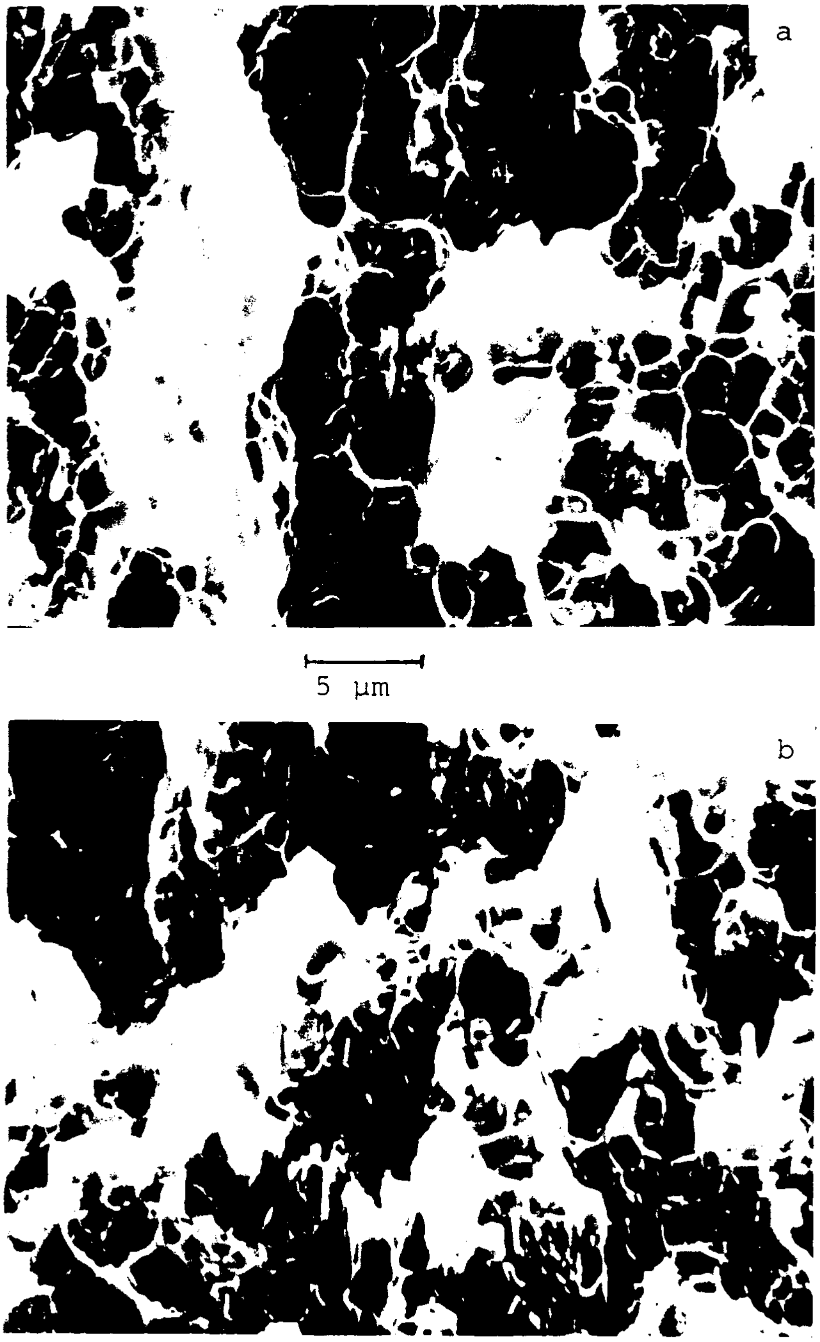

Figure 12 - Scanning Electron Micrographs of Overload Region in 20 V/O SiC Whisker Reinforced 2124-F Compact-Tension Samples. (a) T-L and (b) L-T Orientation.

CONCLUSIONS

1. The fracture toughness of SiC whisker reinforced 2124 aluminum is a function of both whisker orientation and sample configuration.
2. Microscopic crack propagation is also a function of orientation and sample configuration, T-L orientations involving crack propagation parallel to SiC whiskers, L-T orientations involving whisker fracture or localized crack deflection at whisker/matrix interfaces

FUTURE RESEARCH EFFORTS

1. Complete fractographic examination of 0.1 inch 20 v/o SiC compact tension samples.
2. Complete testing of 10 v/o 2124-F whisker extrusion.
3. Initiate aging study to define matrix heat treatments required to define matrix plasticity effects on toughness.
4. Initiate detailed microscopic study of fracture phenomena utilizing 5 v/o SiC whisker reinfroced 2124 as a model material.
5. Initiate micromechanical modeling of fracture phenomena in SiC whisker reinforced aluminum.

REFERENCES

1. Bates, Jr., W. F., "New Aluminum Structural Materials for the 1980's," Transportation Engineering Journal of the American Society of Civil Engineering, Proc. of the American Society of Civil Engineers, 106-TE6, 1980, pp. 845-853.

2. Schoutons, J. E., Particulate, Whisker and Fiber-Reinforced Metals: A Comparison and Discussion, Metal Matrix Composites Information Center Report, November 1981.

3. Reedy, E. D., "On the Specimen Dependence of Unidirectional Boron/Aluminum Fracture Toughness," Journal of Composite Materials Supplement, Vol. 14, 1980, pp. 118-131.

4. Crowe, C. R., Gray, R. and Hasson, D., "Microstructural Controlled Fracture Toughness of SiC/Al Metal Matrix Composites," Proceedings 5th International Conference on Composite Materials, W. C. Harrigan, Jr., J. R. Strife and A. K. Dhingra, ed., AIME, Warrendale, PA, 1985, pp. 843-866.

5. Nieh, T. G., R. A. Rainen and Chellman, D. J., "Microstructure and Fracture in SiC Whisker Reinforced 2124 Aluminum Composite," Proceedings 5th International Conference on Composite Materials, W. C. Harrigan, Jr., J. R. Strife and A. K. Dhingra, ed., AIME, Warrendale, PA, 1985, pp. 825-842.

6. Rack, H. J. and Santner, J. E., ARCO Metals, unpublished Research, 1984.

7. Carroll, J. R., and Waitz, C. R., "Structural Advanced Material/Manufacturing Development," Proc. 5th Annual Metal Matrix Review Mtg., Evandale, Ohio, November, 1985.

8. Nardone, V. C. "Factors Affecting K IC of Discontinuously Reinforced Composites," Proc. 9th Discontinuously Reinforced MMC Working Group, Park City, Utah, January, 1987.

9. Logsdon, W. A., and Liaw, P. K., "Tensile, Fracture Toughness and Fatigue Crack Growth Properties of Silicon Carbide Whisker and Particulate Reinforced Metal Matrix Composites," Engineering Fracture Mechanics, Vol. 24, 1986, pp. 737-751.

10. Nair, S. V. Tien, J. K. and Bates, R. C., "SiC-Renforced Aluminum Metal Matrix Composites," International Metals Review, Vol. 30, 1985, pp. 275-290.

11. Christman, T. and Suresh, S. "Effects of SiC Reinforcement and Aging Treatment on fatigue Crack Growth in an Al-SiC Composite," submitted to Materials Science and Engineering, January, 1988.

12. Suresh, S. and Lewis, R. E., "Geometrical Consequences of fatigue Crack Deflection in Composite Materials," Proceedings 5th International Conference on Composite Materials, W. C. Harrigan, Jr., J. R. Strife and A. K. Dhingra, ed., AIME, Warrendale, PA, 1985, pp. 315-330.

13. Pearson, H. Private Communication, Lockheed-Georgia Company, Fall 1986.

14. Hayes, S. V. and Knight, R. C., Metal Matrix Composite Structural Demonstration for Missiles, LTV Aerospace and Defense Company, January 1987.