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NASA Technical Memorandum 103760

Matrix Plasticity in SiC/Ti-15-3 Composite

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July 1991

NASA

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Summary

An experimental method is described which allows for the observation of slip bands due to matrix plasticity in the SiC/Ti-15-3 composite system. A post-test heat treatment and subsequent chemical etch is employed to reveal slip bands in the titanium matrix. Composite specimens of various laminates were examined after tensile testing at room temperature. This method definitively shows that matrix plasticity has occurred in all the laminates investigated and at load/strain levels which were insufficient to cause fiber breakage.

Introduction

Before metal matrix composites can be used in critical applications, their deformation behavior must be thoroughly understood and accurately modelled. Knowing the behavior of each constituent may not be sufficient, since the constituents may behave differently in the composite, especially in the case of the matrix. The matrix may exhibit plastic flow in the unreinforced state, but due to the constraint on it in the composite as a result of the fibers, the matrix may experience constrained flow or be incapable of deforming plastically.

Testing of SiC/Ti composite specimens has shown behavior which could be explained by plastic flow in the matrix. For instance, during unloading, the stress-strain behavior does not follow that of the loading portion of the curve, but traces a new path. Upon reaching zero load, there remains a permanent strain offset (ref. 1). During tension-tension fatigue, open hysteresis loops, strain ratcheting and a decrease in the secant modulus all are evidence of irreversible deformation (ref. 2). This nonlinear and irreversible deformation could be attributed to several mechanisms, such as fiber and/or matrix cracking, debonding, and matrix plasticity. Therefore, detailed investigations must be performed to determine which damage modes or combinations of modes are operative.

Until now, conclusive metallographic evidence of plastic deformation in the Ti-15-3 matrix in either unreinforced or composite forms has been unsuccessful. Chemical etchants fail to reveal slip bands -- indicators of plastic flow. A method to reveal slip bands is described herein. The method uses a post-test heat treatment which discontinuously precipitates fine particles on slip bands. The particles, believed to be alpha titanium, are subsequently revealed by a chemical etchant which preferentially attacks this phase, thus highlighting the slip bands. This method is used on composite specimens of various laminates of the SiC/Ti-15-3 system.

Experimental Procedure

The composite consisted of Ti-15V-3Cr-3Sn-3Al (w/o) matrix reinforced by continuous, SiC (SCS-6) fibers in 8-ply layups. The composite specimens contained a nominal fiber volume fraction of 34 percent. Specimens of various fiber layups, $[0^\circ]_8$, $[90^\circ]_8$, $[\pm30^\circ]_{2s}$, and $[\pm45^\circ]_{2s}$, along with an unreinforced matrix specimen, were heat treated for 24 h at 700 °C in vacuum and were subsequently tested in tension at room temperature. After testing, the specimens were given a second heat treatment consisting of a 24-h age at 427 °C in vacuum. Sections of the specimens were then mounted and polished by metallographic techniques developed for this material (ref. 3). To reveal slip bands, specimens were etched in a 3-percent aqueous solution of ammonium bifluoride.

Results

Slip bands were easily revealed in an unreinforced matrix specimen which was pulled to failure at room temperature in tension. Gross plasticity in this specimen was evident by its 20-percent strain to failure. A longitudinal cross-section of the specimen taken at the transition between the straight gage section and the radius shows a gradual decrease in the slip band density as the cross-sectional area of the specimen increases (fig. 1) until finally, no slip bands are observed. Enlargements of this area depict isolated slip bands in each grain (fig. 2).

Unidirectional Composite Tests

Unidirectional composite specimen tests were interrupted in the nonlinear portions of the stress-strain curves for slip band analysis. A $[0]_8$ composite specimen was pulled in tension to a strain of 0.85 percent. This strain is just short of the average failure strain of 0.90 percent for this orientation (ref. 4). As can be observed in the stress-strain curve in figure 3, a strain of 0.85 percent is well into the nonlinear portion of the stress-strain response. Upon unloading, a permanent strain offset was observed and equaled 0.04 percent at zero load, indicating that some damage had been incurred. Slip bands are readily seen in the matrix of this specimen between fibers within a ply (fig. 4). A through-thickness section (fig. 5) from the same specimen indicates slip bands in the matrix between plies, initiating near the fibers and decreasing both in number and in intensity as mid-ply is approached. It should be pointed out that these slip bands might have been a result of plastic deformation during the consolidation process. To investigate this possibility, as-fabricated coupons of both unidirectional and $[\pm30^\circ]_{2s}$ layups were heat treated and etched similarly, and subsequently examined for slip bands. No slip bands were found in either specimen.

A $[90]_8$ specimen was pulled in tension to a strain of 0.60 percent. The corresponding stress-strain curve (fig. 6) shows that the specimen is well into the nonlinear regime. Similar to the $[0^\circ]_8$ specimen, a permanent strain offset is observed upon unloading, which indicates that the specimen contained some form of damage. Metallographic examination revealed the damage to consist of matrix plasticity and interfacial debonding. Figure 7 shows slip bands which occurred in this specimen. Slip is again concentrated mostly near the fibers and occurs on the portion of the circumference which is perpendicular to the load axis (i.e., at 6 and 12 o'clock in the figures). The slip bands also seem to connect fibers of adjacent plies at approximately a 45° angle, indicating the planes of maximum shear. Debonding of the fiber/matrix interface at several locations was also observed in this specimen, but is not shown in figure 7.

Crossply Laminate Composite Tests

Crossply composite specimens were tested and analyzed in a manner similar to that used on the unidirectional specimens. A $[\pm30^\circ]_{2s}$ specimen was interrupted after a tensile strain of 0.80 percent, again in the nonlinear region (fig. 8). The unloading portion of this curve was not recorded. Slip bands were observed in the matrix throughout this specimen as well. The effects of small matrix cracks and local fiber/matrix interface debonding on slip concentration were also evident at a few locations in this specimen. Figure 9 shows a section from this specimen at a matrix crack, which has initiated at the fiber/matrix interface of one fiber and is propagating toward the next fiber within this ply. Concentrations of slip bands are observed at the crack tip and are oriented approximately 45° above and below the crack plane.

Another area of concentrated slip in this specimen is depicted in figure 10. In this area, the matrix between two fibers within a ply has debonded locally and is beginning to neck down, clearly indicating the enhanced triaxial stress state in this area. Two intersecting concentrations of slip bands are observed at approximately ±60° to the fiber axis.

A $[\pm45^\circ]_{2s}$ specimen was pulled to a strain of 4 percent and shows, as one might expect due to the large strain, large amounts of slip. Figure 11 shows several matrix grains, each showing slip on multiple slip systems, as indicated by the intersecting slip bands.

Discussion

The results have conclusively shown that matrix slip occurs in the nonlinear regions of the tensile stress-strain curves for the SiC/Ti-15-3 system. The slip bands were <u>not</u> a result of the consolidation process, as evidenced by the lack of slip bands in as-fabricated material. As a result of a post-test heat treatment, slip bands were revealed in the matrix for all orientations studied: $[0^\circ]_8$, $[90^\circ]_8$, $[\pm30^\circ]_{2s}$, and $[\pm45^\circ]_{2s}$. These specimens were not failed specimens, but were interrupted at strains smaller than the composite failure strain. In the case of the $[0^\circ]_8$, $[90^\circ]_8$, and $[\pm30^\circ]_{2s}$ specimens, no fiber breakage was observed, thus indicating that the matrix can plastically deform before fibers break. The $[\pm45^\circ]_{2s}$ specimen did contain fiber cracks, but this specimen was deformed to a much greater extent than those of the other orientations.

The heaviest concentration of slip bands was found at the tips of matrix cracks (fig. 9). This reflects the higher stresses and strains expected at the crack tip. The slip band density was also higher near the fibers (figs. 5 and 6). This likewise reflects the higher stresses and strains expected near and at the fiber/matrix interfaces. Large slip band concentrations were often seen in areas of the matrix where debonding had occurred (fig. 10). However, slip bands were also observed in areas where the fiber/matrix bond appeared intact, especially in the $[0^\circ]_8$ specimens (figs. 4 and 5). Thus, it appears that debonding, like fiber breakage, is not necessary for matrix flow to occur. Although debonding is not necessary to induce matrix flow, debonding may occur first in certain composite layups and under certain loading conditions, since the fiber/matrix interface is weak and separates at low stresses (refs. 1 and 4). A detailed stress analysis is required to determine which mechanism will occur first for each composite layup and loading condition.

Although this method reveals slip bands in the matrix, the sensitivity of this method concerning what strain levels within the matrix are necessary to produce observable slip bands is at this time unknown. Some measure of this technique's sensitivity is observed in an unreinforced matrix specimen in figure 1, in which the slip bands cease after a small increase of approximately 14 percent in the cross sectional area is attained. Simple load/area calculations indicate that the stress at this location was equal to the matrix yield stress. This suggests that slip bands will be observed once the local stress is larger than the yield stress of the matrix.

This technique has not been refined to provide optimum viewing areas for identifying slip bands. The etchant used in this method is unpredictable in that the matrix background is sometimes light and sometimes very dark (see figs. 11 and 2, respectively). The dark background can be due to the precipitation of very fine alpha titanium particles which rapidly over-etch. This has been observed in both unreinforced matrix and composite specimens which were aged at similar, low temperatures (ref. 5). The dark background can also result from a very high density of slip bands. This is indicated in figure 1, in which the straight gage section, which is heavily deformed, is much darker than the radius. Here, the dark areas in which no individual slip bands are evident could be areas of very high deformation. Further work is necessary to allow discrimination between these two cases.

Summary of Results

By using a post-test heat treatment and etching method, matrix plasticity in the form of slip bands has been observed in the SiC/Ti-15-3 composite. These slip bands were not a result of composite fabrication, because they were not observed in as-fabricated specimens. Slip bands were observed in $[0^\circ]_8$, $[90^\circ]_8$, $[\pm30^\circ]_{2s}$, and $[\pm45^\circ]_{2s}$ specimens, which were strained into the nonlinear portions of their stress-strain curves and interrupted before failure. No fiber breakage was observed in the $[0^\circ]_8$, $[90^\circ]_8$, and $[\pm30^\circ]_{2s}$ specimens, which indicates that the matrix can plastically deform before fibers crack. Slip bands were observed in areas where the matrix was still bonded to the fibers (especially in the $[0^\circ]_8$ specimens), thus indicating that the matrix can flow before fiber/matrix debonding occurs.

Acknowledgment

The author would like to thank W. McCort for refining the etching procedure needed to provide maximum contrast for viewing the slip bands.

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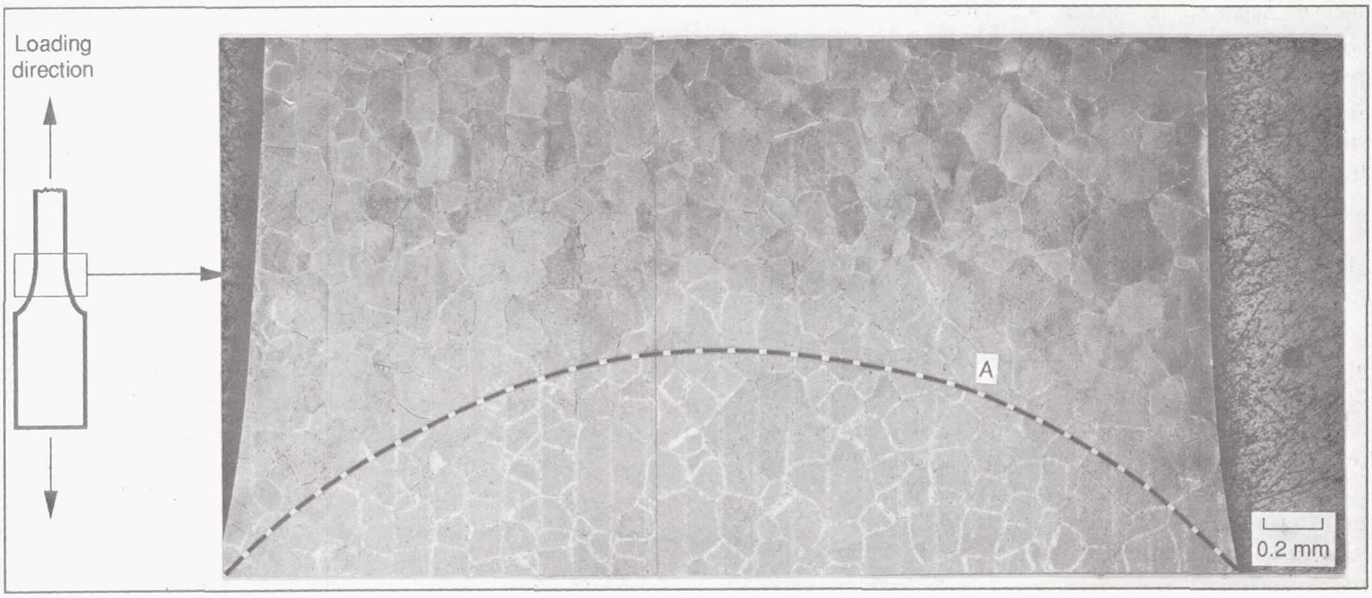

Figure 1.—Unreinforced Ti-15-3 matrix tensile specimen depicting the extent of matrix plasticity.

Figure 2.—Enlargement of the transition area "A" in figure 1 showing slip bands in some grains.

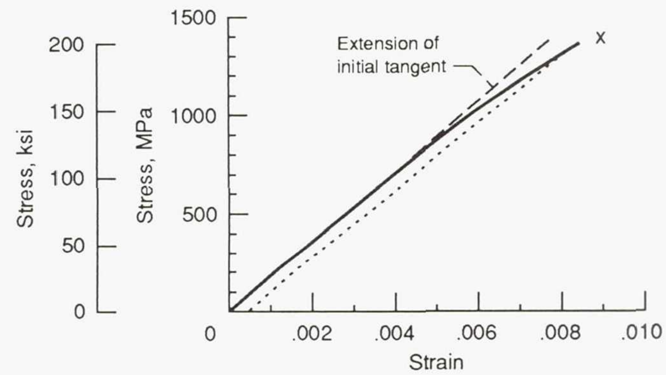

Figure 3.—Loading and unloading curve for a $[0°]_8$ specimen. (The "x" indicates the average failure stress and strain for this layup.)

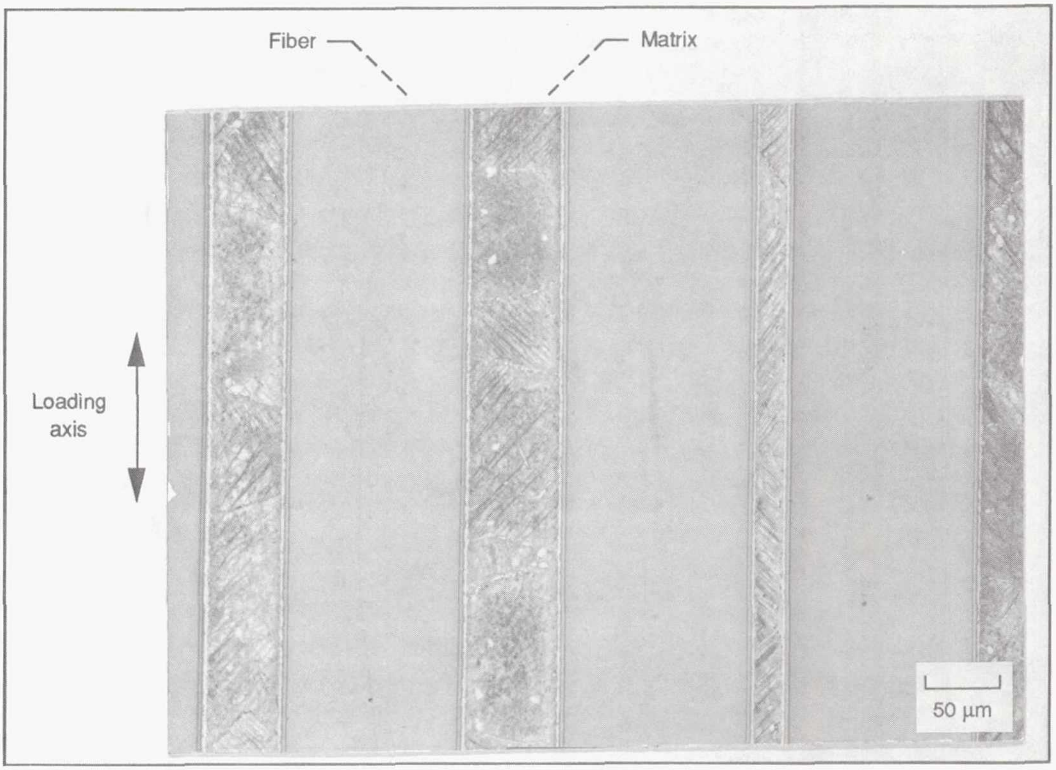

Figure 4.—Slip bands in the matrix of a single ply from a $[0°]_8$ specimen strained to 0.85 percent.

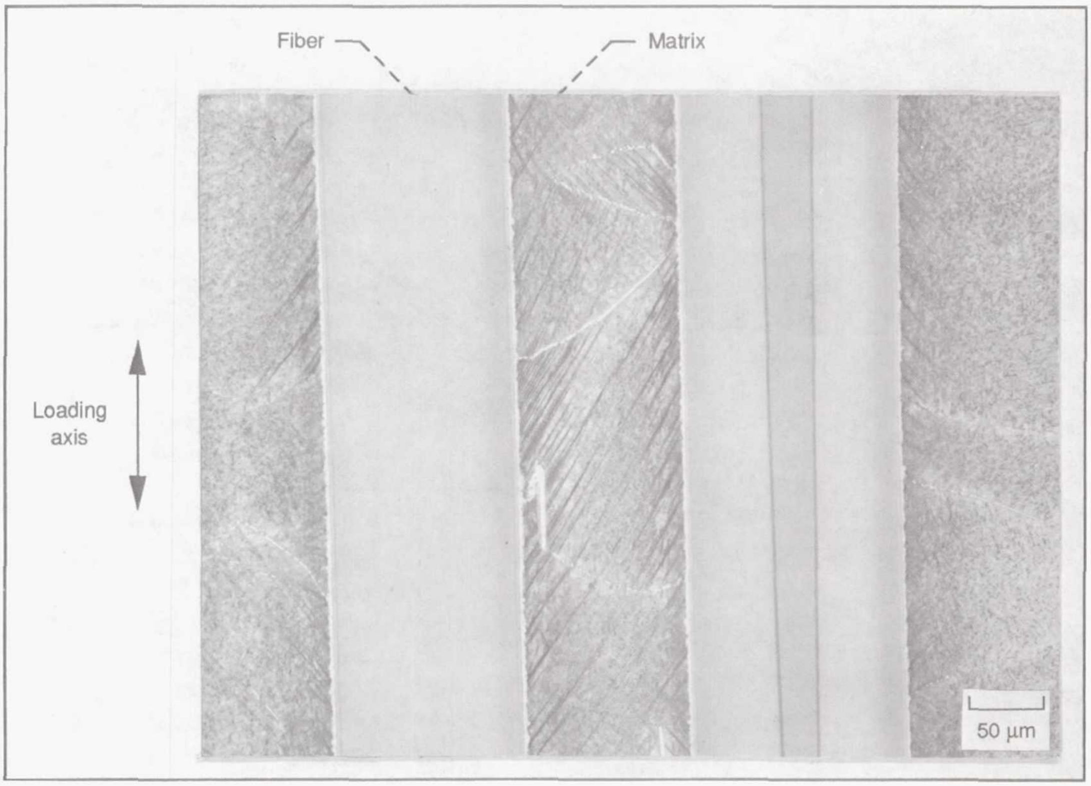

Figure 5.—Through-thickness section illustrating matrix plasticity between two plies of a $[0°]_8$ specimen.

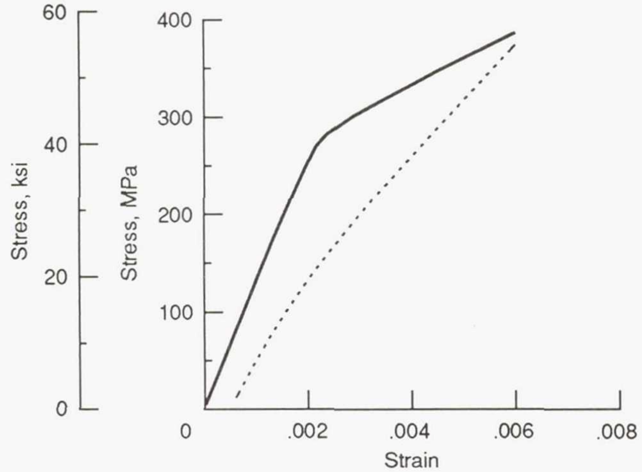

Figure 6.—Loading and unloading curve for a $[90°]_8$ specimen. Average failure strain, 0.014.

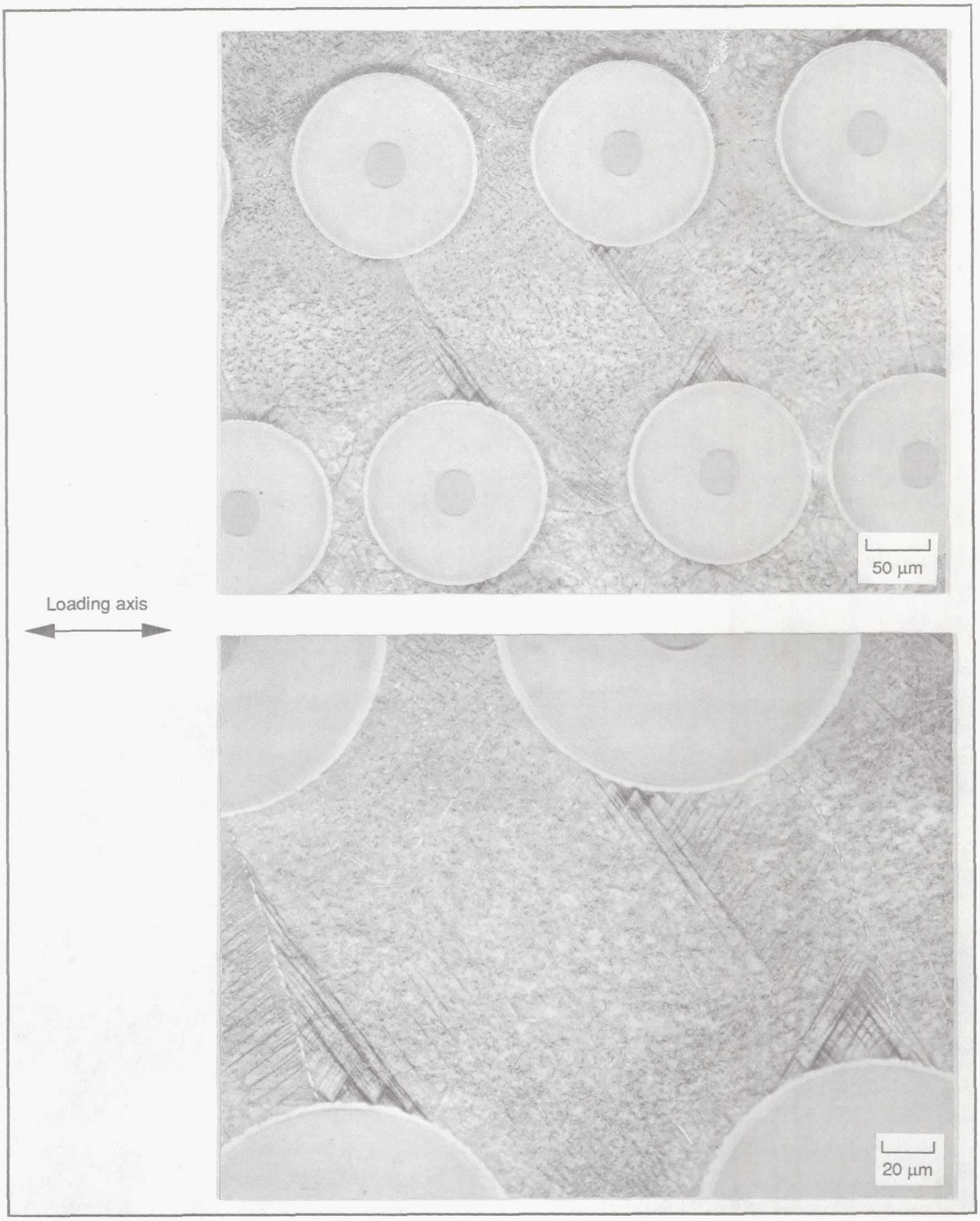

Figure 7.—Slip bands in the matrix of a $[90°]_8$ specimen which was interrupted after a tensile strain of 0.6 percent.

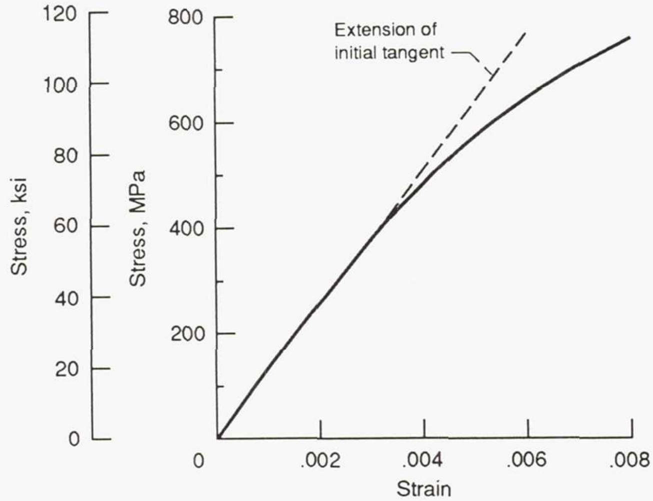

Figure 8.—Tensile data for a $[\pm 30°]_{2s}$ specimen. Average failure strain, 0.013.

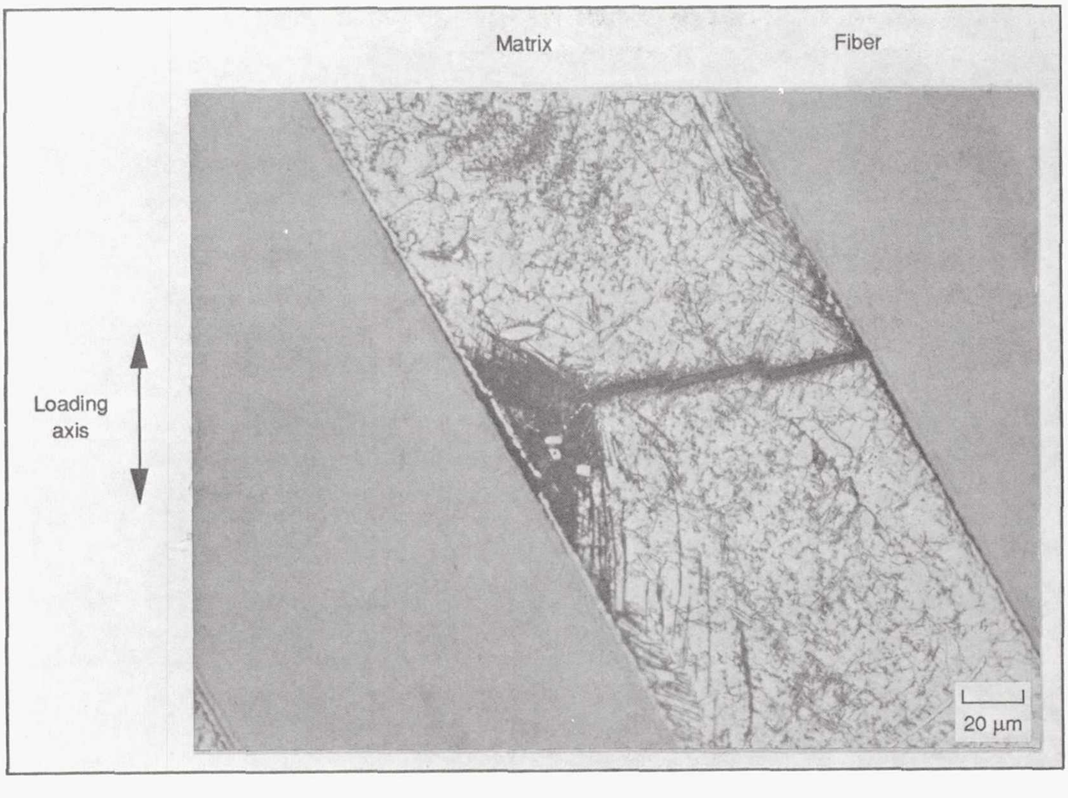

Figure 9.—Concentration of slip bands at the tip of a matrix crack in a $[\pm 30°]_{2s}$ tensile specimen strained to 0.8 percent.

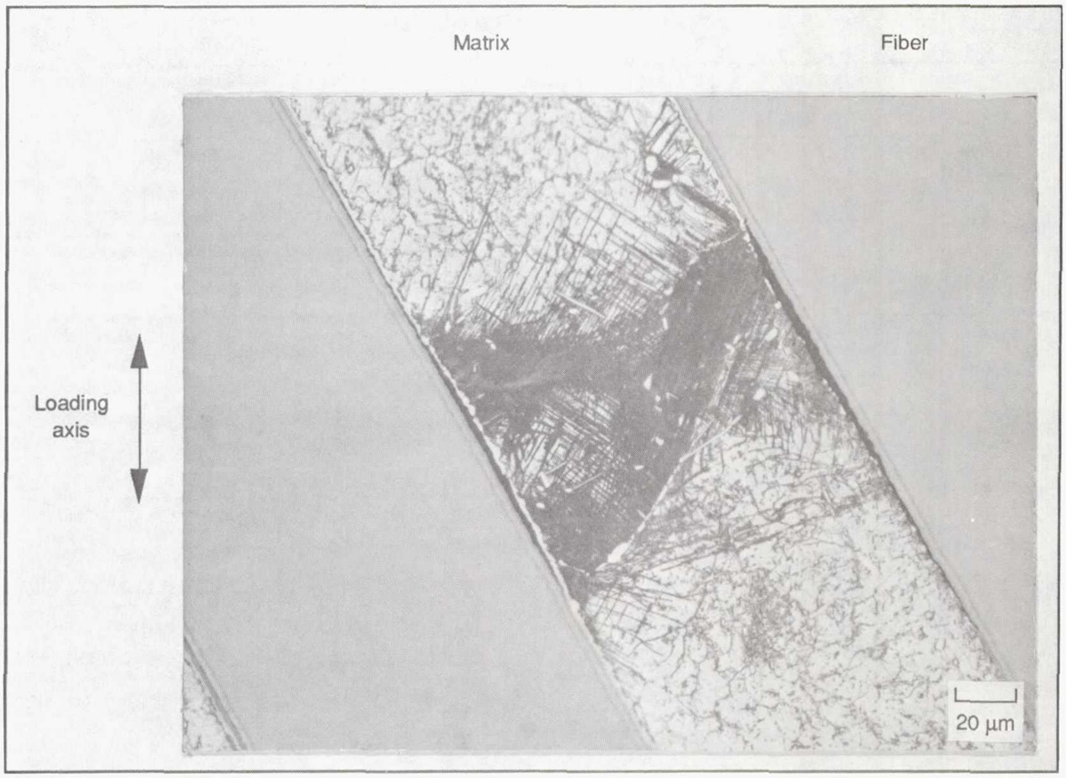

Figure 10.—Concentration of slip bands at an area of matrix necking in a $[\pm 30°]_{2s}$ tensile specimen strained to 0.8 percent.

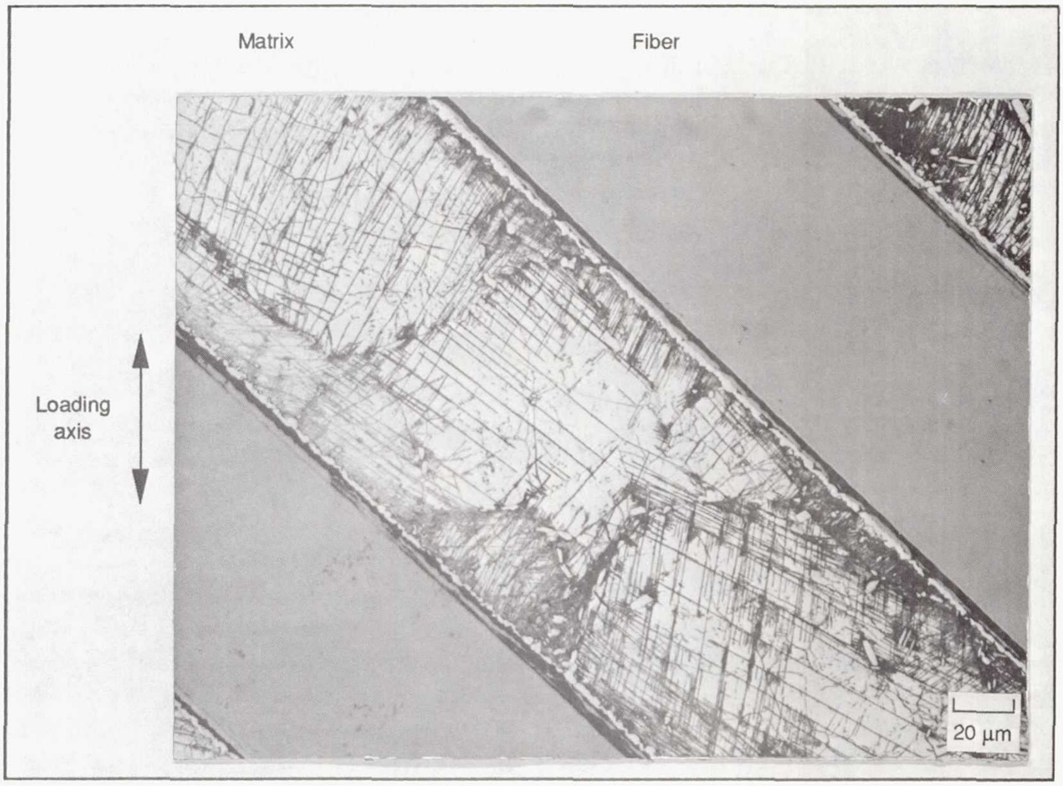

Figure 11.—Matrix slip on multiple slip systems as indicated by intersecting slip bands. (Specimen is a $[\pm 45°]_{2s}$ strained to 4 percent.)

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Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM - 103760		

4. Title and Subtitle	5. Report Date
Matrix Plasticity in SiC/Ti-15-3 Composite	July 1991
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Bradley A. Lerch	E-6017
	10. Work Unit No.
	510-01-50
9. Performing Organization Name and Address	11. Contract or Grant No.
National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191	
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address	Technical Memorandum
National Aeronautics and Space Administration Washington, D.C. 20546-0001	14. Sponsoring Agency Code

15. Supplementary Notes

Responsible person, Bradley A. Lerch, (216) 433-5522.

16. Abstract

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17. Key Words (Suggested by Author(s))	18. Distribution Statement
SiC/Ti-15-3 Matrix plasticity Laminates Composite	Unclassified - Unlimited Subject Category 24

19. Security Classif. (of the report)	20. Security Classif. (of this page)	21. No. of pages	22. Price*
Unclassified	Unclassified	10	A02

NASA FORM 1626 OCT 86

*For sale by the National Technical Information Service, Springfield, Virginia 22161