X-ray Elastic Lattice Strains under Applied Stress in a Metal Matrix Composite

J. C. Hanan, G. A. Swift, E. Üstündag
Department of Materials Science, California Institute of Technology, Pasadena, CA, U.S.A.

Introduction

A composite's response to damage under stress is the primary micromechanical process determining its fracture toughness, strength, and lifetime. This response depends on the properties of the fiber/matrix interface, the constitutive behavior of the matrix and fibers, the geometric arrangement of the fibers, the fiber volume fraction, and the fiber strength distribution. The composite's response is complicated further since the *in situ* mechanical properties of the constituents show significant differences from those of their monolithic forms.

Through the use of x-ray microdiffraction, the elastic lattice strains of both phases in a metal matrix composite (MMC) were revealed to determine the *in situ* load transfer under applied tensile stress at the scale of the microstructure. The transverse strains were measured previously as part of the development for this method, as stated in Ref. 1. In the Ti-SiC MMC system, no other analysis method could resolve the *in situ* strains. A first use of this method for damage evolution in Ti-SiC is described in Ref. 2, with a comparison of the strains to a micromechanics model.

Methods and Materials

The Ti matrix-SiC fiber laminate composite was examined with 25- and 65-keV microbeam x-rays at the Synchrotron Radiation Instrumentation Collaborative Access Team (SRI-CAT) 1-ID-C beamline at sector 1 of the APS. A similar composite was also examined with a 2×2-mm^2 beam. The first 25 keV of energy was chosen to provide a through thickness average of the strains from each phase. The second 65 keV of energy allowed the use of an image plate to observe the strains. The microbeam analysis was conducted with a 90×90-μm^2 beam around a broken fiber in the composite. The composite was examined before, during, and after the application of tensile load.

The elastic lattice strains in the matrix and fibers were obtained by monitoring one reflection from the dominant phases in each: (10·2) from α-Ti and (220) from β-SiC. This was justified since results from the 2×2-mm^2 beam analysis show the α-Ti (10·2) reflection is representative of the average in terms of its susceptibility to plastic deformation as well as its effective elastic constant [3].

To obtain the desired diffraction geometry, a four-circle goniometer was used in transmission mode. The diffraction vector was along the fiber axis; thus, the diffraction patterns provided the longitudinal (or axial) strain in the plane of the composite. The diffraction intensity was first collected with a NaI scintillator detector equipped with a Si(111) analyzer crystal at 25 keV and then with an image plate at 65 keV. The x-ray beam size was defined by slits on the incident beam side. An internal standard Si powder (National Institute of Standards and Technology [NIST], Standard Reference Material 640a), attached to the specimen surface, verified beam and sample stability.

Results

The change in lattice spacing under stress provided by x-rays revealed the phase-specific strains at an array of selected positions around the broken fiber. The fibers adjacent to the broken fiber show an increase in strain because of the damage at the break (Fig. 1). The matrix

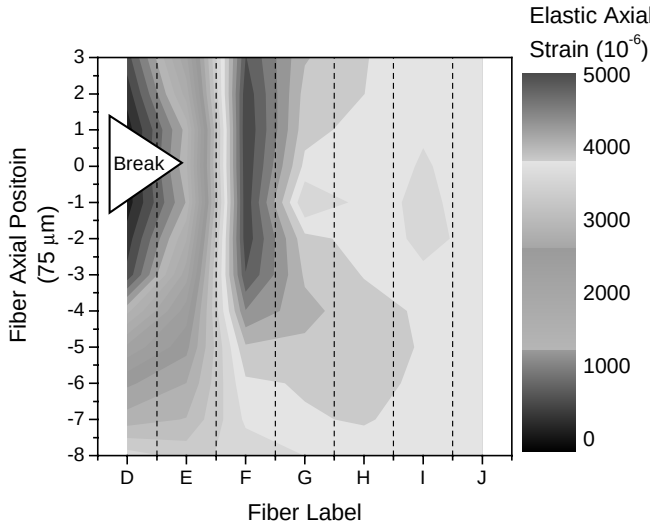

FIG. 1. A strain map of the applied elastic axial strains in the fibers (separated by dashed lines). The strains reveal a decrease in strain near the broken fibers D and E, with the first-nearest-neighbor fibers (such as C and F) compensating with larger strains. The rest of the fibers show absolute strains around 0.11%.

around these fibers also shows an increase in strain (Fig. 2).

In the second composite, without a broken fiber, the applied stress as a function of average strain for many fibers is shown in Fig. 3. The matrix strains are given in Fig. 4. Since the entire diffraction ring was available for analysis, the strains in the axial direction ε_{11}, transverse direction ε_{22}, and shear direction ε_{12} were available for analysis. As reported in Ref. 3, the residual stresses and strain evolution were also measured in the composite.

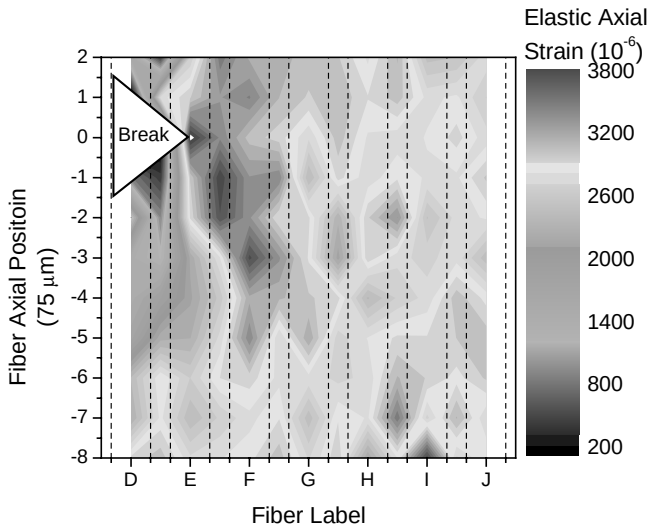

FIG. 2. A contour map of the axial elastic strains in the Ti matrix. The fiber positions are labeled and separated from the "matrix only" columns by dashed grid lines. The broken fibers (labeled D and E) are seen to appreciably affect axial matrix strains two fiber diameters from the break.

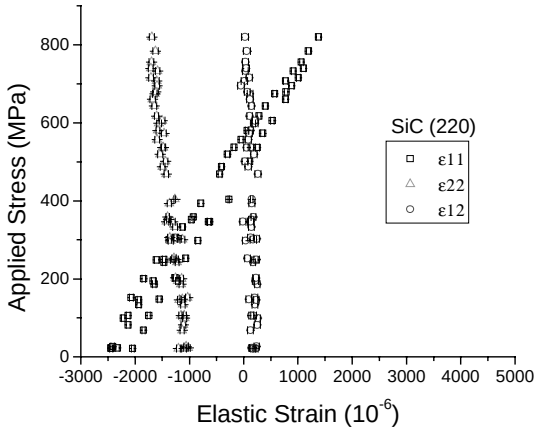

FIG. 3. Fiber strains at the investigated appied loads from a gage volume including many fibers. The axial ε_{11}, transverse ε_{22}, and shear ε_{12} directions are represented in the graph.

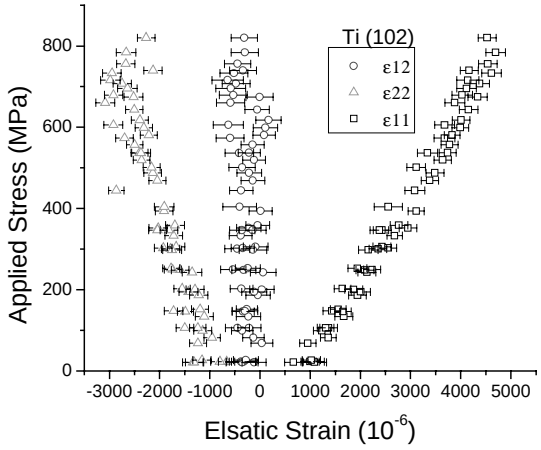

FIG. 4. Matrix strains at each applied load from the same gage volume as that used for Fig. 3. The axial ε_{11}, transverse ε_{22}, and shear ε_{12} directions are also represented in this graph.

Discussion

The strains from x-ray diffraction (XRD) provided a clear picture of the elastic strain of both the matrix and fibers at the scale of microstructure and allowed for *in situ* studies under applied stress. The technique provides spatially resolved high-resolution mechanical information in an MMC not available through any other method. The results show that the irradiation of a small number of grains (60 grains in a matrix region for the 90×90-μm^2 beam) provides strain measurements comparable to a continuum mechanical state predicted in the material. The result is surprising since the number of grains diffracting, as predicted by the Lorentz factor, is a subset of the grains irradiated. It is the collection of the entire Debye ring, with correct accounting for the deviatoric strain, which allows strain measurements for such a small number of grains and strong preferred orientation. Finally, by using the two x-ray microdiffraction methods, the phase-specific *in situ* residual and applied tensile strains in the MMC were also investigated.

Because of the coefficient of thermal expansion (CTE) mismatch, average thermal residual stresses of −740 MPa in the fibers and +350 MPa in the matrix were found along the fiber axes [3]. Although, when conventional mechanical testing is used, the global yielding of the Ti-SiC composite is not detected until at least 700 MPa of applied stress, XRD strains reveal that local yielding occurs as early as 500 MPa. In the residual stresses and under the applied tensile load, plastic anisotropy was observed in the matrix. It provides a source for the grain-to-grain strain variation also observed in the composite.

Acknowledgments

This study was supported by the National Science Foundation (CAREER Grant No. DMR-9985264) at

Caltech and Laboratory-directed Research and Development Project No. 2000043 at Los Alamos National Laboratory. Use of the APS was supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. W-31-109-ENG-38. We also acknowledge support from the SRI-CAT.

References

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