IN-SITU ULTRASONIC CHARACTERIZATION OF FAILURE STRENGTH OF FIBER-MATRIX INTERFACE IN METAL MATRIX COMPOSITES REINFORCED BY SCS SERIES FIBERS

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INTRODUCTION

An understanding of the dependence of the fiber-matrix interface deformation and debonding on residual stresses, the fiber-matrix bond strength, and matrix properties under transverse loading conditions is needed for the improvement of the transverse properties of titanium matrix composites (TMC) reinforced with continuous silicon carbide (SiC) fibers. This paper presents a new methodology to assess the interfacial stress at fracture. The newly developed method is based on an ultrasonic NDE technique which is used in-situ to monitor the deformation and failure of the fiber-matrix interface under transverse loading.

ULTRASONIC EXPERIMENTAL APPROACH

The composite samples used for this study were fabricated by hot pressing two Ti-6Al-4V sheets with a single SiC fiber (SCS-6 or SCS-0) between them at a condition of 960 ^{o}C at 17 MPa for 1.5 hours. The interfacial microstructure obtained with this processing condition clearly indicates that some chemical reaction between the graded carbon coating and the matrix has taken place during the consolidation process. Furthermore, this reaction is non uniform. The consolidated samples were cut into dog-bone shape specimens with the fiber axis perpendicular to the loading axis of the samples as shown in Figure 1a. Transverse tensile tests were carried out using a micro-straining stage (Figure 1b) built in WL / Materials Directorate [1] . The loading was applied stepwise so that the ultrasonic scanning could be done in-situ under the loaded condition at different stress levels. Ultrasonic shear wave back reflectivity technique [2, 3] was used for this purpose. The transversely loaded composite specimens were ultrasonically imaged in a pulse-echo mode at a beam incident angle of 24o so that vertically polarized shear waves were incident on the fiber-matrix interface.

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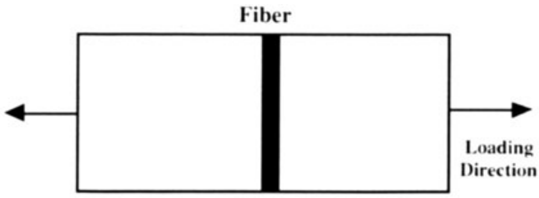
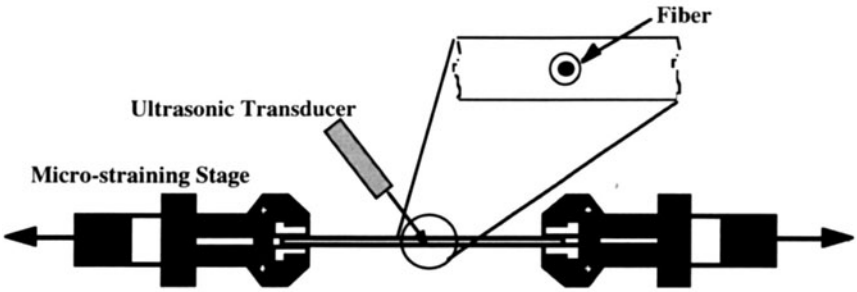


(a)



(b)

Figure 1 (a) Experimental Configuration Showing Transverse Orientation of the Fiber in a Sample and the Direction of Loading. (b) Configuration of the Micro-Straining Stage for Ultrasonic In-Situ Imaging Arrangement.

One typical loading curve for the transverse tensile test (Ti-6Al-4V/SCS-6) and the corresponding ultrasonic shear wave images at different levels of stresses of the sample are shown in Figure 2. The labels 'a' through 'k' in Figure 2 correspond to the various stress levels as shown in the stress strain diagram. The image labeled 'a' in Figure 2 corresponds to the fiber-matrix interface before the commencement of the mechanical loading of the sample. It should be noted that the amplitude along the fiber axis varies with position (Figure 3), suggesting a non uniform interfacial "shear stiffness coefficient" [2, 3]. Figure 3 shows selected reflectivity plots from the fiber at various stages of loading (a, f, and k). Reflectivity plot 'f' shows reflectivity when the fiber-matrix interface has fractured at several places in three regions of the fiber, and curve 'k' shows the load where most of the interface is fractured. It can be observed from Figures 2 and 3, the amplitude of the back-reflected ultrasound generally increases with an increasing stress level until the interface finally fractures. The above results indicate that SBR technique is sensitive to the fracture and deformation of the interfaces in metal matrix composites. The information provided by SBR technique is complementary [4] to the information obtained by other experimental techniques and analyses including replica method, metallography, electro-etching of the matrix, acoustic emission, elasticity modeling, and Finite Element Analysis.

One of the primary conclusions drawn from using in situ SBR imaging of transverse tests contradicts the common belief that the entire interface is likely to fracture almost instantaneously at a certain stress level, because of the existence of a weak diffusion bonding as contrasted to mechanical bonding as reported by Wright et al. [5]. However, the work reported here suggests that the debonding progresses from a small number of isolated points at a low load, to the entire interface over a finite range of applied stresses (almost 350 MPa as shown in Figure 2). This range is dependent on the homogeneity of the fiber-matrix interface as well as the stress redistribution phenomenon that occurs due to the growing interfacial crack.

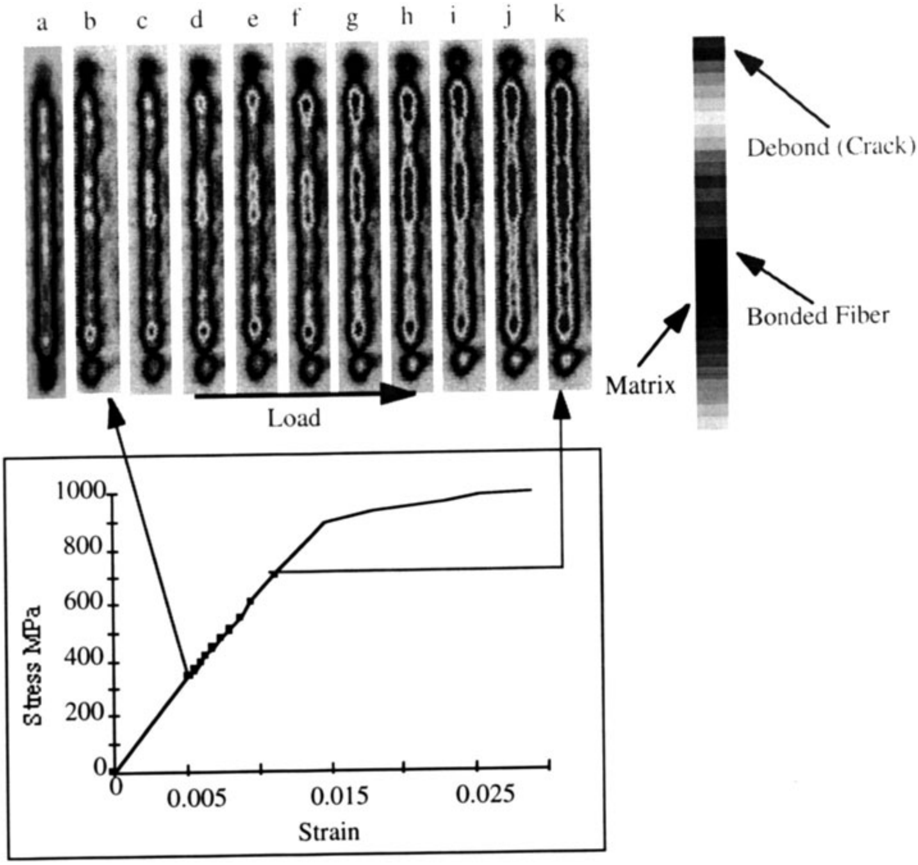


Figure 2 In-situ Ultrasonic Imaging of an Embedded Fiber During Various Stages of Loading.

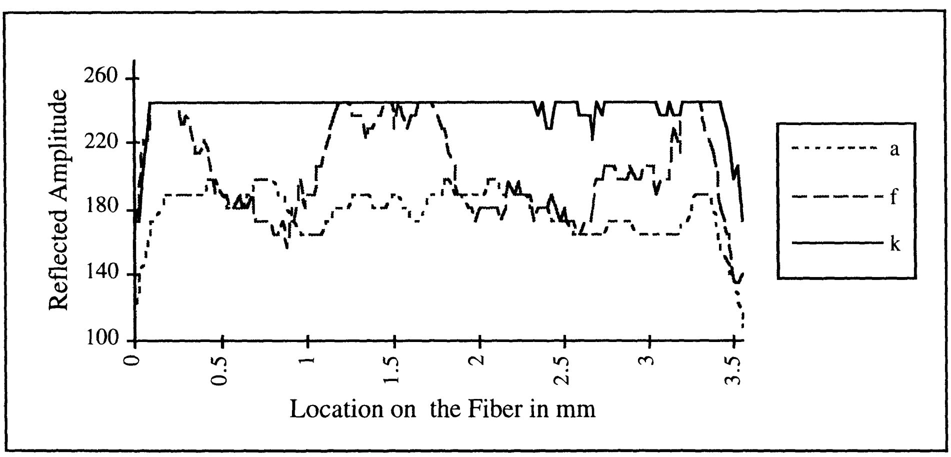


Figure 3 Ultrasonic Reflectivity from the Fiber-Matrix Interface at Various Locations for Selected Stages of Loading of the Test Specimen (indicated by a, f, and k in Figure 2).

THE ROLE OF RESIDUAL STRESS IN THE ULTRASONIC IMAGING OF FIBER-MATRIX INTERFACE

The model monofilament composite used for the transverse loading experiment was made with an embedded fiber with exposed ends as shown in Figure 1a. Ultrasonic imaging of such a fiber always showed dumbbell shaped ends [6] as seen in Figure 4a. However, when a completely embedded fiber was imaged, such a dumbbell appearance was not seen as in Figure 4b. This behavior is due to the presence of tensile residual stress at the exposed end of the fiber-matrix interface, as it is explained in the next paragraphs.

The free edge model by Pagano and Pipes [7, 8] was used to calculate the radial residual stresses at the fiber-matrix interface of the test sample being evaluated. The model [40] is based on elasticity theory for the free edge effect in a single fiber composite and predicted a reversal in sign of the radial stress in the edge region. For composites of titanium matrix reinforced with silicon carbide fibers, the matrix coefficient of thermal expansion (CTE) is much larger than the fiber CTE, resulting in a large and negative (compressive) thermally-induced residual radial stress in the interior of the body. However, in the neighborhood of the singular point within less than a fiber radius there the analysis predicted a very steep gradient in radial stress varying from negative to positive (tensile) shown in Figure 5.

Additionally, a two-dimensional axisymmetric finite element analysis of this problem was used to predict the state of stresses using the commercially available finite element package ANSYS. The mesh in the region of interest was very fine so that the shear stress and longitudinal normal stress was very close to zero at the free edge to satisfy the free surface boundary conditions. The stress results in the neighborhood of the singular point show excellent agreement with the elasticity model [7] as shown in Figure 5.

The existence of large tensile stresses of about 1 GPa (Figure 5) at the free end of the fiber (higher than the stress at fracture of the interface) leads to the existence of an interfacial crack growing a few microns along the interface. Therefore, finite element analysis was performed to simulate the cracking behavior using bi-linear contact elements at the possible fracture area. The contact element incorporates a bi-linear stress/strain relationship under loading. When in tension, the element does not function, which allows the separation of fiber and matrix. When in compression, the element functions like a stiff spring and satisfies displacement continuity. By performing a similar finite element analysis for single fiber completely embedded in the matrix, it has been found that the radial stress remains negative throughout entire interface (Figure 5) thereby no pre-test interface crack was predicted. This confirms the observation in Figure 4a and 4b suggesting that the reason for the appearance of the dumbbell shape is phase alteration of the reflected wave caused by the existence of the pre-test interfacial cracks in the case of a fiber with exposed ends. If the focal zone of the ultrasonic beam covers part of the bonded interface area with compressional residual stress, and part of the crack area initiated because of the large tensile residual stress, the signal can be canceled due to the phase reversal of the wave reflected from the two regions as described in the section on fiber fragmentation and can be found in the literature [8,9]. Using the SBR technique together with the phenomenon of signal phase alteration, it is feasible to detect an interfacial crack which is much smaller than the ultrasonic wavelength. This provides a nondestructive technique to detect defects which usually are too small to detect using conventional ultrasound.

CONCLUSIONS

It has been conclusively shown in this paper that the fiber-matrix interface in metal matrix composite (Ti-6Al-4V sheets with a single SiC fiber) fails over an applied range of stresses rather than failing instantaneously. Also, the residual stresses due to the mismatch of coefficients of thermal expansions of the fiber and the matrix play a substantial role in the complex failure process of the interface because of the reversal of radial residual stresses near any exposed ends of the fibers.

(a)

(b)

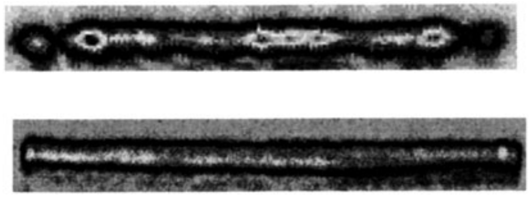


Figure 4 Ultrasonic shear wave images of (a) fiber with free edge, and (b) completely embedded fiber.

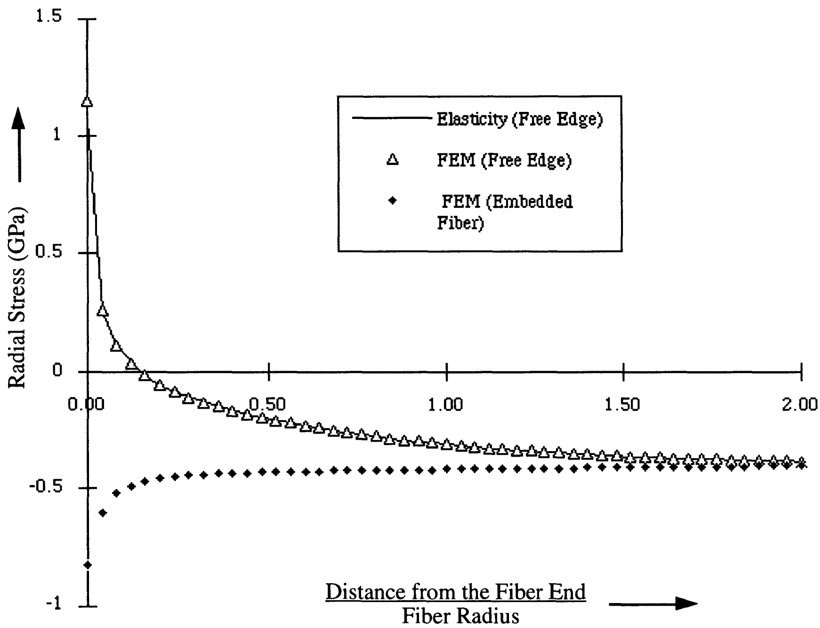


Figure 5 Interfacial radial stress distributions near the fiber tip.

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