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Residual Strength of a Thermomechanically Fatigued TIMETAL 21S/SCS-6 Composite

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The factors contributing to the residual strength of a thermomechanically-fatigued SiC fiber-reinforced metal matrix composite were assessed based on fracture surface features. The estimated residual strength was found to be in reasonable agreement with the measured value.

Keywords

composite, fatigue, metal-matrix composite, residual strength, titanium

1. Introduction

A CRITICAL need exists for structural materials with high specific strength and stiffness and good oxidation resistance for advanced aerospace applications. A family of materials that promises to answer many of these needs is titanium metal-matrix composites. Such materials present a challenge in terms of tailoring their properties to match the specific requirements for a given application. To do this requires a clear and accurate understanding of the deformation and failure behavior of these composites and the underlying mechanisms that affect them.

The present study assists in developing this understanding through a quantitative examination of fracture surfaces produced in a thermomechanical fatigue test of a TIMETAL (Titanium Metals Corporation of America, Henderson, NV) 21S/SCS-6 (Textron Specialty Materials, Sub. of Textron, Inc., Lowell, MA) composite specimen. The sources of residual strength after thermomechanical fatigue are assessed from a quantitative analysis of the fracture surfaces, and the individual contributions to the total residual strength of the composite are estimated.

2. Test Method

The fracture surface of a thermomechanically tested continuous-fiber composite consisting of silicon carbide fibers (SCS-6) and a TIMETAL 21S β-titanium matrix (Ti-15Mo-3Nb-3Al-0.2Si) was examined. The specimen was acquired from a test program performed at Wright Aeronautical Laboratories (Ref 1). The composite material was fabricated by hot isostatic pressing of alternating layers of rolled titanium foils and woven SCS-6 fibers and consisted of four unidirectional laminates with the fibers oriented in the direction of the applied stress (i.e., $[0]_4$). The fibers were 140 μm in diameter, and the total thickness of the composite was about 0.9 mm, which resulted in a fiber volume fraction of 0.32. The test specimen was 10 mm in width and was heat treated at 621 °C for 8 h before thermomechanical testing.

The thermomechanical test was conducted by applying axial loads with a servohydraulic load frame and thermal excursions by quartz-lamp heating in an air environment. A section of the specimen about 38 mm in length was uniformly heated and loaded in this manner. The mechanical load cycle consisted of a symmetric triangular wave-form with a maximum stress of 800 MPa (or load of 785 kg), an R (P_{min}/P_{max}) of 0.1, and a cycle time of 180 s. The thermal cycle was triangular with a 180 s cycle time and with maximum and minimum temperatures of 150 and 650 °C, respectively. The mechanical and thermal cycles were conducted out of phase (i.e., the stress was a maximum when the temperature was a minimum and vice versa). The test was run until failure (complete separation), which occurred at 1414 cycles.

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3. Discussion

Figure 1(a) shows a fracture surface of the thermomechanical test specimen. The right-hand side is dominated by fatigue-induced flat fracture that extends from the outer surface of the specimen and penetrates toward the center. Neu and Nicholas (Ref 1) considered such areas to be matrix dominated because failure initiates in the matrix at the outer surface of the specimen and, with the aid of the environment, propagates through the matrix of the composite. However, propagation of the fatigue-induced cracks is incomplete, so a region of ductile rupture is evident between the innermost rows of fibers. It is the ductile fracture regions that fail in the last loading cycle and which thus contribute to the residual strength of the composite. On the left-hand side of Fig. 1(a), the region of fatigue-induced fracture features is small, so fracture is predominantly ductile. A map that delineates the ductile and the fatigue-induced regions of the fracture surface is shown in Fig. 1(b).

To estimate the contribution of the matrix and the fiber constituents to the residual strength of the composite, we considered the following load paths: (1) fibers that were not broken during thermomechanical fatigue loading, (2) the matrix that did not fail due to thermomechanical fatigue loading, (3) the regions of the matrix that failed in shear as fatigue cracks linked together during the final stages of fracture, and (4) the friction between the matrix and fibers that were broken during fatigue. In the following discussion, the magnitude of the total load is estimated as the sum of the loads from each of these sources.

As a first estimate, we considered the fibers that were surrounded by ductile matrix failure to be unbroken by the thermomechanical fatigue. Figure 1(b) shows the locations of the 48 fibers within the region of ductile matrix failure. Using a fiber strength of 3450 MPa reported in Ref 2, we estimated the load supported by the 48 unbroken fibers to be 260 kg.

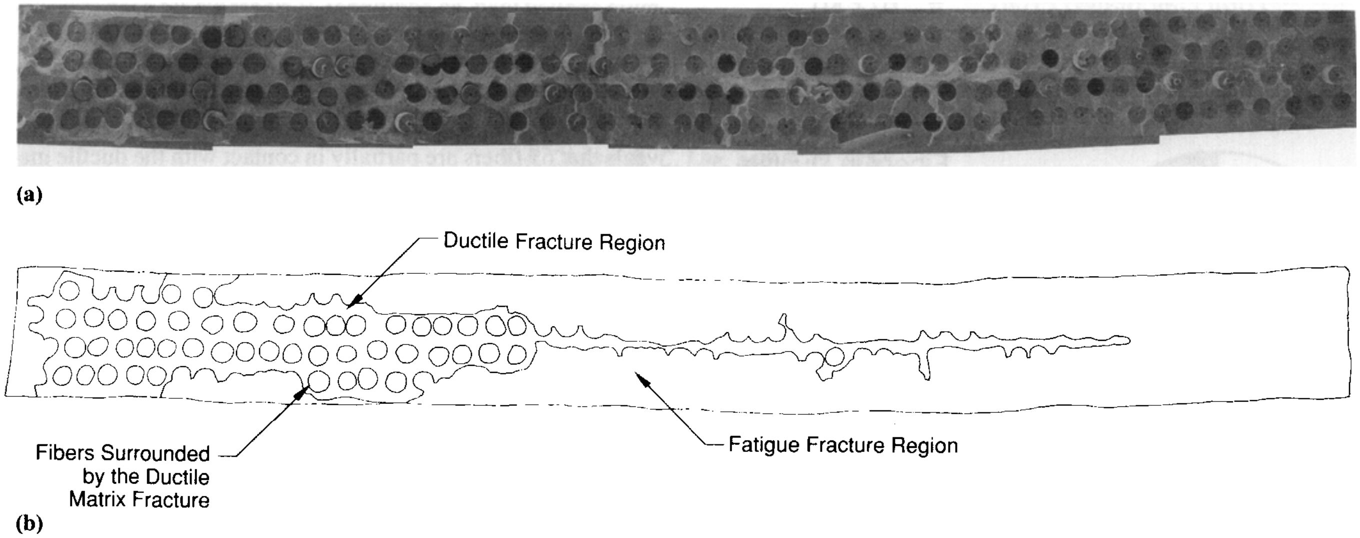

Fig. 1 Fracture surface of thermomechanical test specimen. (a) Scanning electron micrograph of fracture surface. (b) Diagram showing regions of fracture

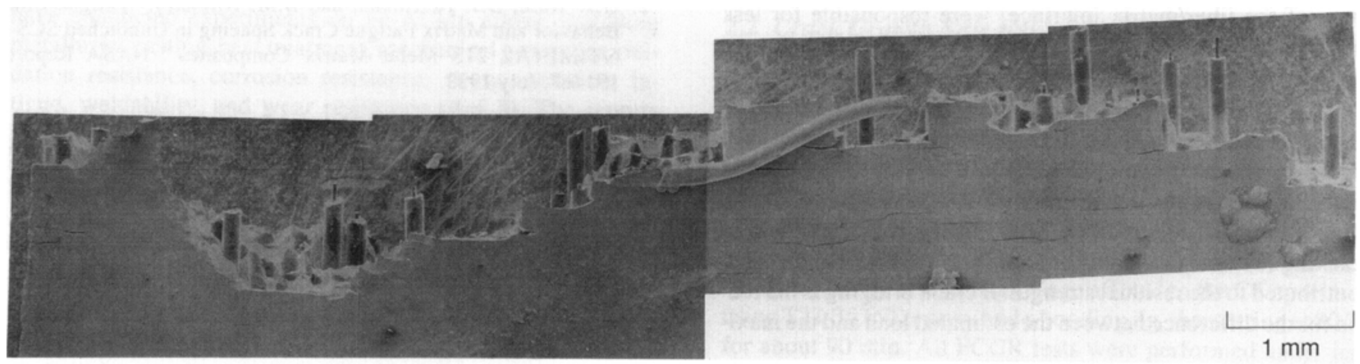

Fig. 2 Side view of fracture surface

The area of ductile failure depicted in Fig. 1(b) was measured as 2.28 mm^2. Experimental measurements reported by Neu (Ref 3) of the tensile properties of similarly processed TIMETAL 21S (i.e., so-called neat material) indicate that the maximum stresses at 25 and 500 °C are 1150 and 970 MPa, respectively. Interpolating to the temperature where the load was a maximum in the thermomechanical fatigue cycle (i.e., 150 °C) indicates that the maximum stress for the matrix was 1050 MPa. This strength value corresponds to a load of 244 kg that is supported by the region of ductile matrix failure shown in Fig. 1. Effects of prior loading history on the matrix strength are not taken into account and are expected to be small in view of the limited work hardening displayed by TIMETAL 21S.

The load required to produce shear failures on the fracture surface was estimated from measurements of the area of shearing measured from scanning electron micrographs. Figure 2 shows a side view of the fracture surface displayed in Fig. 1. Multiple cracks below the ultimate fracture surface are evident. The ultimate fracture surface appears to result from the linking up of parallel thermomechanical fatigue cracks with shear cracks. The dimensions of the heights of the sheared regions were measured from Fig. 2, and the sheared area estimated from these measurements was 0.833 mm^2. We estimated the maximum shear stress to be the maximum tensile stress divided by $\sqrt{3}$, which, when multiplied by the sheared area, results in a load estimate of 52 kg.

The load supported by friction between the broken fibers and the matrix was estimated by measuring the total length of exposed fiber on the fracture surface shown in Fig. 2 and doubling that value to account for exposed fibers on the conjugate fracture surface. Using the diameter of the fibers (140 μm), we computed the area of the exposed fiber/matrix interface to be 7.59 mm^2. An estimate for the interface shear strength of 150 MPa was obtained from measurements reported in Ref 4 for prefatigued Ti-15-3/SCS-6 composite, which provides an estimated 116 kg load from friction between broken fibers and the matrix.

Figure 3 shows the estimated contribution of each of the four load paths involved in residual strength. The contribution of the fibers is roughly equal to that of the matrix. The shear

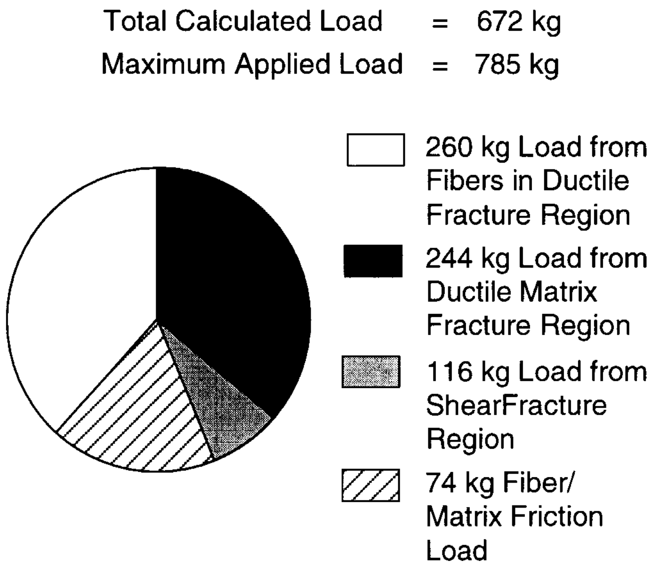

Fig. 3 Estimated contributions to the residual strength

load paths (i.e., shear of the matrix between fatigue cracks and shear of the fiber/matrix interface) were responsible for less than one-fourth of the total residual strength.

The sum of the estimated contributions of the four sources of the residual strength is 672 kg, which is less than the maximum applied load of 785 kg. Perhaps the greatest uncertainty in the estimated loads comes from the estimate of the number of fibers that broke during thermomechanical fatigue. If crack bridging occurred, unbroken fibers in the region of fatigue cracking (i.e., the flat matrix fracture surface area) would have contributed to the residual strength. If crack bridging is the reason for the difference between the estimated load and the maximum applied load, an additional 21 fibers would need to be unbroken in the region of the flat matrix cracking.

As previously mentioned, only those fibers that were completely surrounded by ductile matrix failure were assumed to contribute to the residual strength. Examination of Fig. 1 reveals that 61 fibers are partially in contact with the ductile matrix failure region. If one-third of these fibers were unbroken, the estimated residual strength would be in good agreement with the maximum applied load.

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