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Cyclic loading/unloading hysteresis behavior of fiber-reinforced ceramic–matrix composites at room and elevated temperatures

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ABSTRACT

In this paper, the cyclic loading/unloading hysteresis behavior of unidirectional C/SiC composite at room and elevated temperatures has been investigated. An approach to predict the hysteresis loops has been developed using the Coulomb friction law to describe the fiber/matrix interface shear stress. The interface debonded length, unloading interface counter-slip length and reloading interface new-slip length were determined by fracture mechanics approach. Based on the slipping range between fibers and matrix in the interface debonded region, the hysteresis loops have been divided into four different cases. The relationship between the hysteresis loops, hysteresis loss energy, interface debonding and interface slipping has been established. The hysteresis loops of unidirectional C/SiC composite have been predicted corresponding to different peak stresses at room and elevated temperatures. With the increase of peak stress, the hysteresis loops at room temperature change from the interface slip Case 2, i.e., the interface partially debonding and fiber partially slipping relative to matrix, to the interface slip Case 3, i.e., the interface completely debonding and fiber partially slipping relative to matrix; however, at an elevated temperature of 800 °C in air atmosphere, the hysteresis loops change from the interface slip Case 2 to Case 4, i.e., the interface completely debonding and fiber completely slipping relative to matrix in the interface debonded region, due to interphase oxidation.

1. Introduction

Ceramic materials possess high strength and modulus at elevated temperature. But their use as structural components is severely limited because of their brittleness. The continuous fiber-reinforced ceramic–matrix composites (CMCs), by incorporating fibers in ceramic matrices, however, not only exploit their attractive high-temperature strength but also reduce the propensity for catastrophic failure. The carbon fiber-reinforced silicon carbide ceramic–matrix composites (C/SiC, CMCs) are one of the most promising candidates for many high temperature applications, particularly as aerospace and aircraft thermostructural components [1].

Upon unloading and subsequent reloading, the hysteresis loops would develop due to the frictional slip occurred along any interface debonded region [2,3]. Holmes and Cho [4] investigated the fatigue loading history and microstructural damages on the fatigue hysteresis loops and frictional heating in unidirectional SiC/CAS composite. The loading frequencies, stress levels, stress ranges and matrix crack spacing would affect the area of hysteresis loops and the extent of specimen surface temperature rising. Reynaud [5] investigated the fatigue hysteresis loops evolution of two different types of CMCs at elevated temperature in inert atmosphere. The hysteresis loops area of 2D SiC/SiC composite increases with the increase of cycle number due to interface radial thermal residual compressive stress. However, the hysteresis loops area of cross-ply SiC/MAS-L composite decreases with the increase of cycle number due to interface radial thermal residual tensile stress. Steen and Valles [6] investigated the average slope, irreversible strain and width of the loading/unloading hysteresis loops of 2D SiC/Al_2O_3 and 2D C/SiC composites under tensile, creep and fatigue tests at room and elevated temperatures. Campbell and Jenkins [7] used the hysteresis modulus degradation and hysteresis energy dissipation to investigate the thermal degradation of an oxide/oxide CMC.

Many researchers have performed theoretical investigations on the hysteresis behavior of unidirectional, cross-ply and woven CMCs. Vagaggini et al. [8] investigated the characteristics of cyclic loading/unloading hysteresis loops in unidirectional SiC/CAS and SiC/SiC composites, and developed the hysteresis loops models based on the Hutchinson–Jensen fiber pull-out model [9]. Yang and Mall [10] investigated the effect of distributed fibers fracture on the cyclic loading/unloading hysteresis loops in unidirectional CMC using a cohesive damage law. Li et al. [11–14] investigated the effects of interface debonding, fibers fracture and matrix

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multicracking on the cyclic loading/unloading hysteresis loops in unidirectional and cross-ply CMCs. Fantozzi and Reynaud [15] investigated the hysteresis behavior of bi- or multi-directional (cross-weave, cross-ply, 2.5D, $[0/+60/-60]_n$) with SiC or C long fibers-reinforced SiC, MAS–L, Si–B–C or C matrix at room and elevated temperatures in the inert or oxidation conditions. By assuming the mechanical behavior of CMCs is mainly controlled by longitudinal yarns, the hysteresis loops shape evolution of these composites under cyclic loading has been analyzed. It should be noted that the above-mentioned hysteresis loops models all assume the constant interface shear stress in the interface debonded region. However, the constant assumption neglects the effect of fibers Poisson contraction on interface shear stress under a cyclic loading, i.e., the interface shear stress decreases when the applied stress increases upon loading, and increases when the applied stress decreases upon unloading.

In this paper, the cyclic loading/unloading hysteresis behavior of unidirectional C/SiC composite at room temperature and 800 °C in air atmosphere has been investigated. An approach to predict the hysteresis loops using the Coulomb friction law to describe interface shear stress in the interface debonded region has been developed. The interface debonded length and interface slip lengths, i.e., the unloading interface counter-slip length and reloading interface new-slip length, are determined by fracture mechanics approach. Based on the damage mechanism of fiber slipping relative to matrix in the interface debonded region upon unloading/reloading, the hysteresis loops were classified into four cases, i.e., (1) the interface partially debonds and the fiber completely slips relative to matrix; (2) the interface partially debonds and the fiber partially slips relative to matrix; (3) the interface completely debonds and the fiber partially slips relative to matrix; and (4) the interface completely debonds and the fiber completely slips relative to matrix. The cyclic loading/unloading hysteresis loops of unidirectional C/SiC composite have been predicted for different peak stresses at room and elevated temperatures.

2. Material and experimental procedures

The T-700™ carbon (Toray Institute Inc., Tokyo, Japan) fiber-reinforced silicon carbide matrix composites (C/SiC, CMCs) were provided by Shanghai Institute of Ceramics, People's Republic of China. The fibers have an average diameter of 7 μm and come on a spool as a tow of 12 K fibers. The unidirectional C/SiC composite was manufactured by hot-pressing method, which offered the ability to fabricate dense composite via a liquid phase sintering method at a low temperature. The volume fraction of fibers was approximately 42%. The low pressure chemical vapor infiltration was employed to deposit about 5–20 layer PyC/SiC with mean thickness of 0.2 μm in order to enhance the desired non-linear/non-catastrophic tensile behavior. The nano-SiC powder and sintering additives were ball milled for 4 h using SiC balls. After drying, the powders were dispersed in xylene with polycarbonsilane (PCS) to form the slurry. The carbon fiber tows were infiltrated by the slurry and wound to form aligned unidirectional composite sheets. After drying, the sheets were cut into a size of 150 mm × 150 mm and pyrolyzed in argon. Then the sheets were stacked in a graphite die and sintered by hot pressing.

The dog-bone shaped specimens, with dimensions of 120 mm length, 3.2 mm thickness and 4.5 mm width in gage section, were cut from 150 mm × 150 mm panels by abrasive water jet machining (AWJM), in which carborundum abrasive with the size of 150 μm along with a jet pressure of 120 MPa and cutting speed of 100 mm/min. The specimens were coated with SiC of about 20 μm thick by chemical vapor deposition to prevent oxidation at elevated temperature. These processing steps resulted in a material

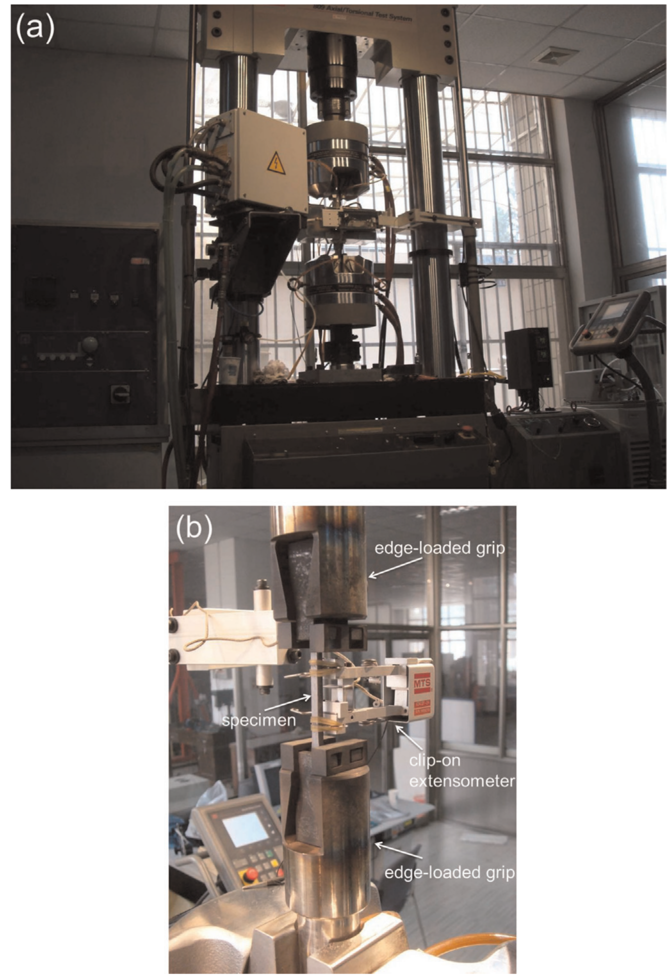

Fig. 1. The photograph of loading/unloading cyclic tensile experimental device of unidirectional C/SiC composite (a) the MTS Model 809 servohydraulic load-frame; and (b) the edge-loaded grips, specimen and clip-on extensometer.

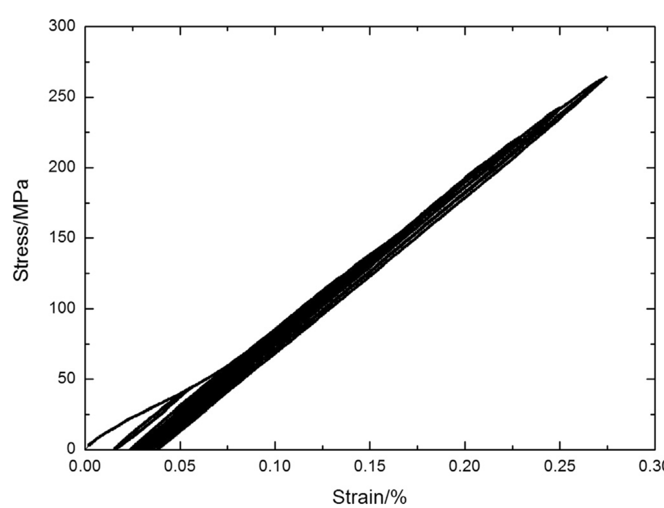

Fig. 2. The cyclic loading/unloading stress–strain curves of unidirectional C/SiC composite at room temperature.

having bulk density about 2.0 g/cm^3, and an open porosity below 5%.

The cyclic loading/unloading tensile experiments at room temperatrue and 800 °C in air atmosphere were conducted on a MTS Model 809 servo hydraulic load-frame (MTS Systems Corp., Minneapolis MN) equipped with edge-loaded grips. The loading