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Cyclic fatigue behavior of carbon fiber-reinforced ceramic–matrix composites at room and elevated temperatures with different fiber preforms

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ABSTRACT

In this paper, the cyclic fatigue behavior of unidirectional, cross-ply, 2D, 2.5D and 3D C/SiC composites at room and elevated temperatures has been investigated. The fatigue life S–N curves, fatigue hysteresis modulus, fatigue hysteresis dissipated energy and interface shear stress versus cycle number curves have been analyzed. An effective coefficient of the fiber volume fraction along the loading direction (ECFL) was introduced to describe the fiber architecture of the preforms. The fatigue limit, the degradation rate of fatigue hysteresis dissipated energy and interface shear stress are highest for unidirectional C/SiC with the highest ECFL, and lowest for 2.5D C/SiC composite with the lowest ECFL. At the same fatigue peak stress level and interface shear stress, the fatigue hysteresis dissipated energy of 2D and 2.5D C/SiC composites are much higher than that of unidirectional and cross-ply C/SiC composites due to low ECFL and fibers bending inside of composites.

1. Introduction

Continuous fiber-reinforced ceramic–matrix composites (CMCs), by incorporating fibers in ceramic matrices, can be made as strong as metal, yet are much lighter and can withstand much higher temperatures exceeding the capability of current nickel alloys typically used in high-pressure turbines, which can lower the fuel burn and emissions, while increasing the efficiency of aero engine [1]. CMCs do have some limiting factors that affect their performance, i.e., the oxidation that occurs within the CMC composite at elevated temperatures [2]. Carbon fiber-reinforced silicon carbide (C/SiC) is a CMC that succumbs to oxidation at high temperatures [3,4]. The oxygen is able to react with carbon and oxidize carbon fibers within the SiC matrix. Despite the oxidation problem, the C/SiC composite is still considered as a candidate for many space and aircraft applications, i.e., combustors, uncooled nozzles, and thrust chambers [5,6]. These applications would involve cyclic fatigue loading at elevated temperatures, leading to damage accumulation and eventually to composites failure.

Many researchers performed experimental investigations on the cyclic fatigue behavior of C/SiC composites. Shuler et al. [7] investigated the effect of loading frequency on the tension–tension fatigue life of a woven 0°/90° C/SiC composite at room temperature. It was found that the fatigue limit decreases with increasing loading frequency. Mall and Engesser [8] investigated the effect of loading frequency on the tension–tension fatigue life of a woven 0°/90° C/SiC composite at 550 °C in air. The oxidation of carbon fibers was almost absent or negligible at high loading frequency of 375 Hz, due to internal friction heating between fibers and the matrix. Dalmaz et al. [9] investigated the tension–tension fatigue behavior of a 2.5D woven C/SiC composite over a range of temperatures of 20, 600, 1000 and 1500 °C under an inert atmosphere. The fatigue hysteresis loops area decreases with increasing cycle number, and becomes lower with increasing testing temperatures. Zhang et al. [10] investigated the tension–tension fatigue behavior of a 2.5D woven C/SiC at room temperature and 900 °C in air. The fatigue limit decreases from $85\%\sigma_{\mathrm{uts}}$ at room temperature to $35\%\sigma_{\mathrm{uts}}$ at 900 °C in air.

The objective of this paper is to investigate the cyclic fatigue behavior of unidirectional, cross-ply, 2D, 2.5D and 3D C/SiC composites at room and elevated temperatures. An effective coefficient of the fiber volume fraction along the loading direction (ECFL) was introduced to describe the fiber architecture of the preforms. The fatigue life S–N curves, fatigue hysteresis modulus, fatigue hysteresis dissipated energy and interface shear stress versus cycle number curves have been analyzed.

2. Materials and experimental procedures

T-700™ carbon (Toray Institute Inc., Tokyo, Japan) fiber-reinforced silicon carbide matrix composites were provided by

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Shanghai Institute of Ceramics, People's Republic of China. The unidirectional and cross-ply C/SiC composites were manufactured by hot-pressing method. The volume fraction of fibers was approximately 40%. The dog-bone shaped specimens were cut from 150 mm × 150 mm panels by water cutting. The tension–tension fatigue tests at room temperature and 800 °C in air were conducted on a MTS Model 809 servo hydraulic load-frame (MTS Systems Corp., Minneapolis MN). The fatigue experiments were in a sinusoidal wave form and a loading frequency of 10 Hz. The fatigue load ratio ($\sigma_{\min}/\sigma_{\max}$) was 0.1, and the maximum number of applied cycles was defined to be 1,000,000 cycles. The fatigue tests were conducted under load control in accordance with the procedure in ASTM standard C 1360 at room temperature and 800 °C in air.

3. Experimental results

3.1. Cyclic fatigue at room temperature

The monotonic tensile strength of unidirectional and cross-ply C/SiC composite are 270 and 124 MPa, respectively. The fatigue peak stresses are 0.51, 0.66, 0.74, 0.88 and 0.96 of tensile strength for unidirectional C/SiC composite, and 0.70, 0.80, 0.85 and 0.90 of tensile strength for cross-ply C/SiC composite, respectively. The fatigue life S–N curves of unidirectional C/SiC, cross-ply C/SiC, 2D-C/SiC [7], 2D-C/SiC [11], 2D-C/SiC [12], 2.5D-C/SiC [10], and 3D-C/SiC [13] composites are given in Fig. 1. The S–N curves can be divided into three regions, i.e., the low-cycle region with $N_f < 1000$, intermediate cycle region with $1000 < N_f < 1{,}000{,}000$, and high-cycle region with $N_f > 1{,}000{,}000$. When fatigue peak stress approaches to tensile strength, fatigue fracture occurs in the low-cycle region; when fatigue peak stress is between tensile strength and fatigue limit, fatigue fracture lies in the intermediate cycle region; and when fatigue peak stress is less than the fatigue limit, composites do not fatigue fracture within 1,000,000 cycles.

The fatigue limit corresponding to unidirectional, cross-ply, 2D, 2.5D and 3D C/SiC composites are 0.88, 0.85, 0.8, 0.85, and 0.86 of tensile strength. Under cyclic fatigue loading, the loading directions were along with fiber for the unidirectional C/SiC, 0° fiber ply for the cross-ply and plain-weave 2D C/SiC composites, warp yarn for the 2.5D C/SiC, and axial fibers at a small angle θ for 3D C/SiC composite. An effective coefficient of the fiber volume content along the loading direction (ECFL) is defined as [14],

$$\lambda = \frac{V_{f\_\mathrm{axial}}}{V_f} \tag{1}$$

in which V_f and V_{f_axial} denote the total fiber volume fraction in the composites and the effective fiber volume fraction in the cyclic loading direction. The values of parameter λ, which can be used to characterize the fiber architectures, corresponding to unidirectional, cross-ply, 2D, 2.5D and 3D C/SiC composites are 1.0, 0.5, 0.5, 0.75 and 0.93. The total fiber volume fraction for unidirectional, cross-ply, 2D, 2.5D and 3D C/SiC composites are 40%, 40%, 45%, 40%, and 45%, respectively. The ECFL for unidirectional, cross-ply, 2D, 2.5D and 3D C/SiC are 40%, 20%, 22.5%, 30% and 42%. For unidirectional and 3D C/SiC composites with high ECFL, i.e., 40% and 42%, the fatigue limit stresses are 0.88 and 0.86 of tensile strength, respectively. Due to fibers bending in the preform of 3D C/SiC composite, the fatigue limit is less than that of unidirectional C/SiC composite although with the highest ECFL. For cross-ply, 2D and 2.5D C/SiC composites, the fatigue limit of cross-ply C/SiC composite is 0.85 of tensile strength with ECFL of 20%; the fatigue limit of 2.5D C/SiC composite is also 0.85 of tensile strength, however with higher ECFL of 30% due to fibers bending inside of composite; and the fatigue limit of 2D C/SiC composite is 0.8 of tensile strength with ECFL of 20% also due to fibers bending in the preform.

The normalized hysteresis modulus E_n/E_0 versus cycle number

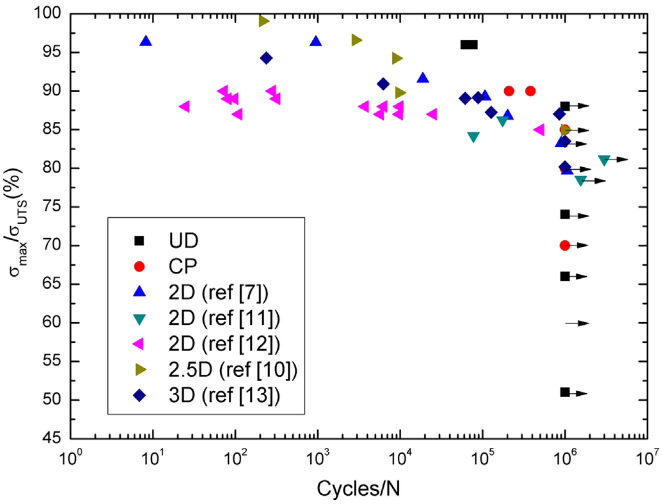

Fig. 1. The fatigue life S–N curves of unidirectional, cross-ply, 2D, 2.5D and 3D C/SiC composites at room temperature.

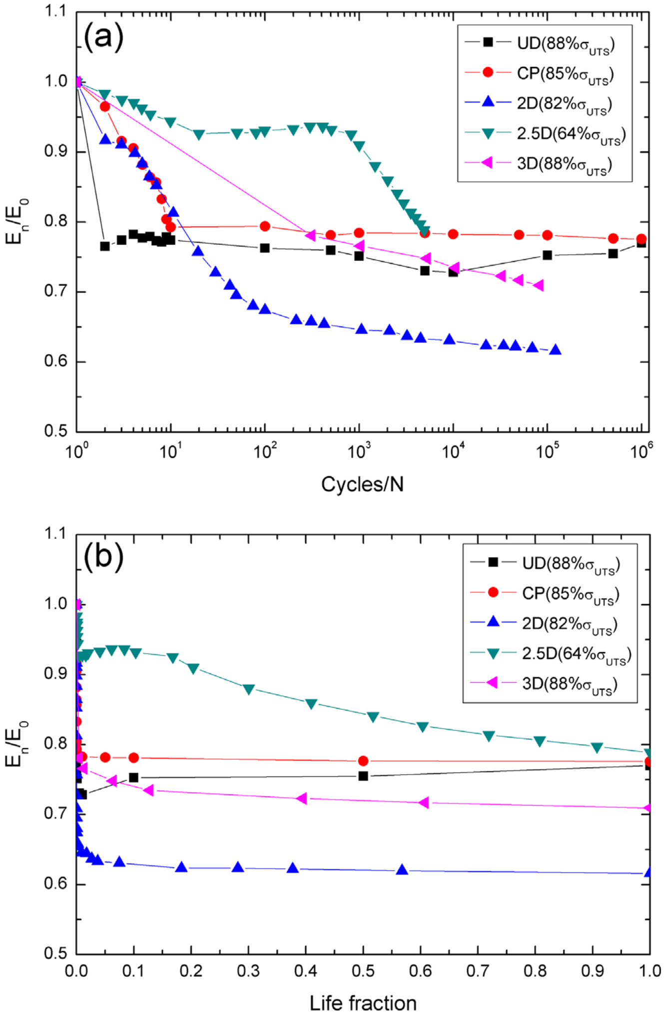

Fig. 2. (a) The fatigue hysteresis modulus E_n/E_0 versus cycle number; and (b) the fatigue hysteresis modulus E_n/E_0 versus life fraction of unidirectional, cross-ply, 2D, 2.5D and 3D C/SiC composites at room temperature.