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Damage evolution and life prediction of different 2D woven ceramic-matrix composites at room and elevated temperatures based on hysteresis loops

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A B S T R A C T

In this paper, the damage evolution and life prediction of different 2D woven fiber-reinforced ceramic-matrix composites (CMCs), i.e., C/SiC, SiC/SiC, SiC/Si–N–C, Nextel 610™/Aluminosilicate, and Nextel 720™/Aluminosilicate, at room and elevated temperatures have been investigated. The evolution of fatigue hysteresis dissipated energy and interface shear stress versus cycle number curves have been analyzed. The fatigue life S–N curves and broken fibers fraction versus cycle number have been predicted. For non-oxide CMCs, i.e., C/SiC, SiC/SiC or SiC/Si–N–C, the fatigue limit stress greatly reduces at elevated temperature in air, i.e., 21% tensile strength of C/SiC at 550 °C in air, 25% tensile strength of SiC/SiC at 800 °C in air, and 25% tensile strength of SiC/Si–N–C at 1000 °C in air; however, for oxide-oxide CMCs, the fatigue limit stress is much higher than that of non-oxide CMCs, i.e., 60% tensile strength of Nextel 610™/Aluminosilicate and Nextel 720™/Aluminosilicate at 1000 °C and 1200 °C in air.

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. Continuous fiber-reinforced ceramic-matrix composites (CMCs), by incorporating fibers in ceramic matrices, however, can be made as strong as metal, yet are much lighter and can withstand much higher temperatures exceeding the capability of current nickel alloys used in high-pressure turbines, which can lower the fuel burn and emissions, while increasing the efficiency of aero engine [1].

Upon cyclic mechanical and thermal loading, the CMCs are subject to fatigue [2–6]. Staehler et al. [7] found that the fatigue life of 2D C/SiC was greatly reduced at the loading frequency of 375 Hz compared with 4 and 40 Hz, however, at 550 °C in air, the fatigue life increases at the loading frequency of 375 Hz [8]. Shi [9] found that the damage evolution in 2D SiC/SiC at room and elevated temperatures in air is governed by temperature, stress level and stress ratio. The hysteresis loop area increases at elevated temperature due to changes in the residual stress, internal damage and oxidation [10,11]. For oxide/oxide CMCs, i.e., 2D Nextel 610™/Aluminosilicate [12] or Nextel 720™/Aluminosilicate [13], at elevated temperature in air, the hysteresis loop area decreases with applied cycles and the values of fatigue hysteresis dissipated energy are very small.

In the present analysis, the damage evolution and life prediction of different 2D woven CMCs, i.e., C/SiC, SiC/SiC, SiC/Si–N–C, Nextel 610™/Aluminosilicate and Nextel 720™/Aluminosilicate, at room and elevated temperatures have been

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Nomenclature

ε_{unload}	unloading strain
ε_{reload}	reloading strain
V_f	fiber volume content in the longitudinal direction
E_f	fiber elastic modulus
r_f	fiber radius
τ_i	interface shear stress
l_c	matrix crack spacing
l_d	interface debonded length
y	interface counter-slip length
z	interface new-slip length
α_f	fiber thermal expansion coefficient
α_c	composite thermal expansion coefficient
ΔT	temperature difference between fabricated temperature and test temperature
η	damage parameter
U	fatigue hysteresis dissipated energy
l_f	interface slip length
T	stress carried by intact fibers
$\langle T_b \rangle$	stress carried by broken fibers
P_{fa}	fiber failure probability of oxidized fibers in the oxidation region
P_{fb}	fiber failure probability of unoxidized fibers in the oxidation region
P_{fc}	fiber failure probability of fibers in the interface debonded region
P_{fd}	fiber failure probability of fibers in the interface bonded region
ζ	oxidation fibers fraction in the oxidized region
χ	oxidation fraction in the multiple matrix cracks
τ_0	initial interface shear stress
τ_s	steady-state interface shear stress
$\tau_i(N)$	interface shear stress at the Nth cycle
b_0, j	interface wear model parameters
φ	degradation/increasing rate of fatigue hysteresis dissipated energy
ψ	degradation rate of the interface shear stress

Superscript and subscript

f	fiber
m	matrix
c	composite

investigated. The damage evolution of fatigue hysteresis dissipated energy and interface shear stress versus cycle number curves have been analyzed. The fatigue life S–N curves and broken fibers versus cycle numbers have been predicted.

2. Damage parameters and life prediction model

2.1. Damage parameters

Under cyclic fatigue loading, the matrix cracking modes in 2D woven CMCs can be divided into five different modes, as shown in Fig. 1 [14]. Upon unloading and reloading, the relative frictional slip occurred in the fiber/matrix interface of matrix cracking mode 3 and mode 5 [15].

For matrix cracking mode 3, the unloading strain ε_{unload} and reloading strain ε_{reload} are determined by Eq. (1) [16].

$$\varepsilon_{unload} = \begin{cases} \frac{\sigma}{V_f E_f} + 4\frac{\tau_i}{E_f}\frac{y^2}{r_f l_c} - 2\frac{\tau_i}{E_f}\frac{(2y-l_d)(2y-l_c+l_d)}{r_f l_c} - (\alpha_c - \alpha_f)\Delta T, l_d < \frac{l_c}{2} \\ \frac{\sigma}{V_f E_f} + 4\frac{\tau_i}{E_f}\frac{y^2}{r_f l_c} - 2\frac{\tau_i}{E_f}\frac{(2y-l_c/2)^2}{r_f l_c} - (\alpha_c - \alpha_f)\Delta T, l_d = \frac{l_c}{2} \end{cases} \tag{1a}$$