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Synergistic effects of temperature, oxidation, loading frequency and stress-rupture on damage evolution of cross-ply ceramic-matrix composites under cyclic fatigue loading at elevated temperatures in oxidizing atmosphere

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ABSTRACT

In this paper, the synergistic effects of temperature, oxidation, loading frequency and stress-rupture on damage evolution of cross-ply ceramic-matrix composites (CMCs) under cyclic fatigue loading at elevated temperatures in oxidizing atmosphere have been investigated. The Budiansky-Hutchinson-Evans shear-lag model was used to describe the micro stress field of the damaged composite considering interface wear and interface oxidation. The damage parameters of fatigue hysteresis dissipated energy, fatigue hysteresis modulus, and fatigue peak strain have been used to monitor the damage evolution inside of CMCs. The relationships between damage parameters and internal damage of matrix cracking, interface debonding and slipping have been established. The experimental fatigue hysteresis, interface slip lengths and peak strain of cross-ply SiC/MAS composite under cyclic fatigue loading at different testing temperatures, loading frequency and stress-rupture time in air condition have been predicted.

1. Introduction

Ceramic-matrix composites (CMCs) possess high strength-to-weight ratio at elevated temperatures, and are being designed and developed for hot section components in commercial aero engine [1]. As new materials, the CMCs need to meet the airworthiness certification requirements, and it is necessary to analyze the degradation, damage, and failure mechanisms subjected to cyclic loading at different temperatures and environments.

Many researchers performed the experimental and theoretical investigations on cyclic fatigue behavior of fiber-reinforced CMCs. Lara-Curzio [2] investigated the stress-rupture behavior of 2D woven SiC/SiC composite at 950 °C in air. It was found that the composite exhibits delayed failure, and the compliance of the composite increases with time. A micromechanical model was developed to predict the reliability and lifetime of CMCs under stress-rupture condition considering fibers oxidation at elevated temperatures [3]. Halverson and Curtin [4] investigated the deformation, strength and stress-rupture lifetime of an oxide/oxide CMC at temperatures of 950 °C and 1050 °C. Based on the global load sharing criterion, a stress-rupture micromechanical model has been developed to predict the lifetime of the oxide/oxide CMC considering fiber strength degradation, matrix damage and fibers pullout. Sullivan [5] found that the stress rupture strength of SiC/SiC composite decreases with increasing time at the intermediate temperature range of 700–950 °C, attributed almost

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Nomenclature

r_f	fiber radius
E_f	fiber elastic modulus
E_m	matrix elastic modulus
E_c	composite elastic modulus
ξ	interface oxidation length
τ_f	interface shear stress in the oxidation region
$\tau_i(N)$	interface shear stress at the Nth applied cycle
τ_0	initial interface shear stress
τ_s	steady-state interface shear stress
V_f	fiber volume fraction
V_m	matrix volume fraction
ρ	shear-lag model parameter
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
U_e	fatigue hysteresis dissipated energy

Superscript and subscript

f	fiber
m	matrix
c	composite

entirely to the slow flaw growth within fibers. Mehrman et al. [6] investigated the influence of hold times on the fatigue behavior of 2D woven Nextel™ 720/Alumina composite at 1200 °C in air and in steam environments. In air condition, the life under combination of cyclic loading and hold time exceeded that under creep loading, but shorter than that under cyclic loading; however, in steam environment, the life under cyclic loading and hold time was close to that obtained in creep. Ruggles–Wrenn et al. [7] investigated the effects of loading frequency, i.e., 0.1, 1.0 and 10 Hz, and testing environment, i.e., in laboratory air and in steam environment, on fatigue behavior of 2D woven Nextel™ 720/Alumina composite at 1200 °C. In air, the fatigue life appears to be independent of the loading frequency; however, in steam environment, the fatigue life and fatigue limit decrease with decreasing loading frequency. Lanser and Ruggles–Wrenn [8] investigated the tension-compression fatigue behavior of 2D woven Nextel™ 720/alumina composite at 1200 °C in air and in steam. It was found that the presence of steam significantly degraded the fatigue performance, and the tension-compression cyclic loading was more damaging than tension-tension cyclic loading. Ruggles–Wrenn and Lee [9] investigated the tension-tension fatigue behavior of 2D woven SiC/SiC composite with an inhibited matrix at 1300 °C in air and in steam condition. The fatigue limit is higher in steam environment than that in air. Under cyclic loading, the damage evolution inside composites should be monitored to predict the lifetime. Maillet et al. [10] developed an acoustic emission (AE) based approach to monitor damage evolution and lifetime of 2D SiC/[Si–B–C] composite with self-healing matrix under static fatigue loading at elevated temperature of 450 and 500 °C. Kordatos et al. [11] investigated the damage detection of cross-ply SiC/BMAS composite through combination of Infrared thermography and acoustic emission. The damage evolution of crack initiation, propagation and final fracture has been observed and analyzed. Li [12,13] established the relationship between hysteresis dissipated energy-based damage parameter, internal damage of matrix cracking, interface debonding and fibers fracture, and predict the damage evolution of unidirectional C/SiC under fatigue loading at room temperature and 800 °C in air condition [14]. Li [15] developed the hysteresis loops model of fiber-reinforced CMCs considering the oxidation subjected to static fatigue loading. However, under cyclic loading at elevated temperatures in oxidative environment, the interface debonding and interface slipping between fibers and the matrix are affected by the combination effects of interface oxidation and interface wear.

The objective of this paper is to investigate the synergistic effects of temperature, oxidation, loading frequency and stress-rupture on the damage evolution of cross-ply CMCs under cyclic fatigue loading at elevated temperatures in air. The Budiansky-Hutchinson-Evans shear-lag model was used to describe the micro stress field of the damaged composite. The damage parameters based on the hysteresis loops models considering the combination effects of interface wear and interface oxidation, i.e., the fatigue hysteresis dissipated energy, fatigue hysteresis modulus, and fatigue peak strain, have been used to monitor the damage evolution inside of CMCs. The experimental fatigue hysteresis and the peak strain of cross-ply SiC/MAS