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Synergistic effect of interface wear and loading sequence on interface debonding and relative slipping of fiber-reinforced ceramic-matrix composites

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ABSTRACT

This study investigates the synergistic effect of interface wear and loading sequence on interface debonding and relative slipping of fiber-reinforced ceramic-matrix composites (CMCs). There are five different fatigue loading sequences considered in the present analysis. Based on the fatigue damage mechanism of fiber slipping relative to the matrix upon unloading/reloading, the interface debonded length and interface slip lengths are determined using the fracture mechanics approach. The relationships between interface debonding, interface slipping, interface wear, cycle number, peak stress and loading sequence have been determined. The fatigue hysteresis loops of C/SiC composite under three-stage cyclic fatigue loading have been predicted using the present analysis.

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1. Introduction

With the demand for high thrust-weight ratio and more efficient aero engine, the temperature of the turbine sections will be raised to a level exceeding the limit of current metallic materials. New materials will have to be tested and validated at very high temperatures that surpass 1300 °C. Ceramic-matrix composites (CMCs) are lighter than superalloys and maintaining the structural integrity even at higher temperatures, desirable qualities for improving aero engine efficiency, and have already been implemented on some aero engines' components [1]. CMC durability has been validated through the ground testing or commercial flight testing in demonstrator or customer gas turbine engines accumulating almost 30,000 h of operation. The CMC combustion chamber and high-pressure turbine components were designed and tested in the ground testing of GEnx aero engine [2]. The CMC rotating low-pressure turbine blades in a F414 turbofan demonstrator engine were successfully tested for 500 grueling cycles to validate the unprecedented temperature and durability capabilities by GE Aviation. The CMC tail nozzles were designed and fabricated by SNECMA (SAFRAN) and completed the first commercial flight on CFM56-5B aero engine on 2015. CMCs will play a key role in the performance of CFM's LEAP turbofan engine, which would enter into service in 2016 for Airbus A320 and 2017 for Boeing 737 max.

Under cyclic fatigue loading, the interface shear stress of CMCs would decrease with increasing cycle number due to interface wear [3–7]. Cho et al. [8] developed an approach to estimate interface shear stress between fibers and the matrix through measurement of temperature rise occurred during cyclic fatigue loading of CMCs. It was found that interface shear stress of unidirectional SiC/CAS-II composite decreases from an initial value over 20 MPa to approximately 5 MPa after 25,000 cycles [9]. Evans et al. [10] investigated the low-cycle fatigue behavior of unidirectional SiC/CAS composite and also found the rapid degradation in the interface sliding stress existed between fibers and the matrix through hysteresis measurements. It was found that the interface shear stress degrades from an initial value of 20 MPa to approximately 5 MPa after experiencing 30 cycles. Upon unloading and subsequent reloading, the interface debonding and interface frictional slipping between fibers and the matrix occur, which plays an important role in the macro-performance of fiber-reinforced CMCs, i.e., the shape, location and area of hysteresis loops [11]. Pryce and Smith [12] investigated the effect of interface partially debonding on hysteresis loops of unidirectional CMCs by assuming purely frictional load transfer between fibers and the matrix. It was found that the hysteresis loop width increases with decreasing interface shear stress when interface partially debonds. Solti et al. [13] investigated the effect of interface partially and completely debonding on hysteresis loops in unidirectional CMCs using the maximum interface shear strength criterion to determine interface slip lengths. It was found that the interface debonded length and

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Nomenclature

E	Young's modulus
l_c	matrix crack spacing
l_d	interface debonded length
r_f	fiber radius
R	matrix radius
V	volume fraction
ρ	shear-lag model parameter
y	unloading interface counter-slip length
z	reloading interface new-slip length
α	coefficient of linear thermal expansion
ΔT	temperature change from 'stress-free' temperature
ξ	interface wear region length
ζ_d	fiber/matrix interface debonded energy
σ	stress
σ_{max}	fatigue peak stress
σ_{fo}	fiber axial stress in the interface bonded region
σ_{mo}	matrix axial stress in the interface bonded region
σ_{tr_u}	unloading transition stress
σ_{tr_r}	reloading transition stress
τ_i	interface shear stress in the interface debonded region
$\tau_i(N)$	interface shear stress at the Nth cycle
τ_{io}	initial interface shear stress, i.e., $\tau_i(N)$ at $N = 1$
τ_{imin}	steady-state interface shear stress
ω	empirical constant of interface shear stress degradation model
λ	empirical constant of interface shear stress degradation model
τ_f	interface shear stress in the interface wear region
ε	strain
ε_c^{unload}	unloading strain
ε_c^{reload}	reloading strain

Superscript and subscript

f	fiber
m	matrix
c	composite

interface slip range would decrease with increasing interface shear strength, which would decrease the hysteresis loops area when interface partially debonds. Vagaggini et al. [14] investigated the effect of interface debonded energy on hysteresis loops of unidirectional CMCs based on the Hutchinson-Jensen fiber pull-out model [15]. When the interface debonded energy is small, the interface counter slip and new slip lengths would not be affected by interface debonding; and when the interface debonded energy is large, the interface counter slip and new slip lengths would be stopped at the interface debonding tip, and the interface slip range would not change upon continually unloading or reloading. Li et al. investigated the effect of interface debonding [16], fibers Poisson contraction [17], fibers fracture [18] and interface wear [19] on hysteresis loops of unidirectional CMCs, and developed an approach to estimate interface shear stress in unidirectional CMCs through hysteresis loops area [20]. The unloading residual strain and hysteresis loops area decrease with increasing of interface debonded energy and interface shear stress. The maximum strain, residual strain, and hysteresis loops area increase with increasing of broken fibers fraction. However, the synergistic effects of interface wear and loading sequences would affect the interface debonding and interface frictional slipping under cyclic fatigue loading. Shi and Zhou [21] investigated interfacial fatigue of fiber-reinforced composites under constant amplitude cyclic loading using modified degradation formula for interface frictional coefficient. However, there would exist complex cyclic loading condition, i.e., variable amplitude cyclic loading, during the applications of ceramic composite structures on aircraft thermostructural components. To understand interface debonding and relative slipping in ceramic composite structures, i.e., 2D or 3D woven CMCs, under complex cyclic loading condition. It should be noted that the above-mentioned theoretical researches of interface debonding, interface slipping, and hysteresis loops models are mainly concerned with constant amplitude cyclic fatigue loading. The theoretical research work on interface debonding, interface friction slipping, and fatigue hysteresis loops models considering different fatigue loading sequences and interface wear mechanism has not been conducted.

The objective of this paper is to investigate the synergistic effects of interface wear and loading sequence on interface debonding and relative slipping of fiber-reinforced CMCs. There are five different fatigue loading sequences considered, i.e., (1) cyclic loading under peak stress σ_{max}; (2) cyclic loading under low peak stress σ_{max1} for N_1 cycles, and high peak stress σ_{max2}, i.e., $\sigma_{max1} < \sigma_{max2}$; (3) cyclic loading under high peak stress σ_{max1} for N_1 cycles, and low peak stress σ_{max2}, i.e., $\sigma_{max1} > \sigma_{max2}$; (4) cyclic loading under low peak stress σ_{max1} for N_1 cycles, and high peak stress σ_{max2} for N_2 cycles, i.e., $\sigma_{max1} < \sigma_{max2}$; and (5) cyclic loading under high peak stress σ_{max1} for N_1 cycles, and low peak stress σ_{max2} for N_2 cycles, i.e., $\sigma_{max1} > \sigma_{max2}$. Based on the fatigue damage mechanism of fiber slipping relative to the matrix upon unloading and reloading, the interface debonded length and interface slip lengths, i.e., interface counter-slip length and interface new-slip length, are determined using fracture mechanics approach. The relationships between interface debonding, interface slipping, interface wear, cycle number, peak stress and loading sequence have been determined. The fatigue hysteresis loops of C/SiC composite under three-stage cyclic fatigue loading have been predicted using the present analysis.

2. Theoretical analysis

The interfacial debonding and slipping would be affected by fatigue loading sequences. Upon first loading to fatigue peak stress σ_{max1}, it is assumed that matrix multicracking and interface debonding occur. The interface shear stress in the interface debonded region decreases from initial value τ_i to τ_f after experiencing N_1 cycles. When fatigue peak stress increases from σ_{max1} to σ_{max2}, the crack propagates along fiber/matrix interface. To analyze stress distributions in fibers and the matrix, a unit cell is extracted from the ceramic composite, as shown in Fig. 1. The unit cell contains a single fiber surrounded by a hollow cylinder of matrix. The fiber radius is r_f, and the matrix radius is $R(R = r_f/V_f^{1/2})$. The length of unit cell is $l_c/2$, which is just half of matrix crack spacing. Holmes and Cho [9] found that the matrix crack spacing approaches to a stable value during the initial cyclic loading. Li [22] found that the load transfer between fibers and the matrix decreases with decreasing interface shear stress. Based on the critical matrix strain energy criterion, there would be no new matrix cracking appears under constant fatigue peak stress as the matrix strain energy decreases with increasing cycle numbers. In the present analysis, the matrix crack spacing l_c is assumed to be constant

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