Engineering Fracture Mechanics 169 (2017) 336–353

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

journal homepage: www.elsevier.com/locate/engfracmech

Effects of loading type, temperature and oxidation on mechanical hysteresis behavior of carbon fiber-reinforced ceramic-matrix composites

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A R T I C L E   I N F O

Article history:
Received 22 August 2016
Received in revised form 17 October 2016
Accepted 20 October 2016
Available online 25 October 2016

Keywords:
Ceramic-matrix composites (CMCs)
Hysteresis loops
Matrix cracking
Interface debonding

A B S T R A C T

The effects of loading type, i.e., cyclic loading/unloading tensile, cumulative tensile fatigue loading, and tension-tension fatigue loading, temperature and oxidation on the mechanical hysteresis behavior of carbon fiber-reinforced ceramic-matrix composites (CMCs) have been investigated. Based on the damage mechanism of fiber sliding relative to the matrix in the interface debonded region, the stress-strain relationships upon unloading/reloading when the interface partially and completely debonded have been determined considering fibers fracture. The effects of material properties, damage mode and cycle number on the interface slip and hysteresis loops have been analyzed. The mechanical hysteresis behavior of different loading types of C/SiC at room temperature and 800 °C in air have been predicted.

1. Introduction

Ceramic materials possess high strength and modulus at elevated temperatures. 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 to improve the toughness, however, not only exploit their attractive high-temperature strength but also reduce the propensity for catastrophic failure. 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].

When CMCs are subjected to cyclic loading, hysteresis loops develop due to frictional sliding along any interface debonded region [2,3]. Many researchers have performed investigations on the hysteresis behavior of CMCs. Kotil et al. [4] investigated the effect of interface debonding on hysteresis loops. Pryce and Smith [5] investigated the hysteresis loops when the interface partially debonded based on the assumption of purely frictional load transfer between fibers and the matrix. Keith and Kedward [6] investigated the hysteresis loops when the interface completely debonded. Solti et al. [7] investigated the hysteresis loops when the interface was chemically bonded and partially debonded by adopting the maximum interface shear strength criterion to determine the interface debonded length. Ahn and Curtin [8] investigated the effect of matrix stochastic cracking on the hysteresis loops by assuming two-parameter Weibull distribution of matrix flaw. Li [9,10] developed an approach to model the hysteresis loops of unidirectional CMCs using the Coulomb friction law to describe the interface shear stress in the interface debonded region. The cyclic loading/unloading tensile hysteresis loops of unidirectional C/SiC composite at room and elevated temperatures have been predicted for different peak stresses. Li [11] investigated the synergistic effect of arbitrary loading sequence and interface wear on the fatigue hysteresis loops of

http://dx.doi.org/10.1016/j.engfracmech.2016.10.010
0013-7944/

Nomenclature

σ	stress
r_f	fiber radius
R	matrix radius
l_c	matrix crack spacing
l_d	interface debonded length
V_f	fiber volume fraction
V_m	matrix volume fraction
E_f	fiber elastic modulus
E_m	matrix elastic modulus
E_c	composite elastic modulus
ρ	shear-lag model parameter
τ_i	interface shear stress
ζ_d	interface debonded energy
T	stress carried by intact fibers
$\langle T_b \rangle$	load carried by broken fibers
$P(T)$	fiber failure volume fraction
σ_c	fiber characteristic strength
$\sigma_o(N)$	fiber strength at the Nth cycle
y	interface counter-slip length
$\Delta\sigma$	additional stress in intact fibers
T^U	stress carried by intact fibers at the matrix cracking plane upon unloading
σ_{fo}	fiber axial stress in the interface bonded region
T^R	stress carried by intact fibers at the matrix cracking plane upon reloading
z	interface new-slip length
ε_c	composite strain
ε_{c_pu}	composite unloading strain when interface partially debonding
ε_{c_pr}	composite reloading strain when interface partially debonding
ε_{c_fu}	composite unloading strain when interface completely debonding
ε_{c_fr}	composite reloading strain when interface completely debonding
α_f	fiber thermal expansion coefficient
α_c	composite thermal expansion coefficient
ΔT	temperature difference between fabricated and test temperature
U	hysteresis loss energy
σ_{tr_pu}	unloading transition stress when interface partially debonding
σ_{tr_pr}	reloading transition stress when interface partially debonding
σ_{tr_fu}	unloading transition stress when interface completely debonding
σ_{tr_fr}	reloading transition stress when interface completely debonding

Superscript and subscript

f	fiber
m	matrix
c	composite

fiber-reinforced CMCs. The difference of interface shear stress existing in the new and original interface debonding region affects the interface debonding and interface frictional slipping between fibers and the matrix. Li [12] investigated the hysteresis loops of C/SiC composites with different fiber preforms, i.e., unidirectional, cross-ply, 2D and 2.5D woven, 3D braided and 3D needled, at room temperature using an effective coefficient of fiber volume fraction along the loading direction (ECFL). The hysteresis loops, hysteresis dissipated energy and hysteresis modulus of C/SiC have been predicted. Li et al. [13] investigated the effect of multiple matrix cracking modes on the hysteresis loops of cross-ply CMCs. The matrix cracking mode 3 and mode 5, which involve matrix cracking and fiber/matrix interface debonding in the longitudinal plies have been considered in the hysteresis loops models. The interface shear stress of cross-ply C/SiC has been predicted using experimental fatigue hysteresis loss energy corresponding to different fatigue peak stresses and cycle numbers at room and elevated temperatures. Fantozzi et al. [14] 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 temperature in inert and oxidation conditions. Li et al. [15–17] developed an approach to estimate the interface shear stress of unidirectional, cross-ply, 2D and 2.5D woven CMCs by comparing the experimental fatigue hysteresis loss energy with theoretical computational values. However, it should be noted that the mechanical hysteresis behavior of CMCs corresponding to different loading types has not been investigated.