Theoretical and Applied Fracture Mechanics xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Theoretical and Applied Fracture Mechanics

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

Modeling first matrix cracking stress of fiber-reinforced ceramic-matrix composites considering fiber fracture

Li Longbiao

College of Civil Aviation, Nanjing University of Aeronautics and Astronautics, No. 29 Yudao St., Nanjing 210016, PR China

ARTICLE INFO

Article history:
Received 10 February 2017
Revised 23 April 2017
Accepted 3 May 2017
Available online xxxx

Keywords:
Ceramic-matrix composites (CMCs)
Matrix cracking
Interface debonding
Fiber failure

ABSTRACT

In this paper, the first matrix cracking stress (FMCS) of fiber-reinforced ceramic-matrix composites (CMCs) has been investigated using the energy balance approach considering fiber fracture. The shear-lag model combined with fiber failure model and interface debonding criteria has been adopted to analyze the stress distributions in CMCs. The relationships between the FMCS, interface debonding and slipping, and fiber fracture have been established. The effects of fiber volume fraction, interface shear stress, interface debonded energy, fiber Weibull modulus, and fiber strength on the FMCS, interface debonded length and fiber broken fraction have been analyzed. The experimental FMCS of three different CMCs, i.e., SiC/borosilicate, SiC/LAS, and C/borosilicate, with different fiber volume fraction have been predicted. It was found that the fiber/matrix interface possesses strong bonding in SiC/borosilicate and SiC/LAS composites, and weak bonding in C/borosilicate composite.

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, by incorporating fibers in ceramic matrices, however, not only exploit their attractive high-temperature strength but also reduce the propensity for catastrophic failure. These materials have already been implemented on some aero engines' components [1]. When the composite material is subjected to a stress along the fiber direction, a critical stress at which the composites exhibit first evidence of matrix cracking is defined as first matrix cracking stress (FMCS) [2]. The FMCS is considered as the maximum allowable design stress for fiber-reinforced CMCs for components subjected to oxidizing environment.

Many researchers performed experimental and theoretical investigations on the FMCS of fiber-reinforced CMCs. The theoretical models can be divided into two types, i.e., (1) the steady-state cracking models based on energy balance analysis, including the model by Aveston, Cooper and Kelly (ACK) [3], Budiansky, Hutchinson and Evans (BHE) [4]; and (2) the non-state cracking models based on stress intensity analysis, including the model by Marshall, Cox and Evans (MCE) [5], and McCartney [6]. The analytical results show that the FMCS was closely related with interface friction stress. Cox [7] investigated the effect of orientation of the fibers on the stiffness and strength of fibrous composites considering the load transfer between fibers. Brighenti, Carpinteri and Scorza [8] investigated the fiber/matrix interface debonding through the fracture mechanics approach. The stress-intensity factors (SIFs) are used to assess the detachment initiation and determined for different remote loadings and composite characteristics. Chaudhuri [9] presented the asymptotic solutions for three-dimensional singular stress field near a partially debonded cylindrical rigid fiber, subjected to far-field extension-bending (mode I), in-plane shear twisting (mode II) and torsional (mode III) loadings. Tvergaard and Hutchinson [10] investigated the effects of combined modes I, II and III at the crack tip along an interface between dissimilar materials for the conditions of small-scale yielding, with the fracture process at the interface represented by a cohesive zone model (CZM). Chiang [11] investigated the effect of interfacial debonding on the FMCS in unidirectional fiber-reinforced ceramics. It was found that the interface properties, i.e., the interface shear stress and the interface debonded energy, have profound influences on the FMCS. Rajan and Zok [12] investigate the mechanics of a fully bridged steady-state matrix cracking in unidirectional CMCs under shear loading. Curtin [13] developed a theory to describe the evolution of multiple matrix cracking in fiber-reinforced CMCs considering the statistical distribution of initial flaws in the matrix and the interface shear stress. The tensile stress-strain relations and unload/reload hysteresis behavior during the evolution of multiple matrix cracking in unidirectional

E-mail address: llb451@nuaa.edu.cn

http://dx.doi.org/10.1016/j.tafmec.2017.05.004
0167-8442/

Please cite this article in press as: L. Longbiao, Modeling first matrix cracking stress of fiber-reinforced ceramic-matrix composites considering fiber fracture, Theor. Appl. Fract. Mech. (2017), http://dx.doi.org/10.1016/j.tafmec.2017.05.004

Nomenclature

σ	applied stress
V_f	fiber volume fraction
V_m	matrix volume fraction
T	the stress carried by intact fibers
$\langle T_b \rangle$	the stress carried by broken fibers
$P(T)$	the fiber failure probability
m	fiber Weibull modulus
σ_c	fiber characteristic strength
σ_0	fiber strength
r_f	fiber radius
R	matrix radius
l_c	matrix crack spacing
l_d	interface debonded length
τ_i	interface shear stress in slip region
$\sigma_f(z)$	fiber axial stress distribution
$\sigma_m(z)$	matrix axial stress distribution
ε_f	fiber strain
ε_m	matrix strain
ε_c	composite strain
E_f	fiber elastic modulus
E_m	matrix elastic modulus
E_c	composite elastic modulus
ζ_d	interface debonded energy
$w_f(z)$	fiber axial displacement
$w_m(z)$	matrix axial displacement
$v(z)$	relative displacement between the fiber and the matrix
ζ_m	matrix fracture energy
G_m	matrix shear modulus

Superscript and subscript

f	fiber
m	matrix
c	composite

CMCs have been predicted [14]. Guillaumat and Lamon [15] investigated the matrix cracking process and fibers failure based on the fracture statistics of SiC/SiC microcomposite consisted of a single fiber coated with interfacial material and matrix and fabricated by Chemical Vapor Deposition (CVD). The Weibull approach is applied to brittle failure of the uncracked matrix fragments, and the matrix strength increases with the number of cracks resulting from the decrease in the volume of fragments. The influence of interfacial properties, i.e., the interface shear stress and the interface debonded length, on the matrix cracking has been analyzed. It was found that when the interface debonded length is large, i.e., $l_d \geq 1$ mm, the propagation of interface debonding did not affect the matrix cracking. Lissart and Lamon [16] investigated the evolution of matrix multicracking as a function of interfacial properties, and the mechanical properties of minicomposite fabricated by Chemical Vapor Infiltration (CVI) of bundles of 500 SiC fibers by a SiC matrix. It was found that the strong fiber/matrix interface favors matrix cracking, high stresses and a high stress at saturation, and the fibers strength degradation during minicomposite infiltration. The mechanical behavior of the composite would be affected by matrix cracking and interface debonding. Brighenti and Scorza [17] developed an energy-based homogenization approach to model the mechanical behavior of fiber-reinforced composites considering interface debonding and fibers breaking. Venkat, Mahajan and Mittal [18] investigated effect of interfacial debonding and matrix cracking on mechanical properties of multidirectional composites, i.e., three-directional orthogonal, three-directional eight-harness stain weave and four-directional in-plane composites, using a cohesive zone model (CZM) for interface debonding and an octahedral shear stress failure criterion for matrix cracking. With increasing of strain, the composite moduli significantly degraded due to the matrix cracking and interface debonding. Romanowicz [19] investigated the effect of interface debonding on composite damage under transverse tension using homogenization approach. It was found that the failure of the composite under transverse tension is mainly controlled by the interface strength and the interphase stiffness. Li et al. [20] developed a micromechanical model to predict the tensile stress-strain curve of unidirectional C/SiC composite using a statistical matrix multiple cracking model, a fracture mechanics interface debonding criterion and a statistical fiber fracture model. However, the models mentioned above do not consider fibers fracture on the FMCS in fiber-reinforced CMCs.

In this paper, the FMCS of fiber-reinforced CMCs has been investigated using the energy balance approach considering fibers fracture. The relationships between the FMCS, interface debonding and slipping, and fibers fracture have been established. The effects of fiber volume fraction, interface shear stress, interface debonded energy, fiber Weibull modulus, and fiber strength on the FMCS, interface debonded length and fibers broken fraction have been analyzed. The experimental FMCS of three different CMCs, i.e., SiC/borosilicate, SiC/LAS, and C/borosilicate, with different fiber volume fraction have been predicted.

2. Stress analysis

Marshall et al. [21] extended the Marshall, Cox and Evans (MCE) [5] model to analyze tensile fracture of unidirectional fiber-reinforced ceramics. In these analysis, the fiber strength is assumed to be single-valued and may be weak enough to be broken in the weak of a matrix crack. The possibility of fiber failure within the matrix due to the statistical nature of fiber strength can be accounted for by using the Weibull analysis. The two-parameter Weibull model is adopted to describe the fiber strength distribution, and the Global Load Sharing (GLS) assumption is used to determine the stress carried by the intact and fracture fibers. [22]

$$\frac{\sigma}{V_f} = T[1 - P(T)] + \langle T_b \rangle P(T) \tag{1}$$

where V_f denotes the fiber volume fraction; σ denotes the applied stress; T denotes the stress carried by intact fibers; $\langle T_b \rangle$ denotes the stress carried by broken fibers; and $P(T)$ denotes the fiber failure probability.

$$P(T) = 1 - \exp\left[-\left(\frac{T}{\sigma_c}\right)^{m+1}\right] \tag{2}$$

where m denotes the fiber Weibull modulus, which describes the variation in fiber strength; and σ_c denotes the fiber characteristic strength of a length δ_c of fiber. [22]

$$\sigma_c = \left(\frac{l_0 \sigma_0^m \tau_i}{r_f}\right)^{\frac{1}{m+1}}, \quad \delta_c = \left(\frac{\sigma_0 r_f l_0^{1/m}}{\tau_i}\right)^{\frac{m}{m+1}} \tag{3}$$

where σ_0 denotes the fiber strength of a length of l_0.

When a fiber breaks, the stress carried by the fiber drops to zero at the position of break. Similar to the case of matrix cracking, the