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Modeling the effect of oxidation on fatigue life of carbon fiber-reinforced ceramic-matrix composites at elevated temperature

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ABSTRACT

An analytical method has been developed to investigate the effect of oxidation on fatigue life of fiber-reinforced ceramic-matrix composites (CMCs) at elevated temperature under air. The Budiansky–Hutchinson–Evans shear-lag model was used to describe the micro-stress field of the damaged composite considering fibers failure. The statistical matrix multicracking model and fracture mechanics interface debonding criterion were used to determine the matrix crack spacing and interface debonded length. The interface shear stress and fiber strength degradation model and oxidation region propagation model have been adopted to analyze the fatigue and oxidation effects on fatigue life of the composite, which is controlled by interface frictional slip and diffusion of oxygen gas through matrix multicrackings. Under fatigue loading, the fibers failure probabilities were determined by combining the oxidation model, interface wear model and fiber statistical failure model based on the assumption that the fiber strength is subjected to two-parameter Weibull distribution and the loads carried by broken and intact fibers satisfy the global load sharing criterion. The fatigue life *S–N* curves of unidirectional, cross-ply and 2.5D C/SiC composites at 800 °C under air have been predicted.

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. The continuous fiber-reinforced ceramic-matrix composites (CMCs), 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]. The CMC flaps for exhaust nozzles of SNECMA M53 and M88 aero engines have already been used for more than one decade [2]. The CMC turbine vanes have been designed and tested in the aero engine environment under the implementation of Ultra Efficient Engine Technology (UEET) program [3]. A CMC turbine blade has already been tested for 4 h by General Electric in a modified GE F414 engine, which represents the first application of CMC material in a rotating engine part. By incorporating the CMC turbine blades on a GE90-sized engine, the overall weight can be reduced by 455 kg, which represents approximately 6% of dry weight of the full sized GE90-115 [4]. The CMC combustion chamber floating wall tiles have been tested in the aero engine environment for 30 min, with the temperature range of 1047–1227 °C and the pressure of 2 MPa [5]. However, one of the barriers to their uses in certain long-term or reusable applications is that degradation of the interphase or carbon fibers in oxidizing environments can lead to strength reduction and component failure [6].

Many researchers performed experimental and theoretical investigations on the effects of oxidation damage on the mechanical behavior of fiber-reinforced CMCs. In the experimental research area, Zhu [7] investigated the effect of oxidation on the fatigue behavior of 2D SiC/SiC composite at elevated temperature. It was found that the fatigue life decreased 13% after oxidation at 600 °C for 100 h due to disappearance of carbon interphase. Mall and Engesser [8] investigated the damage evolution in 2D C/SiC composite under different fatigue loading frequencies at 550 °C under air. The oxidation of carbon fibers caused a reduction in fatigue life of C/SiC composite under lower loading frequency. However, the oxidation of carbon fibers was almost absent or negligible at higher frequency at elevated temperature. Ruggles-Wrenn et al. [9] investigated the tension–tension fatigue behavior of 2D SiC/SiC composite at 1200 °C in air and steam environment under different loading frequencies. The damage development and final failure are accelerated in the presence of steam. Fantozzi and Reynaud [10] investigated the static fatigue behavior of 2.5D C/[Si–B–C] composite at 1200 °C under air. The areas of stress–strain hysteresis loops after a static fatigue of 144 h have significantly decreased, attributed to time-dependent of PyC interface recession by oxidation. Zhang et al. [11] investigated the damage evolution

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in 3D SiC/SiC composite under fatigue-oxidation environment. The interior of the composite is oxidized by oxidizing atmosphere infiltrating the composite through multicracking of matrix.

In the theoretical research area, much work has been performed to analyze and model the oxidation of fibers, matrices and interfaces without loading by assuming steady-state diffusion of oxidation [12,13]. Halbig et al. [14] investigated the stressed oxidation of different fiber-reinforced CMCs, i.e., C/SiC, SiC/SiC and SiC/SiNC, et al., and developed a model to predict the oxidation pattern and kinetics of carbon fiber tows in a nonreactive matrix. Halbig and Cawley [15] investigated the distribution of local oxygen concentration from the edge to the interior of an open column in a matrix bounded by carbon fiber tows using differing finite difference models. Lara-Curzio [16] developed a model to estimate the time-to-failure of unidirectional CMCs under high stress level beyond matrix cracking stress. Pailler and Lamon [17] developed a fatigue-oxidation model to investigate the strain response of a SiC/SiC minicomposite under matrix multicracking and interface oxidation. Casas et al. [18] developed a creep-oxidation model for fiber-reinforced CMCs at elevated temperature, including the effects of interface and matrix oxidation, creep of fibers and degradation of fibers strength with time. Mei et al. [19] developed a model to analyze the strain evolution of C/SiC composite considering the effects of thermal, mechanical and chemical applied conditions. Under fatigue loading at elevated temperature under air, fibers gradually fracture due to degradation of interface shear stress and fibers strength [20–22]. It should be noted that the systematic theoretical research work has not been performed on the effect of oxidation on fatigue life of fiber-reinforced CMCs.

The objective of this paper is to develop a micromechanics fatigue life prediction model considering the effect of oxidation on fiber/matrix interface and fibers. The Budiansky–Hutchinson–Evans shear-lag model was used to describe the micro-stress field of the damaged composite considering fibers failure. The statistical matrix multicracking model and fracture mechanics interface debonding criterion were used to determine the matrix crack spacing and interface debonded length. Under fatigue loading, the fibers failure probabilities were determined by combining the oxidation model, interface wear model and fibers statistical failure model based on the assumption that the fiber strength is subjected to two-parameter Weibull distribution and the loads carried by broken and intact fibers satisfy the global load sharing criterion. The fatigue life *S*–*N* curves of unidirectional, cross-ply and 2.5D C/SiC composites at 800 °C under air have been predicted.

2. Stress analysis

To analyze stress distributions in the fiber and the matrix, a unit cell is extracted from the ceramic composite system, 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 the unit cell is $L/2$, which is just the half matrix crack space. The interface debonded length is L_d. At the matrix crack plane, fibers carry all the loads of σ/V_f, in which σ denotes the far-field applied stress and V_f denotes the fiber volume content. The shear-lag model adopted by Budiansky et al. [23] is used to perform the stress and strain calculations in the interface debonded region ($x\in[0, L_d]$) and interface bonded region ($x\in[L_d, L/2]$).

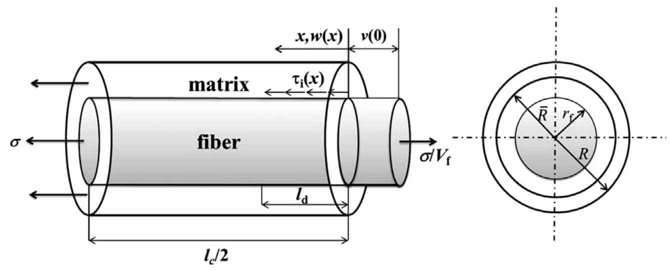

Fig. 1. The unit cell of the Budiansky–Hutchinson–Evans shear-lag model.

$$\sigma_f(x)=\begin{cases}\dfrac{\sigma}{V_f}-\dfrac{2\tau_i}{r_f}x, & x\in(0,L_d)\\ \sigma_{fo}+\left(\dfrac{V_m}{V_f}\sigma_{mo}-2\dfrac{L_d}{r_f}\tau_i\right)\exp\left(-\rho\dfrac{x-L_d}{r_f}\right), & x\in(L_d,L/2)\end{cases}\tag{1}$$

$$\sigma_m(x)=\begin{cases}2\tau_i\dfrac{V_f}{V_m}\dfrac{x}{r_f}, & x\in(0,L_d)\\ \sigma_{mo}-\left(\sigma_{mo}-2\tau_i\dfrac{V_f}{V_m}\dfrac{L_d}{r_f}\right)\exp\left[-\dfrac{\rho(x-L_d)}{r_f}\right], & \\ \quad x\in(L_d,L/2)\end{cases}\tag{2}$$

$$\tau_i(x)=\begin{cases}\tau_i, & x\in(0,L_d)\\ \dfrac{\rho}{2}\left(\dfrac{V_m}{V_f}\sigma_{mo}-2\tau_i\dfrac{L_d}{r_f}\right)\exp\left[-\dfrac{\rho(x-L_d)}{r_f}\right], & x\in(L_d,L/2)\end{cases}\tag{3}$$

where V_m denotes the matrix volume fraction; τ_i denotes the fiber/matrix interface shear stress; and ρ denotes the shear-lag model parameter [23].

$$\rho^2=\frac{4E_cG_m}{V_mE_mE_f\varphi}\tag{4}$$

where G_m denotes the matrix shear modulus, and

$$\varphi=-\frac{2\ \ln V_f+V_m(3-V_f)}{2V_m^2}\tag{5}$$

σ_{fo} and σ_{mo} denote the fiber and matrix axial stress in the interface bonded region, respectively.

$$\sigma_{fo}=\frac{E_f}{E_c}\sigma+E_f(\alpha_c-\alpha_f)\Delta T\tag{6}$$

$$\sigma_{mo}=\frac{E_m}{E_c}\sigma+E_m(\alpha_c-\alpha_m)\Delta T\tag{7}$$

where E_f, E_m and E_c denote the fiber, matrix and composite elastic modulus, respectively; α_f, α_m and α_c denote the fiber, matrix and composite thermal expansion coefficient, respectively; and ΔT denotes the temperature difference between fabricated temperature T_0 and room temperature T_1($\Delta T=T_1-T_0$). The axial elastic modulus of the composite is approximated by rule of mixture.

$$E_c=V_fE_f+V_mE_m\tag{8}$$

When matrix multicracking and fiber/matrix interface debonding occur, matrix cracks will serve as avenues for the ingress of the oxidizing environmental atmosphere into the composite. When the oxidizing environment ingresses into the composite, a sequence of events is triggered starting first with the oxidation of fiber coating, leading to local notch-like or neck-shrink phenomenon of fibers. As a result of this, both the axial stress distribution in the fibers and their probability of failure will change, because longer portions of the fibers are subject to peak stress *T*. During the process of oxidation, the unit cell can be divided into three regions, i.e., interface oxidation region ($x\in[0, L_t]$), interface debonded region ($x\in[L_t, L_d]$) and interface bonded region ($x\in[L_d, L/2]$). When fibers fracture, the fiber axial stress distributions in the interface oxidation region, interface debonded region and