Journal of the European Ceramic Society 36 (2016) 465–480

Contents lists available at www.sciencedirect.com

Journal of the European Ceramic Society

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

Modeling the effect of oxidation on hysteresis loops of carbon fiber-reinforced ceramic-matrix composites under static fatigue at elevated temperature

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 9 September 2015
Received in revised form 1 November 2015
Accepted 3 November 2015
Available online 12 November 2015

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

ABSTRACT

An analytical method has been developed to investigate the effect of oxidation on the hysteresis loops of fiber-reinforced ceramic-matrix composites (CMCs) under static fatigue at elevated temperature. The oxidation region propagating model has been adopted to analyze the oxidation effect on the hysteresis loops, which is controlled by interface frictional slip and diffusion of oxygen gas through matrix multicrackings. Based on the damage mechanism of fiber slipping relative to matrix, the hysteresis loops models corresponding to different interface slip cases considering interface oxidation have been established. The relationships between hysteresis loops, hysteresis dissipated energy, interface slip and oxidation time have been established. The effects of stress level, matrix crack spacing, fiber volume content and oxidation temperature on the hysteresis dissipated energy, interface debonding, oxidation and slip lengths versus oxidation time have been analyzed. The experimental hysteresis loops of C/[Si–B–C] composite under static fatigue in air at 1200 °C 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. 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. 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 [1–3]. However, one of the barriers to their uses in certain long-term or reusable applications is that degradation of the carbon fibers in oxidizing environments can lead to strength reduction and component failure [4].

Many researchers performed the experimental and theoretical investigations on the effects of oxidation damage on mechanical behavior of fiber-reinforced CMCs. In the experimental research area, Zhu [5] investigated the effect of oxidation on the fatigue behavior of 2D SiC/SiC composite at elevated temperatures. 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 [6] investigated the damage evolution in 2D C/SiC composite under different fatigue loading frequencies at an elevated temperature of 550 °C in air atmosphere. 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. Fantozzi and Reynaud [7] investigated the static fatigue behavior of C/[Si–B–C] composite at 1200 °C in air atmosphere. The areas of stress–strain hysteresis loops after a static fatigue of 144 h have significantly decreased, attributed to time dependent of fiber/matrix PyC interface recession by oxidation or by a beginning of carbon fibers recession by oxidation.

In the theoretical research area, much work has been conducted to analyze and model the oxidation of fibers, matrices and interfaces without loading by assuming steady-state diffusion of oxidation [8,9]. Halbig et al. [10] 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. Pailler and Lamon [11] developed a fatigue-oxidation model to investigate the strain response of a SiC/SiC minicomposite under matrix multicracking and interface oxidation. Casas et al. [12] developed a creep-oxidation model for fiber-reinforced CMCs at elevated

---

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

http://dx.doi.org/10.1016/j.jeurceramsoc.2015.11.005
0955-2219/

temperature, including the effects of interface and matrix oxidation, creep of fibers and degradation of fibers strength with time. The broken fibers fraction increases with time in an accelerated manner due to fibers strength degradation. Under static fatigue loading at elevated tempereture, the shape, location and area of the stress–strain hysteresis loops would evolve with increase of the oxidation time, which can be used to monitor the damage evolution inside of the damaged composite. However, there is no research work on the hysteresis loops models considering oxidation at elevated temperature.

The objective of this paper is to develop the stress–strain hysteresis loops models of fiber-reinforced CMCs considering interface oxidation at elevated temperature. The Budiansky–Hutchinson–Evans shear-lag model was used to describe the micro stress field of the damaged composite considering interface oxidation. The statistical matrix multicracking model and fracture mechanics interface debonding criterion were used to determine the matrix crack spacing and interface debonded length. The oxidation region propagating model has been adopted to analyze the oxidation effect on the stress–strain hysteresis loops of the composite under static fatigue at elevated temperature, which is controlled by interface frictional slip between the fiber and the matrix, and diffusion of oxygen gas through matrix cracks. Based on the damage mechanism of fiber slipping relative to matrix in the interface debonded region upon unloading and subsequent reloading, the hysteresis loops models corresponding to different interface slip cases considering interface oxidation have been established. The relationships between the stress–strain hysteresis loops, hysteresis dissipated energy, interface frictional slip and oxidation time have been established. The effects of stress level, matrix crack spacing, fiber volume content and oxidation temperature on the hysteresis dissipated energy, interface debonding, oxidation and frictional slip lengths versus oxidation time have been analyzed. The experimental stress–strain hysteresis loops of C/[Si–B–C] composite under static fatigue in air at 1200 °C have been predicted.

2. Stress analysis

The composite is subjected to a remote applied stress σ at elevated temperature. When the applied stress is higher than initial matrix cracking stress, matrix multicracking and fiber/matrix interface debonding occur. The unit cell contained a single fiber surrounded by a hollow cylinder of matrix is extracted from the ceramic composite system, as shown in Fig. 1. 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 half matrix crack spacing $l_c/2$. Budiansky et al. [13] assumed that the matrix axial load is concentrated at $\bar{R}$ and the region between r_f and $\bar{R}$ only carries the shear stress. At elevated temperature, matrix cracks will serve as avenues for the ingress of the environment atmosphere into the composite, as shown in Fig. 2. The oxygen reacts with carbon layer along fiber length at a certain rate of $d\xi/dt$, in which ξ is the length of carbon lost in each side of the crack [12].

$$\xi = \phi_1\left[1 - \exp\left(-\frac{\phi_2 t}{b}\right)\right] \tag{1}$$

where ϕ_1 and ϕ_2 are parameters dependent on temperature and described using the Arrhenius type laws [12],

$$\phi_1 = 7.021 \times 10^{-3} \times \exp\left(\frac{8231}{T}\right) \tag{2}$$

$$\phi_2 = 227.1 \times \exp\left(-\frac{17090}{T}\right) \tag{3}$$

in which ϕ_1 is in mm and ϕ_2 in s^{-1}; ϕ_1 represents the asymptotic behavior for long times, which decreases with temperature; the product $\phi_1\phi_2$ represents the initial oxidation rate, which is an increasing function of temperature. T is the absolute temperature; and b is a delay factor considering the deceleration of reduced oxygen activity.

In the interface oxidation region, i.e., $x \in [0,\xi]$, the stress transfer between the fiber and the matrix is controlled by a sliding stress $\tau_i(x) = \tau_f$, different from the interface shear stress in the interface debonded region, i.e., $x \in [\xi, l_d]$, $\tau_i(x) = \tau_i$. This new interface shear stress τ_f is lower than τ_i. The shear-lag model adopted by Budiansky et al. [13] is applied to perform the stress and strain calculations in the interface debonded region ($x \in [0, l_d]$) and interface bonded region ($x \in [l_d, l_c/2]$).

$$\sigma_f(x) = \begin{cases} \dfrac{\sigma}{V_f} - \dfrac{2\tau_f}{r_f}x, x \in \left(0, \xi\right) \\ \dfrac{\sigma}{V_f} - \dfrac{2\tau_f}{r_f}\xi - \dfrac{2\tau_i}{r_f}\left(x - \xi\right), x \in \left(\xi, l_d\right) \\ \sigma_{fo} + \left[\dfrac{V_m}{V_f}\sigma_{mo} - 2\dfrac{\tau_f}{r_f}\xi - 2\dfrac{\tau_i}{r_f}\left(l_d - \xi\right)\right]\exp\left(-\rho\dfrac{x - l_d}{r_f}\right), x \in \left(l_d, \dfrac{l_c}{2}\right) \end{cases} \tag{4}$$

$$\sigma_m(x) = \begin{cases} 2\dfrac{V_f}{V_m}\dfrac{\tau_f}{r_f}x, x \in \left(0, \xi\right) \\ 2\dfrac{V_f}{V_m}\dfrac{\tau_f}{r_f}\xi + 2\dfrac{V_f}{V_m}\dfrac{\tau_i}{r_f}\left(x - \xi\right), x \in \left(\xi, l_d\right) \\ \sigma_{mo} - \left[\sigma_{mo} - 2\dfrac{V_f}{V_m}\dfrac{\tau_f}{r_f}\xi - 2\dfrac{V_f}{V_m}\dfrac{\tau_i}{r_f}\left(l_d - \xi\right)\right]\exp\left(-\rho\dfrac{x - l_d}{r_f}\right), x \in \left(l_d, \dfrac{l_c}{2}\right) \end{cases} \tag{5}$$

$$\tau_i(x) = \begin{cases} \tau_f, x \in \left(0, \xi\right) \\ \tau_i, x \in \left(\xi, l_d\right) \\ \dfrac{\rho}{2}\left[\dfrac{V_m}{V_f}\sigma_{mo} - 2\dfrac{\tau_f}{r_f}\xi - \dfrac{2\tau_i}{r_f}\left(l_d - \xi\right)\right]\exp\left(-\rho\dfrac{x - l_d}{r_f}\right), x \in \left(l_d, \dfrac{l_c}{2}\right) \end{cases} \tag{6}$$

in which V_m denotes the matrix volume fraction; and ρ denotes the shear-lag model parameter [13].

$$\rho^2 = \frac{4E_cG_m}{V_mE_mE_f\phi} \tag{7}$$

where G_m denotes the matrix shear modulus, and

$$\phi = -\frac{2\ln V_f + V_m(3 - V_f)}{2V_m^2} \tag{8}$$

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

$$\sigma_{fo} = \frac{E_f}{E_c}\sigma + E_f(\alpha_c - \alpha_f)\Delta T \tag{9}$$

$$\sigma_{mo} = \frac{E_m}{E_c}\sigma + E_m(\alpha_c - \alpha_m)\Delta T \tag{10}$$

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; ΔT denotes the temperature difference between the fabricated temperature T_0 and room temperature T_1 ($\Delta T = T_1 - T_0$).

3. Matrix multicracking and interface debonding

3.1. Matrix multicracking

When loading of fiber-reinforced CMCs, cracks typically initiate within the composite matrix since the strain-to-failure of matrix is usually less than that of fiber. The matrix crack spacing decreases with the increases in stress above the initial matrix cracking stress