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Technical note

Modeling thermomechanical fatigue hysteresis loops of long-fiber-reinforced ceramic-matrix composites under out-of-phase cyclic loading condition

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In this paper, the thermomechanical fatigue hysteresis loops of long-fiber-reinforced ceramic-matrix composites (CMCs) subjected to out-of-phase (OP) cyclic loading have been investigated using the micromechanical approach. The fiber/matrix interface shear stress is determined as a function of the testing temperature and material properties, which affects the matrix multicracking and fiber/matrix interface debonding and sliding upon unloading and reloading. The relationships between the cyclic temperature and stress level, matrix multicracking, interface debonding and sliding, and the shape, location and the area of the thermomechanical fatigue hysteresis loops have been established. The effects of the fiber volume fraction, fatigue peak stress, matrix cracking space, fiber/matrix interface debonded energy and cyclic temperature range on the thermomechanical fatigue hysteresis loops subjected to out-of-phase cyclic loading have been analyzed. The differences of the thermomechanical fatigue hysteresis loops, interface debonding and sliding between the out-of-phase (OP) and in-phase (IP) thermomechanical cyclic loading have been analyzed. The thermomechanical fatigue hysteresis loops of cross-ply SiC/MAS composite under out-of-phase tension-tension cyclic loading have been predicted.

1. Introduction

Ceramic-matrix composites (CMCs) possess high specific strength and specific modulus at elevated temperature, and are being designed and developed for hot section components in commercial aero engine [1]. As new materials, the CMCs need to meet the airworthiness certification requirements, and it is necessary to analyze the degradation, damage and failure mechanisms subjected to cyclic loading at different temperatures and environments. Real life applications, such as turbine blades in a turbofan engine, dictate the need to determine the mechanical behavior of this material in an environment involving both cycling loads and cycling temperature which is commonly known as thermomechanical fatigue (TMF) [2–4].

Many researchers performed the experimental and theoretical investigations on the thermomechanical fatigue (TMF) behavior of long-fiber-reinforced CMCs. Butkus et al. [5] investigated the thermomechanical fatigue behavior of unidirectional SiC/CAS composite at elevated temperature between 550 °C and 1100 °C. It was found that the accumulated strains in the TMF tests were greater than those in the isothermal fatigue tests under identical loading conditions. Allen and Mall [6] investigated the thermomechanical fatigue behavior of cross-ply SiC/MAS composite at the temperature range of 566 °C and 1093 °C with the loading frequency of 0.00556 Hz and a stress ratio of 0.1. It was found that the damage caused by out-of-phase (OP) thermomechanical fatigue is much higher than that by the in-phase (IP) thermomechanical fatigue. Xie et al. [7] investigated the thermomechanical fatigue testing of long-fiber-reinforced CMC plates with a hole at temperature between room temperature and 1200 °C. It was found that the modulus degradation and fatigue life reduction depended upon the thermal and loading cycling. Mei and Cheng [8] investigated the thermal cycling response of 2D C/SiC composite subjected to the load constraint and displacement constraint in an oxidizing environment. It was found that the load control could develop thermal microcrackings and assist in oxidizing the internal fibers, however, the displacement control reduced the crack propagations and fibers oxidation due to the increasing of the compressive stress. Kim, Mall and Zawada [9] investigated the thermomechanical fatigue behavior of 2D SiC/SiC composite at the surface temperature of approximately 1235 °C with the loading frequency of

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1.0 Hz and stress ratio of 0.05. It was found that in the turbine airfoil applications, thermal stress and intermediate temperature embrittlement could be just as much damage factors in reducing the fatigue life of the CMCs as the exposure to the harsh combustion environment and mechanical loading. Cluzel et al. [10] investigated the thermomechanical behavior and lifetime modeling of self-healing CMCs by coupling of mechanical and physicochemical mechanisms. Reynaud et al. [11] investigated the effects of temperature and oxidation on the mechanical hysteresis behavior in long-fiber-reinforced CMCs. It was found that the testing temperature affects the fiber/matrix interface shear stress due to thermal expansion coefficient mismatch between the fiber and the matrix. Li [12,13] investigated the cyclic fatigue hysteresis loops under multiple loading stress levels, considering loading sequence and interface wear, and analyzed the damage evolution in cross-ply CMCs under cyclic loading and stress-rupture at elevated temperature in oxidizing atmosphere using the hysteresis loops-based damage parameter. The relationships between the fatigue hysteresis loops, fatigue hysteresis modulus, fatigue hysteresis loops area and fatigue peak strain and internal damages inside of CMCs, i.e., matrix multicracking, fiber/matrix interface debonding and interface wear, have been established. It was found that the fatigue hysteresis loops can be used as an effective tool to monitor the damage evolution in CMCs [14]. However, in the researches mentioned above, the fatigue hysteresis loops models of long-fiber-reinforced CMCs subjected to thermomechanical fatigue loading have not been developed.

In this paper, the fatigue hysteresis loops of long-fiber-reinforced CMCs subjected to out-of-phase (OP) thermomechanical fatigue loading have been investigated. The effects of fiber volume fraction, peak stress, matrix cracking space, fiber/matrix interface debonded energy and cyclic temperature range on the fatigue hysteresis loops under out-of-phase thermomechanical fatigue loading have been analyzed. The differences of fatigue hysteresis loops, interface debonding and sliding lengths between out-of-phase (OP) and in-phase (IP) thermomechanical fatigue loading have been analyzed. The thermomechanical fatigue hysteresis loops of cross-ply SiC/MAS composite under out-of-phase cyclic loading have been predicted.

2. Theoretical analysis

The testing temperature affects the mechanical behavior of long-fiber-reinforced CMCs, i.e., matrix microcracking, fiber/matrix interface debonding and thermal residual stress. The two cases would be if the load and temperature were at the same frequency and either in-phase (IP) TMF, where the load and temperature peak together, with the phase angle of $\theta = 0$; and out-of-phase (OP) TMF, where the load peaks while the temperature is at a minimum value, and the temperature peaks while the load is at a minimum value, with the phase angle of $\theta = \pi$, as shown in Fig. 1. If the radial thermal expansion coefficient of the matrix is higher than that of the fibers, at a testing temperature T lower than the processing temperature T_0, i.e., $T < T_0$, the radial thermal residual stresses are compressive stresses. The temperature-dependent fiber/matrix interface shear stress ($\tau_i(T)$) can be determined using Eq. (1). [11]

$$\tau_i(T) = \tau_0 + \mu \frac{|\alpha_{rf} - \alpha_{rm}|(T_0 - T)}{A} \tag{1}$$

where τ_0 denotes the steady-state fiber/matrix interface shear stress; μ denotes the fiber/matrix interface frictional coefficient; α_{rf} and α_{rm} denote the fiber and matrix radial thermal expansion coefficient, respectively; and A is a constant depending on the elastic properties of the matrix and fibers [11].

2.1. Stress analysis

Upon fist loading to the fatigue peak stress of σ_{max}, it is assumed that matrix cracking and fiber/matrix interface debonding occur. To analyze the stress distributions in the fiber and the matrix, a unit cell is extracted from the long-fiber-reinforced ceramic matrix composites, as shown in Fig. 2. 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 $l_c/2$, which is just the half of the matrix crack space. The fiber/matrix interface debonded length is l_d. At the matrix cracking plane, fibers carry all the applied stress (σ/V_f), where σ denotes the far-field applied stress and V_f denotes the fiber volume fraction. The shear-lag model adopted by Budiansky-Hutchinson-Evans [15] is applied in the present paper to perform the stress and strain calculations in the interface debonded region ($x \in [0, l_d]$) and interface bonded region ($x \in [l_d, l_c/2]$).

$$\sigma_f(x) = \begin{cases} \frac{\sigma}{V_f} - \frac{2\tau_i(T)}{r_f}x, x \in (0, l_d) \\ \sigma_{fo} + \left(\frac{V_m}{V_f}\sigma_{mo} - 2\frac{l_d}{r_f}\tau_i(T)\right)\exp\left(-\rho\frac{x - l_d}{r_f}\right), x \in (l_d, l_c/2) \end{cases} \tag{2}$$

$$\sigma_m(x) = \begin{cases} 2\tau_i(T)\frac{V_f}{V_m}\frac{x}{r_f}, x \in (0, l_d) \\ \sigma_{mo} - \left(\sigma_{mo} - 2\tau_i(T)\frac{V_f}{V_m}\frac{l_d}{r_f}\right)\exp\left[-\frac{\rho(x - l_d)}{r_f}\right], x \in (l_d, l_c/2) \end{cases} \tag{3}$$

where V_m denotes matrix volume fraction; and ρ denotes the BHE shear-lag parameter [15].

$$\rho^2 = \frac{4E_c G_m}{V_m E_m E_f \varphi} \tag{4}$$

where G_m denotes 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.

$$\sigma_{fo} = \frac{E_f}{E_c}\sigma + E_f(\alpha_{lc} - \alpha_{lf})\Delta T \tag{6}$$

$$\sigma_{mo} = \frac{E_m}{E_c}\sigma + E_m(\alpha_{lc} - \alpha_{lm})\Delta T \tag{7}$$

where E_f, E_m and E_c denote the fiber, matrix and composite elastic modulus, respectively; α_{lf}, α_{lm} and α_{lc} denote the fiber, matrix and composite axial thermal expansion coefficient, respectively; and ΔT denotes the temperature difference between the fabricated temperature T_0 and room temperature T_1 ($\Delta T = T_1 - T_0$).

2.2. Matrix multicracking

The cracking of the matrix depends upon the internal flaw inside of the matrix. The matrix cracking density increases with increasing of the applied stress above the initial matrix cracking stress of σ_{mc}, and may eventually approach to the saturation at the applied stress of σ_{sat}. There are four dominant damage models for predicting the matrix multiple cracking development inside of the long-fiber-reinforced CMCs, i.e., the maximum stress criterion, the energy balance approach, the critical matrix strain energy criterion and the statistical failure approach. The maximum stress criterion assumes that a new matrix crack forms at the matrix stress exceeding the ultimate strength in the matrix, which is assumed to be a single-valued and a known material property. The energy balance failure criterion involves calculation of the energy balance relationship