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Effects of temperature, oxidation and fiber preforms on interface shear stress degradation in fiber-reinforced ceramic-matrix composites

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ABSTRACT

In this paper, the interface shear stress in fiber-reinforced ceramic-matrix composites (CMCs) with different fiber preforms, i.e., unidirectional, cross-ply, 2Dwoven, and 3D braided at room and elevated temperatures has been estimated through hysteresis loops. An effective coefficient of the fiber volume fraction along the loading direction (ECFL) was introduced to describe the fiber architecture of preforms. Based on the damage mechanisms of fiber slipping relative to matrix in the interface debonded region, the hysteresis loops models considering different interface slip cases have been developed. The hysteresis dissipated energy for the strain energy lost per volume during corresponding cycle is formulated in terms of the fiber/matrix interface shear stress. By comparing experimental fatigue hysteresis dissipated energy with theoretical computational values, the interface shear stress of unidirectional, cross-ply, 2D woven, and 3D braided CMCs at room temperature, 600 °C, 800 °C, 1000 °C, 1200 °C, and 1300 °C in inert, air and steam conditions, have been estimated. The effects of test temperature, oxidation and fiber preforms on the degradation rate of interface shear stress have been investigated.

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, however, can be made as strong as metal, yet are much lighter and can withstand much higher temperatures exceeding the capability of current nickel alloys used in high-pressure turbines, which can lower the fuel burn and emissions, while increasing the efficiency of aero engine [1]. CMC durability has been validated through the ground testing or commercial flight testing in the demonstrator or customer gas turbine engines accumulating almost 30,000 h of operation. The CMC combustion chamber and high-pressure turbine components were designed and tested in the ground testing of GEnx aero engine [2]. The CMC rotating low-pressure turbine blades in a F414 turbofan demonstrator engine were successfully tested for 500 grueling cycles to validate the unprecedented temperature and durability capabilities by GE Aviation. The CMC tail nozzles were designed and fabricated by Snecma (SAFRAN) and completed the first commercial flight on CFM56–5B aero engine on 2015. CMCs will play a key role in the performance of CFM's LEAP turbofan engine, which would enter into service in 2016 for Airbus A320 and 2017 for Boeing 737 max.

Upon first loading to fatigue peak stress, matrix multicracking and fiber/matrix interface debonding occur [3]. The fiber/matrix interface shear stress transfers loads between fibers and the matrix, which is critical for the inelastic behavior of CMCs. Under cyclic fatigue loading, interface wear is the dominant fatigue mechanism [4,5]. The slip displacements between fibers and the matrix could reduce interface shear stress [6]. Evidences of interface wear that a reduction in the height of asperities occurs along the fiber coating for different thermal misfit, surface roughness and frictional sliding velocity have been presented by push-out and push-back tests on a ceramic composite system [7]. The interface wear process can be facilitated by temperature rising that occurs along the fiber/matrix interface, as frictional dissipation proceeds [8–10], i.e., the temperature rising exceeded 100 K under cyclic fatigue loading at 75 Hz between stress levels of 220 and 10 MPa in unidirectional SiC/CAS – II composite [8]. Under cyclic fatigue loading at elevated temperature in air, the interphase would react to form CO if the fiber coating is carbon or PyC, resulting in a large reduction in interface shear stress. Evidences of interface oxidation, i.e., a uniformly reduction in fiber diameter and a longer fiber pullout length occurs in a 2D C/SiC composite, have been presented by a non-stress oxidation experiment at 700 °C in air [11], and a tensile fatigue experiment at 550 °C in air [12]. Moevus et al. [13] investigated the static fatigue behavior of 2.5D C/[Si – B – C] composite at 1200 °C in air. The hysteresis loops area after a static fatigue of 144 h under a steady stress of 170 MPa, significantly decreased, attributed to a decrease of interface shear

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stress caused by PyC interface recession by oxidation. There are currently several approaches used to determine fiber/matrix interface shear stress, i.e. fiber pullout [14], fiber push-in [15] and push-out [16], and so on. However, these approaches can only get individual fiber's interfacial properties at room temperature, and only provide information regarding the interface shear stress which would exist under monotonic loading conditions.

Under cyclic fatigue loading, the hysteresis loops appear as the fiber slips relative to matrix in the interface debonded region [17]. The shape, location and area of hysteresis loops can be used to reveal the internal damage evolution in CMCs [18]. Cho et al. [19] developed an approach to estimate interface shear stress from frictional heating measurement. By analyzing the frictional heating data, Holmes and Cho [8] found that the interfacial shear stress of unidirectional SiC/CAS – II composite undergoes an initially rapid decrease at the initial stage of cyclic fatigue loading, i.e., from an initial value of over 20 MPa, to approximately 5 MPa after 25,000 cycles. Evans et al. [5] developed an approach to evaluate interface shear stress by analyzing parabolic regions of hysteresis loops based on the Vagaggini's hysteresis loops models [20]. The initial interface shear stress of unidirectional SiC/CAS composite was approximately 20 MPa, and degraded to about 5 MPa at the 30th cycle. Li et al. [21,22] developed an approach to estimate the interface shear stress of unidirectional CMCs. By comparing experimental hysteresis dissipated energy with theoretical values, the interface shear stress of unidirectional C/SiC composite has been estimated. The objective of this paper is to investigate the evolution of fiber/matrix interface shear stress of CMCs based on fatigue hysteresis loops, to reveal the internal fatigue damage evolution.

In this paper, the interface shear stress of fiber-reinforced CMCs with different fiber preforms, i.e., unidirectional, cross-ply, 2D woven, and 3D braided at room and elevated temperatures has been estimated through hysteresis loops. An effective coefficient of the fiber volume fraction along the loading direction (ECFL) was introduced to describe the fiber architecture of preforms. Based on the damage mechanisms of fiber slipping relative to matrix in the interface debonded region, the hysteresis loops models considering different interface slip cases have been developed. The hysteresis dissipated energy for the strain energy lost per volume during corresponding cycle is formulated in terms of interface shear stress. By comparing experimental fatigue hysteresis dissipated energy with theoretical computational values, the interface shear stress of unidirectional, cross-ply, 2D woven, and 3D braided CMCs at room temperature, 600 °C, 800 °C, 1000 °C, 1200 °C, and 1300 °C in inert, air and steam conditions, have been estimated. The effects of test temperature, oxidation and fiber preforms on the degradation rate of interface shear stress have been investigated.

2. Hysteresis theories

If matrix multicracking and fiber/matrix interface debonding are present upon first loading, the stress-strain hysteresis loops develop as a result of energy dissipation through frictional slip between fibers and the matrix upon unloading and subsequent reloading. Upon unloading, the counter slip occurs in the interface debonded region. The interface debonded region can be divided into two regions, i.e., the interface counter-slip region and interface slip region, as shown in Fig. 1(a). The interface counter-slip length is denoted to be y. Upon reloading, the new slip occurs in the interface debonded region. The interface debonded region can be divided into three regions, i.e., the interface new-slip region, interface counter-slip region and interface slip region, as shown in Fig. 1(b). The interface new-slip region is denoted to be z.

Based on the damage mechanisms of fiber slipping relative to matrix upon unloading/reloading, the stress – strain hysteresis loops can be classified into four different cases, i.e., (1) the interface partially debonds, and the fiber completely slips relative to matrix; (2) the interface partially debonds, and the fiber partially slips relative to matrix; (3) the interface completely debonds, and the fiber partially slips relative to matrix; and (4) the interface completely debonds, and the fiber completely slips relative to matrix in the interface debonded region.

When interface partially debonds, the unloading and reloading stress – strain relationships are determined by Eqs. (1) and (2), respectively.

$$\varepsilon_{cu} = \frac{\sigma}{V_f E_f} + 4\frac{\tau_i}{E_f}\frac{y^2}{r_f l_c} - 2\frac{\tau_i}{E_f}\frac{(2y - l_d)(2y + l_d - l_c)}{r_f l_c} - (\alpha_c - \alpha_f)\Delta T \tag{1}$$

$$\varepsilon_{cr} = \frac{\sigma}{V_f E_f} - 4\frac{\tau_i}{E_f}\frac{z^2}{r_f l_c} + 4\frac{\tau_i}{E_f}\frac{(y - 2z)^2}{r_f l_c} + 2\frac{\tau_i}{E_f}\frac{(l_d - 2y + 2z)(l_d + 2y - 2z - l_c)}{r_f l_c} - (\alpha_c - \alpha_f)\Delta T \tag{2}$$

where V_f denotes the fiber volume fraction; E_f denotes the fiber elastic modulus; r_f denotes the fiber radius; α_f and α_c denote the fiber and composite thermal expansion coefficient, respectively; and ΔT denotes the temperature difference between the fabricated temperature T_0 and test temperature T_1 ($\Delta T = T_1 - T_0$); τ_i denots the interface shear stress; l_d denots the interface debonded length; l_c denotes the matrix crack spacing; and y and z denotes the unloading interface counter-slip length and reloading interface new-slip length, respectively.

$$y = \frac{1}{2}\left\{l_d - \left[\frac{r_f}{2}\left(\frac{V_m E_m \sigma}{V_f E_c \tau_i} - \frac{1}{\rho}\right) - \sqrt{\left(\frac{r_f}{2\rho}\right)^2 + \frac{r_f V_m E_m E_f}{E_c \tau_i^2}\zeta_d}\right]\right\} \tag{3}$$

$$z = y - \frac{1}{2}\left\{l_d - \left[\frac{r_f}{2}\left(\frac{V_m E_m \sigma}{V_f E_c \tau_i} - \frac{1}{\rho}\right) - \sqrt{\left(\frac{r_f}{2\rho}\right)^2 + \frac{r_f V_m E_m E_f}{E_c \tau_i^2}\zeta_d}\right]\right\} \tag{4}$$

where V_m denotes the matrix volume fraction; E_m and E_c denote the matrix and composite elastic modulus, respectively; ρ denots the shear-lag model parameter; and ζ_d denotes the interface debonded energy.

When interface completely debonds, the unloading and reloading stress – strain relationships are determined by Eqs. (5) and (6), respectively.

$$\varepsilon_{cu} = \frac{\sigma}{V_f E_f} + 4\frac{\tau_i}{E_f}\frac{y^2}{r_f l_c} - 2\frac{\tau_i}{E_f}\frac{(2y - l_c/2)^2}{r_f l_c} - (\alpha_c - \alpha_f)\Delta T \tag{5}$$

$$\varepsilon_{cr} = \frac{\sigma}{V_f E_f} - 4\frac{\tau_i}{E_f}\frac{z^2}{r_f l_c} + 4\frac{\tau_i}{E_f}\frac{(y - 2z)^2}{r_f l_c} - 2\frac{\tau_i}{E_f}\frac{(l_c/2 - 2y + 2z)^2}{r_f l_c} - (\alpha_c - \alpha_f)\Delta T \tag{6}$$

where

$$y = \frac{r_f}{4\tau_i}\frac{V_m E_m}{V_f E_c}(\sigma_{max} - \sigma) \tag{7}$$

$$z = y - \frac{r_f}{4\tau_i}\frac{V_m E_m}{V_f E_c}(\sigma_{max} - \sigma) \tag{8}$$