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Micromechanical analysis of fiber and titanium matrix interface by shear lag method

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ABSTRACT

The model based on fracture mechanics is developed to evaluate the fracture toughness Γ of the fiber/matrix interface in titanium alloys reinforced by SiC monofilaments. Theoretical model for single fiber push-out testing is obtained by shear-lag method. The influences of several key factors (such as the applied stress needed for crack advance, crack length, and interfacial frictional shear stress) are discussed. Using the model, the interfacial toughness of typical composites including Sigma1240/Ti-6-4, SCS-6/Ti-6-4, SCS-6/Timetal 834, SCS-6/Timetal 21s, SCS-6/Ti-24-11 and SCS-6/Ti-15-3 are successfully predicted compared with previous results of these composites. It is verified that the model can reliably predict the interfacial toughness of the titanium matrix composites as well as other metal matrix composites, due to interfacial debonding usually occurs at the bottom face of the samples in such composites.

1. Introduction

SiC fiber reinforced titanium matrix composites (TMCs) have been considered as high temperature structural materials in many applications, such as aerospace and motor-mobile industries due to their low density, high performance, high specific strength and stiffness at room and elevated temperatures [1,2]. It is well known that the performance of such composites have been critically influenced by the properties of fiber/matrix interface [3–5]. Therefore, determining the interfacial behavior is vital for this class of composites. Push-out test, which at first was widely used in ceramic matrix composites (CMCs) [6–8], has been introduced as an important experimental technique owing to the simplicity of preparing a specimen and conducting an experiment. For TMCs, there exists high bonding strength at the interface owing to the strong chemical activation of titanium. Thus it is necessary to use thin slices of composites to avoid the fracture of indenter or the crush of fiber [9]. Moreover, the higher thermal residual stresses are induced at fiber/matrix interface owing to the mismatch of thermal expansion coefficients between fiber and matrix. These two factors (thinner thickness of specimen and higher residual stresses) prompt that interface failure initiates from the bottom face of the specimen [9–16]. It is different from CMCs, in which interface failure initiates at the loaded (top) face [17,18]. Therefore, it is necessary to build new theoretical models for TMCs in order to evaluate their interfacial properties.

There are two approaches on the theoretical analysis of the interface debonding in the push-out test. One is based upon the stress (including quadratic [6,12] and maximum [13,19,20] shear stress) criterion, which is that debonding occurs when the interfacial stress exceeds the interfacial strength. The other is based on fracture mechanics in which the debonded region is considered as an interfacial crack and its propagation is dependent on the energy balance in terms of interfacial fracture toughness (critical strain energy release rate) [21–24]. In the latter, most detailed fracture mechanics, such as crack propagation during the push-out testing and energies of the interfacial debonding have been addressed [25]. Therefore, the fracture mechanics approach is more attractive in the analysis of push-out test. Extensive works have been carried out to analyze the crack growth behavior and interfacial debonded energies in push-out testing through the fracture mechanics approach. For pull-out test, Hutchinson et al. [26] defined interfacial fracture toughness to be the change in strain energy of the system and the work done by the loading system due to crack propagating a unit area, with consideration of Poisson effect and frictional sliding stress. The model was based on shear lag theory and neglected the work done against friction. For push-out test,

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Dollar [27,28] presented interfacial toughness by cohesive zone model method. Kerans [29] and Zhou [30,31] defined the interfacial fracture toughness to be the change in strain energy of the system due to crack propagation by shear-lag method. Subsequently, Majumdar [32] considered the work done by applied load to the system due to the crack propagation in addition to the strain energy of the system. On this basis, the work against frictional stress is considered by Kalton et al. [33]. The interfacial toughness above was given under the situation of the top face debonding. However, for almost all thin slice specimens of TMCs, interface failure is likely to initiate at the bottom face during push-out testing. The expressions of the interfacial fracture toughness for the situation of bottom face failure are different from those for the top face failure owing to the different stress distribution in the debonded and bonded regions. In the case of the bottom face debonding, the interfacial toughness was presented by compliance function by Majumdar [32]. Yuan [34] also deduced an expression of the interfacial fracture toughness, including the strain energy U_P produced by the applied load, the strain energy U_R generated by thermal residual stress, and the strain energy U_F consumed by interfacial friction stress. This formula also considered such factors as Poisson's ratio and the effect of the free end surface.

In this paper, an analytical model is presented for evaluating the interfacial fracture energy from loading curves obtained during push-out testing. The model is based on shear-lag analysis, taking into account the effects of specimen thickness, fiber volume fraction, Poisson's ratio, interfacial friction coefficient, thermal residual stresses and interfacial frictional sliding stress, and so on. The interface debonding is characterized by a shear fracture (mode 2). Two characterizations of sliding friction are considered: Case I, a constant frictional sliding stress τ_0, and Case II, a combination of a constant frictional sliding stress τ_0 and the effect of Poisson contraction of the fiber. Both expressions of Γ are deduced based on Kalton's basic energy balance equation [33]. In addition, the effects of several key factors are discussed, such as the applied stress needed for crack advance, crack length, and interfacial frictional shear stress. The interfacial toughness of the composites Sigma1240/Ti-6-4, SCS-6/Ti-6-4, SCS-6/Timetal 834, SCS-6/Timetal 21s, SCS-6/Ti-24-11 and SCS-6/Ti-15-3 is predicted by the two Γ expressions.

2. Model of micromechanical analysis

2.1. Basic governing equations

Two kinds of SiC fiber, C-coated and uncoated, are used for TMCs. The debonding occurs between C coating and reaction layer for C-coated SiC fiber in push-out testing, while the debonding occurs between SiC and reaction layer for uncoated SiC fiber [35], as shown in Fig. 1. This paper employs a simplified two-phase model neglecting the C coating and reaction layer, as C coating (if with C coating) can be considered to be together with the fiber, and reaction layer together with the matrix. In the analytical model, it is assumed that the fiber/matrix interface is perfectly bonding before loading, and there is no spontaneous debonding caused by thermal residual stresses.

The geometry of the cylinder model is shown in Fig. 2, which is widely used to evaluate interfacial propertied [25,29–31,36,37]. In the model, a fiber with radius r_f is embedded at the center of a coaxial cylindrical shell of the matrix with a radius r_m and a total length L. A set of cylindrical coordinates (r, θ, z) is employed, where the z-axis corresponds to the axis of the fiber and r is the perpendicular distance to the z-axis. It is assumed that the model of deformation is symmetric about the fiber axis (i.e. axisymmetric) and thus the stress components $(\sigma_{rr}, \sigma_{\theta\theta}, \sigma_{zz}, \tau_{rz})$ and the displacement components (u_r, u_z) are independent of the tangential coordinate θ, and the remaining stress and displacement components are all zero. At the same time, the compliance of the fiber and matrix is neglected. At the end of the specimen, $z = 0$, the fiber is loaded by a force P, and at the other end, $z = L$, the matrix is fixed. Therefore, for perfectly elastic and isotropic fiber and matrix, the general relationships between strains and stresses are

$$\varepsilon_{zf}(r,z) = \frac{1}{E_f}\left\{\sigma_{zzf}(r,z) - \upsilon_f\left[\sigma_{rrf}(r,z) + \sigma_{\theta\theta f}(r,z)\right]\right\} \tag{1}$$

for the fiber (i.e. $0 \le r \le r_f$), and

$$\varepsilon_{zm}(r,z) = \frac{1}{E_m}\{\sigma_{zzm}(r,z) - \upsilon_m[\sigma_{rrm}(r,z) + \sigma_{\theta\theta m}(r,z)]\} \tag{2}$$

$$\varepsilon_{rzm}(r,z) = \frac{1}{2}\frac{\partial u_{zm}(r,z)}{\partial r} = \frac{1+\upsilon_m}{E_m}\tau_{rzm}(r,z) \tag{3}$$

for the matrix (i.e. $r_f \le r \le r_m$, $\tau_{rzm}(r_f,z) = \tau(z)$, $\tau_{rzm}(r_m,z) = 0$, $u_{zm}(r_f,z) = u_{zf}(r_f,z)$), where E denotes elastic modulus, υ denotes Poisson's ratio, the subscripts f and m denote fiber and matrix, respectively, and $\tau(z)$ represents the interfacial frictional shear stress $\tau_d(z)$ in the debonded region and the interfacial shear stress $\tau_b(z)$ in the bonded region. For the matrix shear strain in equation (3), compared to the axial displacement gradient along the r-direction, the radial displacement gradient along the z-direction is neglected. In the r-direction, the axial stresses in the fiber and the matrix are assumed as the average stresses to simplify analysis [38], i.e.

$$\sigma_{zzf}(z) = \frac{2}{r_f^2}\int_0^{r_f}\sigma_{zzf}(r,z)rdr \tag{4}$$

$$\sigma_{zzm}(z) = \frac{2V_f}{r_f^2}\int_{r_f}^{r_m}\sigma_{zzm}(r,z)rdr \tag{5}$$

where $V_f(= r_f^2/(r_m^2 - r_f^2))$ is the volume ratio of the fiber to the matrix. The internal stress is transferred from the fiber to the surrounding matrix through the interfacial shear stress. The mechanical equilibrium conditions between fiber, matrix and interface are

$$\sigma_P = \sigma_{zzf}(z) + \frac{1}{V_f}\sigma_{zzm}(z) \tag{6}$$

$$\frac{d\sigma_{zzf}(z)}{dz} = -\frac{2}{r_f}\tau(z) \tag{7}$$

$$\frac{d\sigma_{zzm}(z)}{dz} = \frac{2V_f}{r_f}\tau(z) \tag{8}$$

$$r\frac{\partial\sigma_{zzm}(z)}{\partial z} + \frac{\partial r\tau_{rzm}(r,z)}{\partial r} = 0 \tag{9}$$

2.2. The axial stresses in bonded and debonded region

An interfacial crack is assumed to propagate from the bottom face $z = L$ towards the top face $z = 0$, in the opposite direction of loading. As shown in Fig. 3, the specimen is divided into three different regions, i.e. a debonded region I ($L-l \le z \le L$), a check tip region II ($l_1 \le z \le L-l$) and a continuous region III ($0 \le z \le l_1$).