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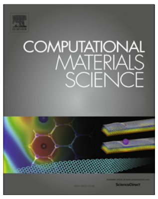

Simulation of interface damage in metal matrix composites under off-axis loading using cohesive zone model

M.M. Aghdam [*], S.M.A. Hosseini, S.R. Morsali

Thermoelasticity Center of Excellence, Department of Mechanical Engineering, Amirkabir University of Technology, Hafez Ave., Tehran, Iran

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ABSTRACT

A finite element, micromechanical model is developed to predict the inelastic behavior of SiC/Ti composites subjected to off-axis loading using a three-dimensional representative volume element (RVE). The model includes the effects of manufacturing process thermal residual stresses together with interface damage and fiber coating. The cohesive zone model is used to consider the imperfect interface between the fiber and matrix. Introducing a unique failure criterion for various off-axis angles is the main novelty of this study. Apart from interface damage, plastic deformation of the matrix is also considered as another source of nonlinearity. Appropriate boundary conditions are imposed on the RVE to allow simultaneous application of a combined normal axial and transverse and axial shear loading plus thermal residual stresses. Results of the presented finite element model are compared with experimental data for stress–strain response, initiation of nonlinearity, and ultimate strength in various off-axis angles which show good agreement. Moreover, parametric studies are conducted to examine the effects of thermal residual stress and fiber volume fraction (FVF) on the mechanical response of the material.

1. Introduction

Using titanium based Metal Matrix Composites (MMCs) for high-temperature applications has drawn the attention of many researchers. MMCs benefit from elevated temperature stability and high specific strength and Young's modulus [1]. However, the main drawback to these types of composites is that they tend to exhibit relatively low bonding strength at the fiber/matrix interface. The weak interface forms during the fabrication process in which a chemical reaction bonds two surfaces of the fiber and matrix at high temperatures. Moreover, due to the great difference in the manufacturing and service temperature of MMCs and also the difference between the coefficient of thermal expansion (CTE) of the titanium matrix and SiC fiber, thermal residual stresses are produced within the composite to a great extent which is not ignorable [2]. Furthermore, in more complicated loading conditions such as off-axis loading, the residual stresses and weak interface phenomena may have specific effects on the failure mechanism depending on the angle of loading axis. Therefore, any accurate modeling of the MMCs response should include these two effective phenomena.

Several models have been used to simulate the fiber/matrix interface in MMCs. To start with, perfectly bonded [3,4] and completely debonded [3,5–7] interfaces have been applied for various types of loadings which over and under-estimates the strength of composites. These two models cannot predict the behavior of the MMCs under transverse and axial shear loadings, so that interface models considering the damage of the interface are presented. Wisnom [8,9] introduced pairs of nodes on opposite sides of the interface which are coupled with stiff springs. The springs between node pairs are released when the combination of normal and shear stresses at the nodes reaches a predefined criterion. This model is proceeded by similar recent studies to model the damage of the interface under transverse [10], combined [11] and axial shear loadings [12] with the effect of thermal residual stresses and fiber coating. Another model for considering the damage of the interface is the cohesive zone model. The model provides independent constitutive relations for the interface. Needleman [13] presented a cohesive zone model in an analytical study to describe the process of debonding in which only normal separation was described. Later, Tvergaard [14] proposed another two dimensional cohesive zone model that describes debonding by tangential separation as well as normal separation. Lissenden [15,16] developed a three dimensional fiber matrix debonding model based on a modified Needleman cohesive zone model. Finally, it is worth mentioning that in addition to long fiber composites, decohesion at the

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[*] Corresponding author. Tel.: +98 (21) 6454 3429; fax: +98 (21) 6641 9736.
E-mail address: aghdam@aut.ac.ir (M.M. Aghdam).

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interface between matrix and short fibers is also considered in various recent studies, see for instance [17,18].

Off-axis loading in a unidirectional fiber reinforced composite occurs when loading direction does not coincide with the fibers direction. Transverse and shear loadings have received particular attention due to the vulnerability of MMCs to failure in relatively low tensile loads. However, off-axis loading which is the combination of the aforementioned loadings is the most practical and complicated case to model. Failure modes including interface debonding, matrix yielding, and fiber fracture are the most common failure mechanisms in off-axis loading.

Among recent off-axis efforts, there are several analytical studies of both polymer and metal matrix composites. The Simplified unit cell method (SUCM) has been presented to obtain the closed-form solution for overall off-axis behavior of polymer matrix composites [19]. Sun et al. have predicted the off-axis behavior of SiC/Ti MMC using an analytical model at room [20,21] and higher temperatures [21]. As one of the earliest works, the results showed acceptable agreement with experimental data. However, these analytical models have used many simplified assumptions including state of plane stress and constant strain in all directions. Moreover, the shape of the fibers has been assumed to be rectangular and the effects of the fiber coating have been ignored in these studies.

The Finite element method (FEM) can implement models with complex geometries without any simplifications in the shape of fibers or considering thermo-mechanical history which is a common assumption in the analytical approach. Nevertheless, off-axis loading has not received sufficient attention in the literature using FEM. Aghdam et al. [3] developed a finite element model to investigate mechanical behavior of SiC/Ti MMC under off-axis loading. A novel boundary condition was presented and imposed on the 3D model to consider thermal and mechanical loadings together. A debonded interface was defined according to Coulomb's law of friction. However, the model was not capable of investigating the transverse behavior of the composites due to ignoring the effects of interface damage and fiber coating.

In this study, a three dimensional micromechanical model is presented to investigate the off-axis behavior of the SiC/Ti composite using the finite element method. A suitable criterion is used to model the damage interface for all angles of loading by using the cohesive zone model. Moreover, the fiber coating which reduces stress concentration at the matrix surface adjacent to the interface is considered. Appropriate periodic boundary conditions are imposed so that the model can handle simultaneous application of combined thermal and off-axis mechanical loadings. The off-axis stress strain curves are compared with experimental data at room temperature. The presented model offers more accurate results compared with the earlier FE and analytical models.

2. Analysis

2.1. Material properties

The composite system is made of titanium alloy matrix, Ti–6Al–4V, reinforced by aligned unidirectional SCS-6 silicon carbide coated fibers. The fibers are assumed to be isotropic and homogenous with temperature independent properties (Table 1). The fibers are assumed to be linearly elastic up to a fracture point which is 4670 MPa [22]. The elastic–plastic properties of the titanium matrix are reported to be temperature dependent taken from [21].

Table 1
Thermo-mechanical properties of the fiber, matrix and coating [9,19].

	SCS-6 Fiber	Ti–6V–4Al Matrix	Coating (Carbon + SiC)
Young modulus, E (GPa)	400.0	$105.5 - 0.0331 \times T$	$E_{aa} = 163$ $E_{cc} = 150$
Poisson's ratio, ν	0.25	0.34	$\nu_{aa} = -0.01$ $\nu_{ac} = 0.72$
Coefficient of thermal expansion, α (°C^{-1})	5.04×10^{-6}	8.28×10^{-6}	$\alpha_{aa} = 4.1$ $\alpha_{cc} = 18.7$
Yield stress, σ_y (MPa)	–	$896 - 16(T - 20)^{0.53}$ $(T \geqslant 20\,°C)$	–
Shear modulus, G (GPa)	–	–	$G_{ca} = 62$

The von-Mises criterion is utilized to determine yield stress in the matrix. In order to determine the plastic deformation of the matrix, the relationship between effective stress, $\bar{\sigma}^M$ and effective plastic strain, $\bar{\varepsilon}^{PM}$ is established as [21]:

$$\bar{\varepsilon}^{PM} = \beta(\bar{\sigma}^M - \sigma_y^M)^n \quad \bar{\sigma}^M \geqslant \sigma_y^M \tag{1}$$

where hardening coefficients are $\beta = 0.273 \times 10^{-5}$ and $n = 2$.

SCS-6 fibers have relatively thick carbon coating. The functions of this thick coating at the outer surface of the fiber are: first, the coating is not totally consumed by the coating/matrix reaction when the fibers are embedded into the matrix at high temperature and second, the coating decreases the stress concentration caused by cracks that occur in the coating/matrix reaction zone. The volume fraction of carbon coating is assumed to be 10% of the whole SCS-6 fiber. Carbon coating assumes to have anisotropic properties reported by Li and Wisnom [9]. The 3.5 μm coating is considered as an independent phase and its properties are assumed transversely isotropic in the cylindrical coordinate system with the plane of symmetry in the θ–Z plane. In the fiber material coordinate system, hoop (θ) and axial (Z) directions are represented by 'a' while the radial (r) direction is denoted by 'c' [9].

Titanium based fiber reinforced composites are fabricated at a temperature range of 850–930 °C [23]. The fiber and matrix are assumed to be stress free at 900 °C and then cooled down to room temperature (20 °C) in order to generate the residual stresses.

2.2. Finite element model and boundary conditions

The idea of the off-axis tensile test is to apply uniaxial tension to a specimen of unidirectional composite where the fibers are aligned at angle θ to the loading direction (Fig. 1). Actually, specimen plates are cut in a way that fibers make an angle with tensile loading. In the material coordinate system the z axis coincides with the fiber direction.

By using transformation equations for Mohr's circle, stress components in material coordination are related to applied off-axis stress.

$$\sigma_z^* = \frac{\sigma_1^*}{2}(1 + \cos 2\theta), \quad \sigma_x^* = \frac{\sigma_1^*}{2}(1 - \cos 2\theta), \quad \tau_{xz}^* = -\frac{\sigma_1^*}{2}\sin 2\theta \tag{2}$$

where σ_1^* is the average tensile stress applied to a sufficiently large volume of the composite and $\sigma_z^*, \sigma_x^*, \tau_{xz}^*$ are stresses in material coordinates.

A representative volume element (RVE) containing a quarter of the fiber and its coating surrounded by the matrix is selected for the analysis. As depicted in Fig. 2a. a three dimensional cubic RVE is selected with one layer of elements in fiber direction since