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Micromechanical modeling of interface damage of metal matrix composites subjected to off-axis loading

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ABSTRACT

A three dimensional micromechanics based analytical model is presented to investigate the effects of initiation and propagation of interface damage on the elastoplastic behavior of unidirectional SiC/Ti metal matrix composites (MMCs) subjected to off-axis loading. Manufacturing process thermal residual stress (RS) is also included in the model. The selected representative volume element (RVE) consists of an $r \times c$ unit cells in which a quarter of the fiber is surrounded by matrix sub-cells. The constant compliance interface (CCI) model is modified to model interfacial de-bonding and the successive approximation method together with Von-Mises yield criterion is used to obtain elastic–plastic behavior. Dominance mode of damage including fiber fracture, interfacial de-bonding and matrix yielding and ultimate tensile strength of the SiC/Ti MMC are predicted for various loading directions. The effects of thermal residual stress and fiber volume fraction (FVF) on the stress–strain response of the SiC/Ti MMC are studied. Results revealed that for more realistic predictions both interface damage and thermal residual stress effects should be considered in the analysis. The contribution of interfacial de-bonding and thermal residual stress in the overall behavior of the material is also investigated. Comparison between results of the presented model shows very good agreement with finite element micromechanical analysis and experiment for various off-axis angles.

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1. Introduction

There has been an increasing interest in metal matrix composites (MMCs), in particular SiC/Ti MMCs, due to their high specific modulus and strength and temperature resistance. Reliable design of MMCs requires detailed modeling and understanding of the behavior of MMCs under various combined loading conditions. It is well established in the literature [1] that MMCs suffer from existence of a high state of thermal residual stresses during manufacturing process and weak interface between fiber and matrix. Therefore, in order to be more accurate, any presented model for MMCs should include existence of both weak fiber/matrix interface and thermal residual stresses. Furthermore, the strength of composites is usually limited by failure of the fibers, failure of the interface or yield of the matrix, depending on the precise loading condition. Among various loadings, the off-axis loading is the most applicable and complicated loading conditions as combination of various normal and shear loading exist depending on the fiber direction.

Many attempts have been made to develop micromechanical models, including finite element (FE) [2–5] and analytical approaches, to predict behavior of composite materials subjected to various loading conditions. FE and analytical micromechanical models [5] were also used to predict both initial yield and collapse envelopes for MMCs under different cases of biaxial and shear loading with and without thermal residual stress effects. The analytical model in [5] which was mainly in the category of unit cell models was later [6] called simplified unit cell (SUC) model. Only fully bonded interface was considered in the SUC model [6]. Micromechanical modeling of off-axis loading received relatively less attention in the literature [7–9] due to complexity of loading and boundary conditions. Analytical [9] and finite element micromechanical models were developed to predict behavior of MMCs subjected to off-axis loading with [7] and without [8] effects of thermal residual stress. The model presented in [7] also includes effects of fully de-bonded interface with a level of friction between fiber and matrix.

On the other hand, there are different analytical [10–13] and numerical [14–24] studies in which the effects of thermal residual and weak interface on the behavior of MMCs in various loading conditions are investigated. Indeed, experimental techniques have also been employed to measure thermal residual stresses and stress–strain response of the MMC materials [18,19]. Aboudi [10] incorporated the flexible interface (FI) model of Jones and Whittier [25] into the method of cells. Later, the FI model concept was em-

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ployed [26] with an added condition that requires the interfacial compliance to be zero when the interface is in compression. This modification was incorporated [27] into a rate-based formulation of generalized method of cells (GMC). This model has been referred to as the constant compliant interface (CCI) model. Inclusion of a finite interfacial strength is a major improvement since previous work on SiC/Ti composites points to the existence of a weak chemical bond at the fiber–matrix interface [15,28,29]. The CCI model, as implemented in GMC, was later employed by Warrier et al. [30] to model the transverse tensile response of SCS-6/TIMETAL 21S. Also a fiber/matrix de-bonding model was presented for MMCs based on modified Needleman type cohesive zone model under normal and shear loading [11]. However, initiation and propagation of fiber/matrix interfacial de-boning for unidirectional MMCs in the off-axis loading were not found in the literature.

In this study, the elasto-plastic response of SiC/Ti unidirectional fiber reinforced composite under off-axis loading is predicted using the SUC model. Nonlinear behavior of the material due to both matrix plastic deformation and interface damage are considered in the model. The model also includes effects of manufacturing process thermal residual stress. In order to provide a more realistic model, the geometry of the RVE in the SUC model is extended to $r \times c$ sub-cells mainly to determine more accurately effects of both nonlinearities. The CCI model is also modified to consider interfacial de-bonding. The successive approximation method is used to obtain elastic–plastic behavior of the material. Results for stress–strain response at various off-axis angles show favorably good agreement with experimental data. In the next section, the SUC micromechanical model is described. Material characterizations of the SiC/Ti composite are expressed in Section 3. The fourth section contains the interfacial de-bonding model employed to obtain the behavior of the SiC/Ti composite using the micromechanical model.

2. Analysis

2.1. Geometry of the RVE

Most analytical and FE models assume regular fiber arrangement. Normally, two types of fiber arrays, square and hexagonal arrays are considered in various analyses. Additional assumption in most analytical models, such as method of cells and SUC is assuming rectangular fibers. However, in order to consider more realistic geometry in the analytical models, one can consider the RVE consisting of $r \times c$ rectangular elements in which fiber sub-cells are surrounded by matrix sub-cells. Geometry of the selected RVE shown in Fig. 1 consists of $r \times c$ elements with L_c and L_r as the length of the RVE in the x and y directions, respectively, and unit length in the z direction. Each sub-cell labeled as ij in which i and j are considered as counters of the sub-cells in the x and y directions, respectively. Also, the model presented in this study is called extended simplified unit cell (ESUC) model in which the selected RVEs contains more than 10×10 sub-cells to consider circular shape of the fiber as shown in Fig. 2.

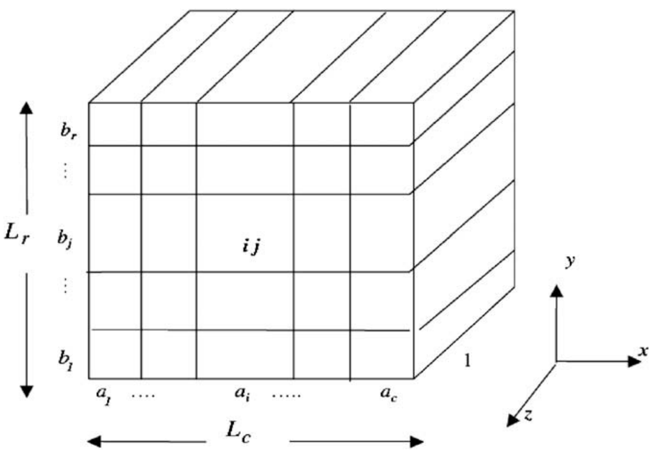

Fig. 1. RVE in the SUC model for unidirectional composite materials.

2.2. Micromechanical governing equations

In off-axis loading, a uniaxial load is applied to a coupon where the fibers are aligned at an angle θ to the loading direction as shown in Fig. 3. Two coordinate systems are defined: the (x, y) system, where the x direction is the loading direction, and the (1–2) system, where the 1 axis coincides with the fiber direction and the 2 direction is perpendicular to the fibers. The stress state within the specimen in the material principle axes consists of three stress components: axial S_1, transverse S_2, and axial shear S_{12} as indicated in Fig. 3. The symbol S is used for various overall stress components on the RVE. These stress components can be determined from the stress (S_x) applied to the off-axis coupon using the following transformation equations:

$$\begin{Bmatrix} S_1 \\ S_2 \\ S_{12} \end{Bmatrix} = \begin{Bmatrix} \cos^2\theta \\ \sin^2\theta \\ \sin\theta\cos\theta \end{Bmatrix} \times S_x \tag{1}$$

where S_1, S_2 and S_{12} are the average normal and shear stresses in the material coordinate system and θ denotes off-axis angle.

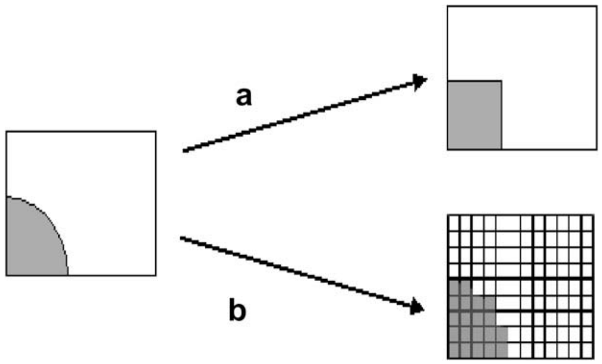

Fig. 2. RVE in the ESUC model for square array of unidirectional composite materials.

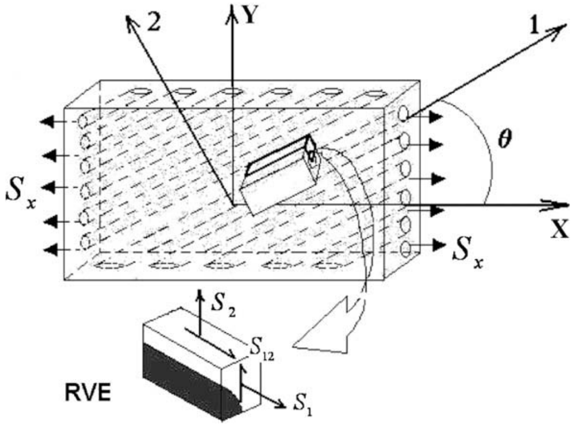

Fig. 3. Composite coupon under off-axis loading and its corresponding RVE.

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