Computational Materials Science 46 (2009) 626–631

Contents lists available at ScienceDirect

Computational Materials Science

journal homepage: www.elsevier.com/locate/commatsci

Interface damage of SiC/Ti metal matrix composites subjected to combined thermal and axial shear loading

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ARTICLE INFO

Article history:
Received 3 December 2008
Received in revised form 4 March 2009
Accepted 13 April 2009
Available online 12 May 2009

Keywords:
Micromechanics
Metal matrix composites
Axial shear loading
Interface damage
Finite element
Thermal residual stress

ABSTRACT

A three-dimensional micromechanical finite element model is developed to study initiation and propagation of interface damage of unidirectional SiC/Ti metal matrix composites (MMCs) subjected to combined thermal and axial shear loading. Effects of various important parameters such as manufacturing process thermal residual stress, fiber coating and interface bonding are investigated. The model includes a representative volume element consists of a quarter of SiC (SCS-6) fibers covered by interface and coating, which are all surrounded by Ti-15-3 matrix. Appropriate boundary conditions are introduced to include effects of combined thermal and axial shear loading on the RVE. A suitable failure criterion for interface damage is introduced to predict initiation and propagation of interface de-bonding during shear loading. It is shown that while predictions based on perfectly bonded and fully de-bonded interface are far from reality, the predicted stress–strain curve for damaged interface demonstrates very good agreement with experimental data.

1. Introduction

Demands on structural materials for better performance under more severe loads and environmental conditions are increasing. Metal matrix composites (MMCs) are used in structures with application at high temperatures that mainly require ductility of the metal matrix in combination with the strength and creep resistance of ceramic fibers [1]. However, experimental [2] and theoretical [3] studies revealed that MMCs suffer from weak interface between the fiber and matrix, which highly affects the behavior of the MMCs in various loading conditions. Furthermore, existence of manufacturing process thermal residual stresses in MMCs could also affect their behavior when they are subsequently subjected to mechanical loads. Fig. 1 shows results of an experimental study carried out by Jansson et al. [2] in Iosipescu shear loading of SiC/Ti composites. The fiber orientation of the specimens is parallel to the shearing direction. It can be seen that predictions of the models based on fully bonded and fully de-bonded interface assumptions are far from reality. Figure 1 also shows that damage in the form of fiber–matrix de-bonding occurs prior to plastic deformation of the matrix. Initially, the stress–strain response is linear and at some point, in which the fiber–matrix de-bonding begins, interfacial damage initiates and progresses in the diffusion bonded zone.

A better understanding of composite material response to different loading conditions with considering the geometry and mechanical properties of its constituents is achieved by analytical/numerical micromechanical modeling of MMCs. More accurate models should include effects of weak interface and thermal residual stresses. For instance, the considerable effects of the fiber/matrix interface on the composite transverse behavior have been investigated using theoretical simulations by Aboudi [3], Wisnom and co-workers [4] and Peters et al. [5] and experimentally by Lissenden et al. [6].

Li and Wisnom [4] carried out a parametric study of unidirectional SiC/Ti. They also studied the C/TiB2 coated SiC fiber-reinforced Ti–6Al–4V composite experimentally and analytically [7] under monotonic and cyclic longitudinal and transverse tension test. A user defined element was developed to model the fiber/matrix interface failure under predefined combination of normal and shear stress. The effect of coating on the transverse tensile properties was also studied. A three-dimensional (3-D) finite element micromechanical model was presented to predict the behavior of unidirectional SiC/Ti–6Al–4V metal matrix composites subjected to off-axis loading by Aghdam et al. [8,9]. The effects of fiber/matrix interface de-bonding was included in the model by considering only a fully de-bonded interface with a level of friction between fiber and matrix in the presence of thermal residual stresses. Recently, Aghdam and Falahatgar [10] developed the micromechanical model for SiC/Ti subjected to uniaxial transverse loading in which effects of coating, interface and residual stresses are considered. Two different interfaces, i.e. fiber/coating and coating/matrix

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0927-0256/$ - see front matter
doi:10.1016/j.commatsci.2009.04.013

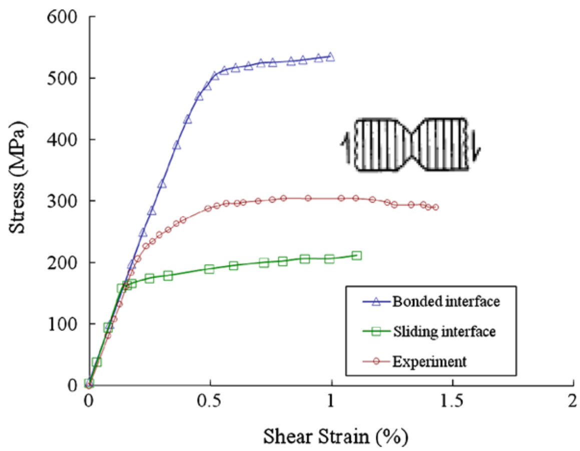

Fig. 1. Axial shear stress–strain response for bonded and sliding interface models compared with experiment [2].

interfaces together with two different failure criteria, which are combinations of normal and shear stresses across the interfaces, were used to predict the failure of interfaces. Predicted results show favorably good agreement with experiment [6] even in higher applied strains. The model was further used to study interface damage of SiC/Ti composites subjected to various combined biaxial loading [11]. Bonora and Ruggiero [12,13] implemented a microstructural damage evolution in SCS-6/Ti-15-3 composite laminates. Fiber failure was modeled by a probabilistic Weibull-based statistics model. A ductile damage model was implemented for metal matrix failure, which incorporates stress triaxiality effects. Fiber–matrix de-bonding including material manufacturing process in the stress/strain history was predicted for 0° and 90° unidirectional laminates, in tension and compression loading.

For the axial shear loading modeling, however, one can refer to the earliest work performed by Adams and Crane [14]. A two-dimensional micromechanical finite element analysis was developed for considering longitudinal shear response of a unidirectional composite material under mechanical loading combined with temperature and moisture effects. A study based on finite element micromechanical modeling was also carried out by Nedele and Wisnom [15] to investigate the overall thermoelastic constants and the local stress distributions of a unidirectional carbon–fiber epoxy composite. The main aspect was the magnitudes and locations of the maximum stress values to find the initial failure under transverse tension and axial shear loading. The effects of residual stress and the fiber–matrix interface were not included in the models. Zhang et al. [16] analyzed nonlinear viscoelastic model for the epoxy matrix material in which matrix cracking was modeled by smeared crack method under off-axis loading. Material nonlinearity, damage initiation and growth, and multi-axial loading, except the residual stress and the interface zone was considered in the micromechanical analysis simultaneously. Lissenden [17] developed a 3-D interface model for weakly bonded composites using the method of cells. The model describes an overall representation of de-bonding in terms of interface strength and ductility under normal and shear loading. The interface model is based on a modified Needleman cohesive zone and the de-bonding initiates when a quadratic interaction of the interfacial tractions reaches the interfacial strength. The model includes residual stress effects as well as interfacial friction after de-bonding initiates.

In this study, initiation and propagation of interface damage of a unidirectional SiC/Ti metal matrix composite (MMC) during axial shear loading is investigated using a 3-D finite element micromechanical model. Effects of manufacturing process thermal residual stresses and interface strength on the shear stress–strain behavior of composites are studied. Appropriate boundary conditions are introduced to apply both cool-down process and axial shear loading on the RVE. The model consists of SiC coated fiber, titanium alloy matrix and an interface layer, which is located between fiber and carbon coating. Interface damage initiates as soon as failure criteria reaches to interface shear strength. Prediction of shear stress–strain curve for SiC/Ti composite system shows very good agreement with existing experimental results.

2. Micromechanical model

2.1. Representative volume element

In order to implement a micromechanical approach for unidirectional fiber-reinforced composite, the actual cross section of the composite should be assumed as regular arrays of fibers. This can be done using a periodic array of fibers either in a square or hexagonal packing. However, the periodic arrangement of the fiber packing is not an unrealistic assumption [18] for SiC/Ti MMCs. Therefore, the presented model consists of a unit cell known as representative volume element (RVE) considering a quarter of fiber surrounded by matrix as a repeating element in a square array of fibers, see Fig. 2. Furthermore, it is assumed that the effective properties of the composite system are similar to the properties of the small RVE.

For the case of axial shear, a variable displacement in the fiber direction exists and therefore a two-dimensional generalized plane strain is no longer valid as used in previous studies [10,11]. A three-dimensional model is constructed as in Fig. 2b where the original and deformed RVE after residual stress and axial shear are shown. The finite element model contains 441 20 noded brick elements to construct geometry of the RVE with one series of elements in the axial direction.

2.2. Material properties

The composite system composed of a titanium alloy matrix, Ti-15-3, reinforced by aligned silicon carbide (SCS-6) coated fibers with a fiber volume fraction of 35%. The silicon carbide fibers considered here are assumed to be isotropic and homogenous with temperature independent properties. The matrix is also isotropic and assumed to follow the Von-misses criterion with a yield stress of 750 MPa [2]. The mechanical and thermal properties of the composite constituents are listed in Table 1. An interface between fiber and coating is assumed in the model whose properties are considered nearly equal to average of the properties of the neighboring materials [19]. A thin layer of carbon is considered as the fiber coating. In addition, minimum thickness is considered for the interface layer and a cool-down of 600 °C [17] is considered for the composite system.

2.3. Boundary conditions of the model

For the finite element analysis of the RVE especial boundary conditions [9] should be applied to the RVE. Considering x–y plane at the beginning of fiber thickness, the RVE is considered as a cubic with dimensions (a, a, t) as length, width and thickness, respectively, shown in Fig. 3. The boundary conditions in Eq. (1) contain pure axial shear loading of the composite. For axial shear loading, the surface (a, y, z) has a displacement with respect to the surface (a, y, z) in the axial direction. The effect of axial shear load is such that all nodes with the same position in the x–y plane have the same displacement in the z direction. These boundary conditions can be expressed as: