Computational Materials Science 79 (2013) 402–407

Contents lists available at SciVerse ScienceDirect

Computational Materials Science

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

Damage initiation and collapse behavior of unidirectional metal matrix composites at elevated temperatures

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

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

ARTICLE INFO

Article history:
Received 12 July 2012
Received in revised form 2 May 2013
Accepted 5 June 2013
Available online xxxx

Keywords:
Micro-mechanics
Metal matrix composites
Elevated temperatures
Interface failure
Thermal residual stress

ABSTRACT

A two-dimensional micromechanical finite element model is developed to investigate the transverse behavior of SiC/Ti–6Al–4V metal matrix composite (MMC) at elevated service temperatures with a square representative volume element (RVE). The effects of various parameters such as manufacturing process thermal residual stress, fiber coating and interface damage are considered. Proper interface elements between fiber/coating (*f*/*c*) and coating/matrix (*c*/*m*) together with appropriate failure criteria are introduced to include interface damage in the model. A user defined subroutine is employed to implement interface failure. Predicted results show good agreement with the available experimental data at various elevated temperatures. Results reveal that initiation of *f*/*c* interface damage is the first failure mode and its sensitive to temperature mainly due to different residual stress states at higher temperatures. Furthermore, due to lower strengths of *c*/*m* interface and matrix at elevated temperatures, collapse stress of the composite decrease critically at elevated temperatures.

1. Introduction

Metal matrix composites (MMCs), in particular SiC/Ti–6Al–4V MMCs, have attracted researchers mainly due to their interesting mechanical characteristics and stability of properties at elevated service temperatures [1]. However, there are serious concerns related to reliability of SiC/Ti–6Al–4V composites mainly in transverse loading. The first crucial concern is related to the existence of a weak interface between the fiber and matrix which substantially reduces the transverse tensile strength of the material. Relatively high state of thermal residual stresses within the MMCs due to cool-down process from high manufacturing temperature to room temperature is the other source of concern. These residual stresses are produced due to mismatch between the coefficients of thermal expansion (CTE) of the constituents. The generated residual stresses influence the overall mechanical properties of the MMC.

Different micromechanical models have been used to study behavior of MMC's in different loading condition at room temperature, see for instance [2–9]. Li and Wisnom [5–7] studied the effects of fiber coating and damaged interface of SiC/Ti MMC's where three distinct phases; e.g., fiber, coating, and matrix, together with fiber/coating interface were employed to predict response of SiC/Ti composite system in longitudinal and transverse tension. A user defined interface element was used to predict fiber/matrix interface failure under predefined combination of normal and shear stresses. Presented results show good agreement with experimental data for relatively small range of applied strains of less than 0.5%. Aghdam and Falahatgar [8] presented new model including two different interfaces, one between fiber and coating and the other between coating and matrix for SiC/Ti system considering the effect of coating and residual stresses. Predicted results show good agreement with experimental results for the whole range of the strain up to failure. Later, Aghdam et al. [9] modified their model to study axial shear behavior of SiC/Ti MMC system at room temperature which also shows good agreement with experimental data. However, titanium based MMCs are mostly used in high service temperature applications such as turbine blades [10–12].

Among high temperature studies, one may refer to the experimental and micro/macro mechanical analytical models carried out by Sun et al. to determine the behavior of SiC/Ti in off axis loading at room temperature [13] and higher temperatures [14]. The strength of interface at different temperatures was calculated from transverse tensile test data which was then used for different off-axis angles. Nimmer et al. [15] studied transverse stress–strain behavior of SiC/Ti system at different temperatures using both experiment and finite element micromechanical model. Fully debonded interface with Coulomb friction was considered to include effects of weak interface. Later, Nimmer et al. [16] employed the same model to investigate the effect of fiber array geometry on the transverse tensile behavior of SiC/Ti MMCs at different elevated temperatures. Eggleston and Krempl [17] performed finite element

---

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

0927-0256/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.commatsci.2013.06.024

models to investigate the transverse behavior of SiC/Ti MMC at 482 °C using two limiting cases of perfectly bonded and fully debonded interface with Coulomb friction. They also performed experimental tests to obtain transverse stress–strain and the creep behavior of the material. Using comparison with experimental data, they have concluded that composite tensile behavior was best approximated by the model with no interface strength.

Naboulsi [18] used analytical and numerical (FEM) approach to determine transverse behavior of SiC/Ti MMC at 23 and 427 °C. Again, a fully debonded interface was considered to include effects of weak interface. Although [13–18] provided valuable experimental results for high temperature behavior of the composite system, they have considered two simple cases of bonded and debonded interface in their analyses. More recently, Lou et al. [19] used a 2D micromechanical model to investigate the effect of temperature on the transverse tensile behavior of SiC/Ti. Their model consisted of fiber, matrix and an interface with specific bonding strength for all temperatures. They used spring elements to simulate interfacial debonding when interfacial radial stress, composed of residual and applied transverse tensile stress, reaches interfacial bonding strength. However, no experiment validation was provided to verify their predictions.

Present study contains a micromechanical model to investigate the transverse tensile behavior of SiC/Ti at elevated temperatures. The effects of interface damage and residual stress are considered. The model contains fiber, matrix, coating together with proper interfaces between fiber/coating (*f*/*c*) and coating/matrix (*c*/*m*). Appropriate failure criteria are introduced to predict failure initiation of the two interfaces. The user subroutine to redefine field variables is employed to consider interface failure, provided by ABAQUS finite element package [20]. The predicted results show good agreement with experimental data at different elevated temperatures.

2. Analysis

2.1. Material properties

The composite system considered in this study is a titanium alloy matrix, Ti–6Al–4V, reinforced by continuous silicon carbide coated fibers. Fiber volume fractions of these composites are usually between 0.25 and 0.40 [15]. Fibers are assumed to be isotropic and homogenous with temperature independent and elastic properties: $E = 400$ GPa, $\nu = 0.3$ and $\alpha = 4.5 \times 10^{-6}\,°\mathrm{C}^{-1}$. The matrix is assumed to be isotropic and homogenous with temperature dependent properties tabulated in Table 1 which are taken from [5,21]. The value of Poisson ratio is 0.33 for all temperatures. The Von Mises criterion is employed to determine yield stress in the matrix. A thin layer of C/TiB2 is considered as the fiber coating. Two interfaces; i.e., fiber/coating and coating/matrix interfaces are considered with isotropic and temperature independent properties. The thermal and mechanical properties of the interfaces are assumed to be average of neighboring materials [1]; i.e., average of fiber and coating properties for the (*f*/*c*) interface and coating and matrix properties for the (*c*/*m*) interface. To consider the effects of thermal residual stresses, the model is cooled-down from fabrication temperature 900 °C to loading temperature. The thermal residual stresses cause a compressive stress on the interface and increasing strength of the composite in transverse loading [15]. Any relaxation of residual stresses due to viscoplastic behavior of matrix is ignored. Hence the model over predicts the residual stresses.

Table 1
Temperature dependent properties of Ti–6Al–4V [5,21].

Temperature (°C)	Young modulus (GPa)	Yield stress (MPa)	α ($10^{-6}\,°\mathrm{C}^{-1}$)	Flow modulus (GPa)
20	110	900	8.9	0.5
127	100	759	9.3	–
227	94	630	9.7	–
327	88	514	9.9	2.2
427	82	493	10.1	2.2
482	79	482	10.3	1.9
527	76	434	10.4	1.9
627	742	327	10.6	1.9
727	–	220	10.7	–
827	–	113	10.9	–
927	21	–	11	–

2.2. Finite element model and boundary condition

A representative volume element consisting of a quarter of fiber, relevant coating, appropriate interfaces and corresponding matrix material is considered to predict composite behavior in the transverse direction. The same as most common fiber array assumptions in finite element studies, a square array of fibers is selected for this study. As shown in Fig. 1, the appropriate periodic boundary conditions to apply transverse loading on the RVE include keeping edges of the RVE parallel to their primary position by using two constraint for nodes on the right and upper side of the RVE to have equal displacement in the *x* and *y* directions, respectively. Furthermore, dimensions of the constituent of the RVE are calculated by assuming fiber volume fraction and using:

$$\frac{\pi R_1^2}{4a^2} = v_f \qquad (1)$$

$$R_2 = R_1\sqrt{(1 - v_c)}$$

where v_f and v_c are fiber and coating volume fractions, respectively. R_1 and R_2 are the outer and inner radius of the coating and a denotes width of the RVE as shown in Fig. 2. It should be noted that for a SiC fiber with 100 μm diameter, the thickness of the coating is reported [22] as 2 μm which is equivalent to 7.8% coating volume fraction, v_c. The transverse load is applied to the right side of the RVE in the *x* direction after cooling down step. The global transverse strain within the RVE ($\bar{\varepsilon}_x$) related to the applied transverse load can be determined using:

$$\bar{\varepsilon}_x = \frac{u_x(a, y)}{a} \qquad (2)$$

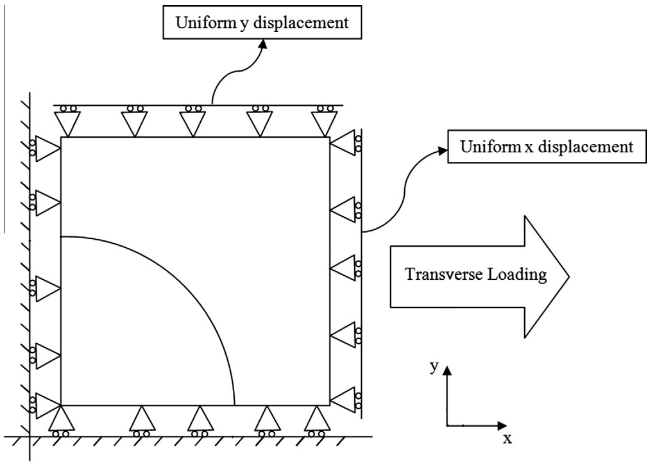

Fig. 1. Selected RVE for transverse loading in the *x* direction.