Computational Materials Science 89 (2014) 102–113

Contents lists available at ScienceDirect

Computational Materials Science

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

Micromechanical study of influence of interface strength on mechanical properties of metal matrix composites under uniaxial and biaxial tensile loadings

Hai Qing *

State Key Laboratory of Mechanics and Control of Mechanical Structures, Nanjing University of Aeronautics and Astronautics, Nanjing 210026, China

ARTICLE INFO

Article history:
Received 6 January 2014
Received in revised form 18 March 2014
Accepted 21 March 2014
Available online 18 April 2014

Keywords:
Metal–matrix composites
Interface
Mechanical properties
Microstructures
Finite element analysis

ABSTRACT

The influence of particle arrangements and interface strengths on the mechanical behavior of the particle reinforced metal–matrix composite (MMC) is investigated under different loading conditions in this work. During the loading process, three different failure mechanisms are distinguished in MMC: ductile failure in metal matrix, brittle failure in SiC particles and interface debonding between matrix and particles. The damage models based on the stress triaxial indicator and maximum principal stress criterion are developed to simulate the failure process of metal matrix and SiC particles. Meanwhile, 2D cohesive element is utilized to describe the debonding behavior of interface. Series of numerical experiments are performed to study the macroscopic stress–strain relationships and microscale damage evolution in MMCs under different loading conditions. An agreement between the simulation results and the experimental data is obtained.

1. Introduction

Metal matrix composites (MMCs) are widely used, but not limited, in the fields of aerocraft [1], automotive [2], electronic packing [3–5], thermal management equipment [6,7], aviation [8,9] and so on, due to a favorable combination of low density and improved mechanical properties. The increasing applications of the MMCs in the different fields require an efficient method to predict their mechanical behaviors from the known properties of the constituents. Furthermore, one can design and optimize the microstructure of MMCs according to the requirement based on the knowledge of the correlation between microstructure, deformation, damage initiation and damage development in MMCs.

Computational micromechanics [10,11] is widely applied to study the influence of the microstructure and phase properties of MMCs on the macroscale mechanical properties of MMCs. Ganesh and Chawla [12] and Peng et al. [13] studied the influence of particle shape on the mechanical behavior of MMCs. Schmauder et al. [14] studied the influence of thermal residual stress on the stress-strain relationships. Song and Huang [15] studied influences of the SiC particles, constituents and precipitates on the fracture toughness of SiCp/Al alloy metal matrix composites. Yan et al. [16] and Ekici et al. [17] studied the effect of particle size on the deformation behavior of the MMCs. Qing [18] studied the influence of applied method of boundary condition on the prediction accuracy of mechanical properties of MMCs. Mishnaevsky et al. [19,20] studied the effect of the spatial distribution of particles on the mechanical properties of MMCs. Meanwhile, a number of computational micromechanical models are developed to predict the influence of interface on the macroscopic strength of MMCs, such as Tursun et al. [21], Zhang et al. [22], Alberto [23], Mahmoodi et al. [24] and Aghdam et al. [25] and Veazie and Qu [26], Sozhamannan et al. [27], and Wang et al. [28].

However, most studies in the literature including the studies mentioned above are based on the uniaxial tensile loading condition through the symmetric boundary condition. In this work, we study the influence of the interface strengths and microstructures on the mechanical properties of MMCs under both uniaxial and biaxial tensile loadings through the periodic boundary conditions which are realized with a multi-point constraint subroutine MPC in Abaqus. A program is developed for automatic generation of 2D micromechanical finite element models with random distribution of particle dimensions and locations. In order to simulate the brittle cracking in particles and ductile failure in matrix, an elastic-damage model based on the maxminum principal stress criterion and a plastic-damage model based on the stress triaxial indicator are developed in Abaqus subroutine USDFLD, respectively. Series of numerical studies are performed to analyze the influence of

* Tel.: +86 25 8489 2461.
E-mail address: qinghai@nuaa.edu.cn

http://dx.doi.org/10.1016/j.commatsci.2014.03.046
0927-0256/

particle arrangements, interface strengths and loading conditions on the macroscopic stress-strain relationships and damage evolution in MMCs.

2. Finite element model

2.1. The generation of representative volume element (RVE)

In order to study the influence of the microstructures of MMC on its deformation and damage evolution process, the microstructure of MMC under consideration should be able to vary according to the requirement. Both the random disturbance of the initial regular arrangements [29–31] and the random sequential adsorption algorithm [18,20,32–34] are widely applied to generate the microstructure of composites. Here, the microstructure with the random particle arrangements is generated through the random sequential adsorption algorithm. In the other words, the particle locations and dimensions are controlled by the random number sequences. We assume that the RVE of the MMC is a square with dimension L_0, and the particle number and volume fraction are n_p and υ_p, respectively. Therefore, we can express the uniform particle radius r_0 as

$$r_0 = \sqrt{\upsilon_p L_0^2 / \pi n_p} \tag{1}$$

The distribution of particle dimension is defined by a sequentially random number stream Rand_1 controlled by the random number generator seed s_1 [32] as following

$$r_i = r_0(\mathrm{Rand}_{1i} + 1/2) \quad (i = 1, 2, \ldots, n_p) \tag{2}$$

where Rand_1 means the 1st random number stream, while Rand_{1i} is the i-th number of the random number stream Rand_1. In order to get the same particle volume fraction, the radius of each particle has to be normalized with a factor f which relates other parameters as

$$n_p(r_0 f)^2 = \sum_{i=1}^{n_p} r_i^2 \tag{3}$$

Both x and y coordinates of particle centers are produced independently and sequentially with two random number streams (Rand_2 and Rand_3) controlled by two random number generator seeds (s_2 and s_3). The distances between the new particle and all existed particles are no less than a given distance related to the particle radius. Furthermore, the new particle should not be too close to the four borders. In order to ensure the periodicity of the RVE, if a particle is cut by the border of the RVE, the remained part is moved L_0 pointing to the opposite boundary.

A program within Matlab, which can generate automatically the 2D micromechanical finite element models, is developed to realize the above algorithm. Fig. 1 shows a RVE example generated through the program with 100 particles for the particle volume fractions equal to 15%. The different colors of particles indicate the different mechanical properties, such as strengths in this study.

2.2. The mechanical properties of the constituents

The degradation behavior of a MMC due to damage initiation and evolution is apparently the main failure mechanism during the loading process. Three different failure mechanisms can be distinguished within MMC: ductile failure of matrix, brittle cracking of reinforcement and interface debonding between particles and matrix.

The SiC particle is assumed to be an isotropic elastic-brittle damageable solid, and its Young modulus and Poisson's ratio are 410 GPa and 0.14, respectively. The strengths of the particles obey Weibull distribution with mean value σ_a = 550 MPa [18] and shape

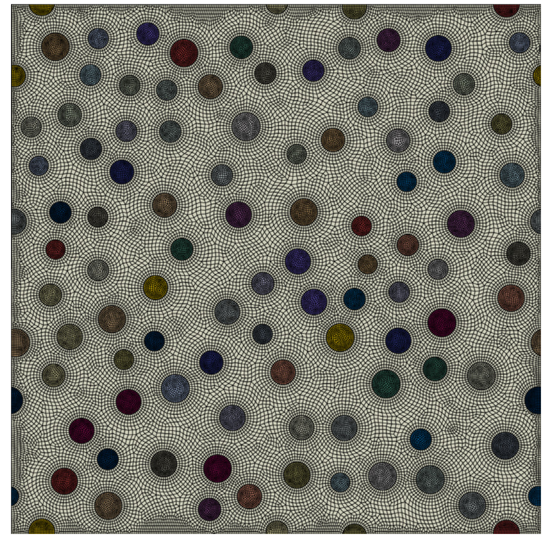

Fig. 1. Example of FE-mesh of microstructural model.

parameter m = 9.62 [35]. A elastic-damage model is developed within Abaqus through the subroutine USDFLD. Damage in the element is assumed to initiate when its maximum principle stress reaches the strength of the corresponding particle. A scalar damage variable, D_p, initially has a value of 0. Damage in particles monotonically evolves exponentially from 0 to 1 upon further loading after the initiation of damage.

The stress–strain relationship of the aluminum alloy can be expressed as the Ramberg–Osgood model [36]

$$\varepsilon = \frac{\sigma}{E_m} + \alpha \frac{\sigma_m}{E_m}\left(\frac{\sigma}{\sigma_m}\right)^n \tag{4}$$

where Young modulus $E_m = 69$ GPa, and two other parameters $\alpha = 1$, $\sigma_m = 275$ MPa, with the Poisson's ratio υ_m = 0.345 and the strength $\sigma_s = 315$ MPa.

Aluminum alloy behaves as typical ductile failure under tensile loadings. In this study, a triaxiality factor D [37] is utilized to describe the incremental damage indicator. The triaxiality factor D is defined as an increment of the plastic strain divided by the reference failure strain

$$D = \int_0^{\varepsilon_p} e^{\sigma_H/\sigma_V} \mathrm{d}\varepsilon_p \tag{5}$$

where σ_H is the hydrostatic stress and σ_V is the Von Mises stress, and ε_p is the cumulative plastic strain. The study [18] shows D_c = 0.05 for aluminum alloy. The damage evolution in matrix, like particle, monotonically evolves exponentially from 0 to 1 upon further loading after the initiation of damage.

The interface debonding is one of the most important failure mechanisms in MMCs. 2D cohesive element in term of traction–separation law, which relates the displacement jump across the interface with the traction vector acting upon it, is applied to simulate the fracture of the elements inserted at the particles/matrix interface. The interface elements initially provide a linear, stiff response which ensures the displacement continuity and avoids any modification of the stress and strain fields around the interface. The initial stiffness K_i of the cohesive elements is set to be a large number, and here K_i = 10^8 GPa is adopted.

The onset of damage is dictated by a maximum stress criterion, and the initial damage strength of the cohesive element is assumed as

$$S_{\mathrm{int}} = k_{coh}(\sigma_m + \sigma_a)/2 \tag{6}$$