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2D micromechanical analysis of SiC/Al metal matrix composites under tensile, shear and combined tensile/shear loads

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ABSTRACT

The influence of interface strength and loading conditions on the mechanical behavior of the metal–matrix composites is investigated in this paper. A program is developed to generate automatically 2D micromechanical Finite element (FE) models including interface, in which both the locations and dimensions of Silicon–Carbide (SiC) particles are randomly distributed. Finite element simulations of the deformation and damage evolution of SiC particle reinforced Aluminum (Al) alloy composite are carried out for different microstructures and interphase strengths under tensile, shear and combined tensile/shear loads. 2D cohesive element is applied to describe the fracture and failure process of interphase, while the damage models based on maximum principal stress criterion and the stress triaxial indicator are developed within Abaqus/Standard Subroutine USDFLD to simulate the failure process of SiC particles and aluminum alloy matrix, respectively. A series of computational experiments are performed to study the influence of particle arrangements, interface strengths and loading conditions of the representative volume element (RVE) on composite stiffness and strength properties.

1. Introduction

Metal matrix composites (MMCs) and the metal matrix syntactic foams, a sub-group of MMCs, are applied widely in aerocraft [1], automotive [2], electronic packing [3–5], thermal management equipments [6,7], aviation [8–10] and so on, due to their good electrical and thermal conductivity and high specific stiffness and strength properties. Based on the knowledge of the relationship between the microstructure and the macroscale response, one can optimize the properties of metal–matrix composites according to the requirement. Generally, the macroscale properties can be achieved through measurement experimentally, and/or micromechanical models [11,12], which initially took into account only the reinforcement and matrix properties and their volume fractions. However, they are not able to predict the exact relationship between microstructure and macroscale properties of composite.

Computational micromechanics [13,14], also defined as virtual test and experiment in different literature, are widely applied to analyze the influence of the microstructure and phase properties of MMCs on their stiffness and strength properties. Compared to the actual experiments, the virtual test presents three important advantages from a mechanical point of view. First, we can easily apply multiaxial loading condition to the composite materials. Second, we can study the influence of the reinforcement (distribution of shape, spatial, size etc.), interphase and matrix on the macroscale response of composites. Third, we can access the detailed microscale stress–strain fields and failure evolution during the loading process.

A number of computational micromechanical models are developed to predict the MMCs mechanical properties. Soppa et al. [15], Ganesh and Chawla [16] and Moulin et al. [17] studied the influence of particle shape on the mechanical behavior of MMCs. Schmauder et al. [18] and Aghdam and Kamalikhah [19] studied the influence of thermal residual stress on the stress–strain relationships. Tursun et al. [20], Zhang et al. [21], Alberto [22], Mahmoodi et al. [23] and Aghdam et al. [24] and Veazie and Qu [25] and Sozhamannan et al. [26] studied the effect of interphase on the macroscopic strength of metal matrix composites. Mishnaevsky et al. [27,28] studied the influence of the particle spatial distributions on the mechanical properties of MMCs. Ekici et al. [29] and Qing [30] studied the influence of particle size and volume fraction on the mechanical response of particle reinforced MMC. Tang et al. [31,32] developed a micromechanics model based on the variational asymptotic method for periodic composite to investigate initial yielding surface and elastoplasticity of metal matrix composites.

In this paper, we study the influence of particle arrangements, interface strengths and loading conditions of the representative

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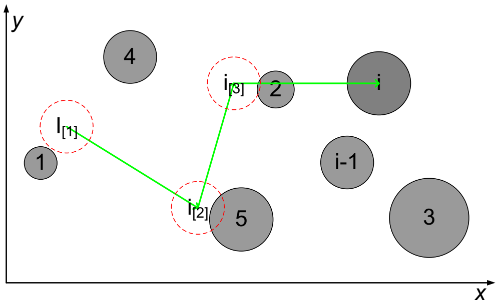

Fig. 1. Schema of the generation process of random particle arrangement. The non-bracketed numbers are the particle numbers, and the bracketed numbers mean iterations.

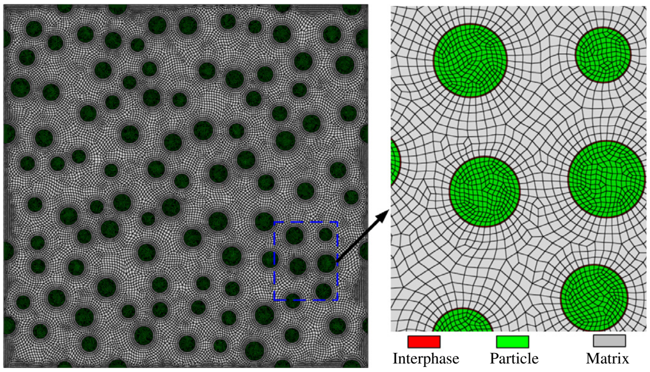

Fig. 2. Example of FE-mesh of microstructural model.

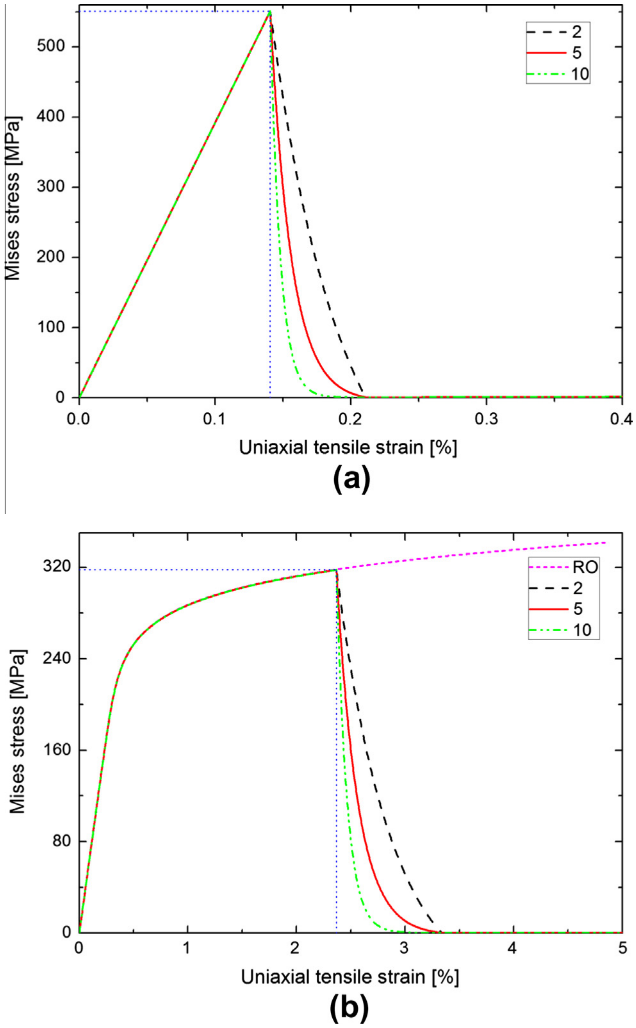

Fig. 3. Damage evolutions in (a) particles and (b) matrix under different damage parameters.

volume element (RVE) on composite mechanical properties. A program is developed for the automatic generation of 2D micromechanical finite element models of multi-particle MMC with random particle dimension distribution and location arrangement. The stress triaxial indicator [33] and the maximum principal stress criterion based elastic brittle damage model are developed to simulate the damage processes in aluminum alloy matrix and SiC particles within Abaqus/Standard Subroutine USDFLD, respectively. A series of computational experiments on the SiC-particle reinforced aluminum matrix composite is performed to study the influence of particle arrangement, interphase strength and loading condition on the macroscopic stress–strain relationships and damage evolution in composite.

2. Automatic generation of 2D multi-particle micromechanical RVE

2.1. The generation of finite element RVE

The microstructure of the composite material under consideration should be able to vary to study the influence of the microstructures on its deformation and damage evolution process. The digital image technique [20,26,34] and disturbance of particles from their initial regular arrangement [35–41], such as hexagonal and/or square lattice arrangements, are applied to generate the microstructure of composites. The digital image technique requires special software/hardware, while local disturbing of initial regular arrangement cannot generate really random distributed particle arrangement.

Here, the microstructures with the random particles arrangement are generated using the random number generators. It's assumed that the RVE of the composite microstructure is a square with dimension of $L_0 \times L_0$, and the particle number and volume fraction are n_p and υ_p, respectively. Firstly, we can calculate the mean particle radius r_0 as

$$r_0 = \sqrt{\frac{\upsilon_p L_0^2}{\pi n_p}} \qquad (1)$$

The distribution of particle dimension is defined by a sequentially random number stream Rand_1 through one random number generator seed s_1 [42] as following:

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

In order to get the right particle volume fraction, the radius of each particle is multiplied with a factor f, which is defined as

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

Both x and y coordinates of particle centers are produced independently and sequentially with two random number streams (Rand_2 and Rand_3) through two random number generator seeds (s_2 and s_3). After the coordinates of a first particle are defined, the coordinates of each new particle are determined both by using next numbers of the two random number streams, and from the condition that the distance between the new particle and all