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Automatic generation of 2D micromechanical finite element model of silicon–carbide/aluminum metal matrix composites: Effects of the boundary conditions

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ABSTRACT

Two-dimensional finite element (FE) simulations of the deformation and damage evolution of Silicon–Carbide (SiC) particle reinforced aluminum alloy composite including interphase are carried out for different microstructures and particle volume fractions of the composites. A program is developed for the automatic generation of 2D micromechanical FE-models with randomly distributed SiC particles. In order to simulate the damage process in aluminum alloy matrix and SiC particles, a damage parameter based on the stress triaxial indicator and the maximum principal stress criterion based elastic brittle damage model are developed within Abaqus/Standard Subroutine USDFLD, respectively. An Abaqus/Standard Subroutine MPC, which allows defining multi-point constraints, is developed to realize the symmetric boundary condition (SBC) and periodic boundary condition (PBC). A series of computational experiments are performed to study the influence of boundary condition, particle number and volume fraction of the representative volume element (RVE) on composite stiffness and strength properties.

1. Introduction

Metal matrix composites (MMCs) are found most often in automotive, electronic, aerospace and defense industries, due to their resistance to fire, moisture and radiation, better electrical and thermal conductivity, and high stiffness-to-weight ratio. Computational micromechanics are widely applied to analyze the influence of the microstructure and phase properties of MMCs on their stiffness and strength properties. The applications of advanced numerical simulation can replace some of the mechanical tests and significantly reduce the design cost. Based on this background, computational mechanics is also defined as virtual experiment/test and numerical experiments in different literature.

A number of publications based on 2D computational micromechanical models are developed to predict the MMCs mechanical properties. Kassam et al. [1] studied the influence of single particle and particle clusters ahead of the crack tip on the stress distribution nearby crack tip based on single- and multi-particle micromechanical models. On the basis of the micromechanical models containing multi-particle, Schmauder and his collaborators [2–4] studied the influence of particle shape, thermal residual stress, interphase between particle and matrix on the stress–strain relationships. Ganesh and Chawla [5] studied the influence of the orientation anisotropy of the reinforcement on the mechanical behavior of MMCs. Mishnaevsky et al. [6,7] studied the influence of the particle distributions (gradient and cluster) on the mechanical properties of MMCs. Ekici et al. [8] studied the influence of particle size and volume fraction on the indentation response particle reinforced MMC. Sozhamannan et al. [9] studied the macroscopic response and the local stress/strain field of MMCs under tensile loading conditions using scanning electron microscope images. Yuan et al. [10] simulated the tensile stress–strain curve through the axisymmetric cell model consisting of interface, matrix and reinforced particle. Zhang et al. [11], Alberto [12] and Orbulov et al. [13,14] studied the effect of interphase on the macroscopic strength of metal matrix composites.

All the models mentioned above adopted the symmetric boundary condition, which is easy to apply but introduce extra face effects compared with the periodic boundary condition. There is no study, to the best knowledge of the author of this article, about the comparison of the simulation results from SBC and PBC. In this paper, a comparison study is performed to demonstrate the influence of SBC and PBC on the stiffness and strength properties of MMCs. A program is developed for the automatic generation of 2D micromechanical finite element models of multi-particle MMC with random particle arrangement. The stress triaxial indicator [15] and the maximum principal stress criterion based elastic brittle damage model are developed to simulate the damage

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processes in aluminum alloy matrix and SiC particles within Abaqus/Standard Subroutine USDFLD, respectively. Both PBC and SBC are implemented in multi-point constraints MPC within Abaqus/Standard Subroutine MPC. A series of computational experiments on the SiC-particle reinforced aluminum matrix composite is performed to study the influence of particle number, boundary conditions and particle volume fraction on the macroscopic stiffness, stress–strain relationships and damage evolution in both particle and matrix.

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

2.1. The generation of finite element RVE

In order to study the influence of the microstructures of composites on its deformation and damage evolution process, the microstructure of the material under consideration should be varied in a required way. In order to represent the microstructure of composites, Tursun et al. [4], Sozhamannan et al. [9] and Zhang et al. [16] applied the digital image technique, which requires special software, to generate the mesh data for simulation. Qing and Mishnaevsky [17–19], Wang et al. [20–22] and Peng et al. [23] generated the microstructure of composites through random movements of particles from their initial regular arrangement, such as hexagonal and/or square lattice arrangements.

Here, the microstructures with the random particles arrangement are generated using the random number generators. Both x and y coordinates of particle centers are produced independently and sequentially with two random number streams through two random number generator seeds [24]. 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 available particles is no less than a given distance related to the particle radius, meanwhile, particle should not be too close to the square boundaries. If the conditions are not met, the coordinates of the new particle are determined by next numbers of the two random number streams. If the surface of a particle cuts any of the square unit cell boundaries, the particle is copied to opposite side of the square unit and the above conditions has to be checked with the particles near the opposite surface because the microstructure of the composite RVE is periodic.

The above algorithm is called the random sequential adsorption method (RSAM) in some literature. A new program code is developed in order to realize the RSAM. The program can generate automatically the 2D micromechanical finite element models with identical circular SiC particles reinforced aluminum alloy. The program code developed in Matlab can generate a command file for the commercial software MSC/Patran. A 2D microstructural finite element model with pre-defined parameters (including the number and volume fraction of particles, interphase thickness, mesh seeds, two random number generator seeds controlling the particle distribution in RVE) is generated by playing the command file with MSC/Patran.

Fig. 1 gives three examples of the RVE generated with this algorithm, for the particle volume fractions equal to 15%, 25% and 35% and identical circular particle number with 100, 64 and 36, respectively. Fig. 2 shows three generated models with different mesh seeds along each particle boundary.

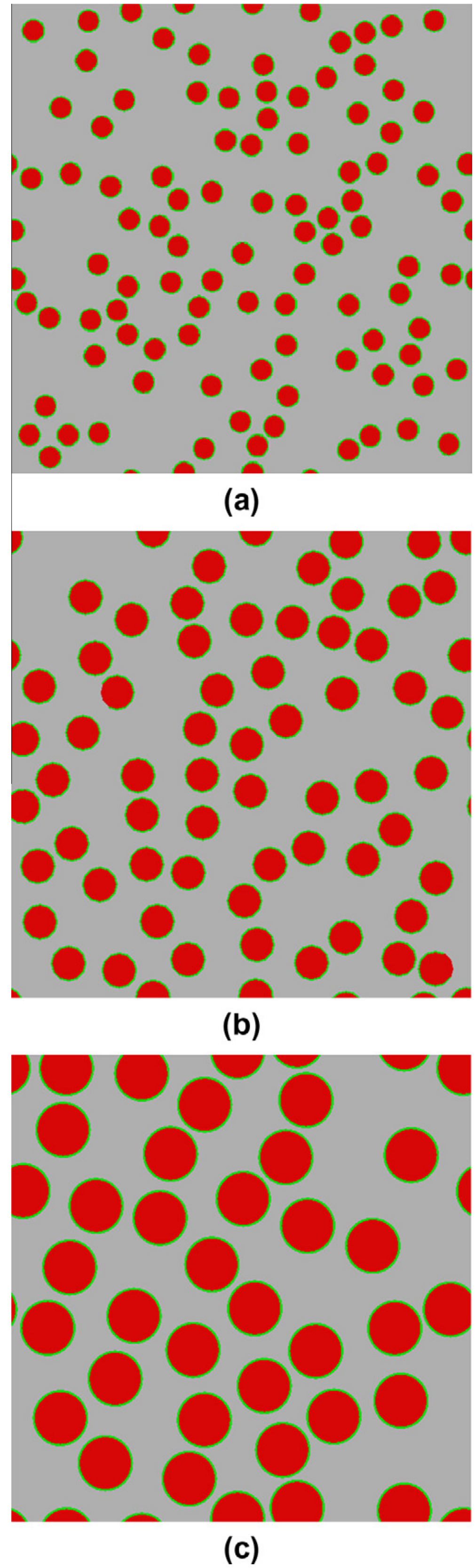

Fig. 1. 2D micromechanical RVE with the reinforcement volume content of: (a) 15% containing 100 particles, (b) 25% containing 64 particles and (c) 35% containing 36 particles.

2.2. Damage mechanisms and mechanical properties of phases

The degradation behavior of a material due to the initiation and evolution of damage is apparently the main failure mechanism, which should be taken into account for the SiC particle reinforced aluminum alloy composites. Three different failure mechanisms