AN ENHANCED FEM MODEL ON THE DEFORMATION BEHAVIOR OF SIC/ALUMINUM COMPOSITES

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1. INTRODUCTION

The development of high performance metal matrix composites (MMCs) requires understanding the complex effects of heterogeneous microstructure on the mechanical properties and failure mechanisms. Experimental observations [1] indicated that fine reinforcement particles increased the composite strengthen and work hardening capacity. A number of dislocation models [1,2] have been proposed in a few decades to predict the particle size dependence. Recently, Gao et al. [3] proposed a mechanism-based theory of strain gradient plasticity (MSG) to illustrate the plastic strain and strain gradient which is dissimilar to the phenomenological strain gradient plasticity theories [4,5]. Gao and Huang [6] developed a Taylor-based nonlocal theory (TNT) of plasticity to account for the size dependence of plastic deformation on the strengthening of particle reinforced composites. Qu et al. [7] have extended the conventional theory of mechanism-based strain gradient plasticity (CMSG) established from the Taylor dislocation model to explain the effect of quench hardening and account for particle/matrix interface debonding via the cohesive zone model (CZM). The numerical results agree well with Lloyd's experimental data [1]. Nan and Clarke [8] extended the effective medium approach (EMA) to demonstrate the influence of particle size and size distribution as well as particle fracturing on the deformation behavior of MMCs. Tohgo et al. [9] extended the incremental damage model of the MMCs by introducing the particle size effects using Nan–Clarke's simple method.

This paper presents the development of a 2D microstructure based finite element model to investigate the effect of particle size on the deformation behavior of the SiCp/Al composites. In the simulation, the two-dimensional randomly distributed multiparticles unit cell model is used. For modeling the matrix behavior of the composites, the Taylor-based nonlocal theory of plasticity is used. The model is enhanced by including contribution of interfacial decohesion and particle fracture damage mechanisms. The simulation provides the stress–strain field of composites during tensile deformation, and calculates the stress–strain curves of the composites with different particle size.

2. NUMERICAL METHODS

In this work we establish a 2-dimensional randomly distributed multiparticles unit cell model of MMC material, as shown in Fig. 1. The unit cell model with 15% SiC particle has an area of 100μm×100μm, which is 10 times the particle diameter in the smaller dimension. A 2D plane strain finite element model was used to conduct analysis of the microstructures using the commercial code ABAQUS/Explicit. The object oriented finite element program was used to generate 4-node quad element meshes on each microstructure. Approximately 3500 elements were used in the final meshes.

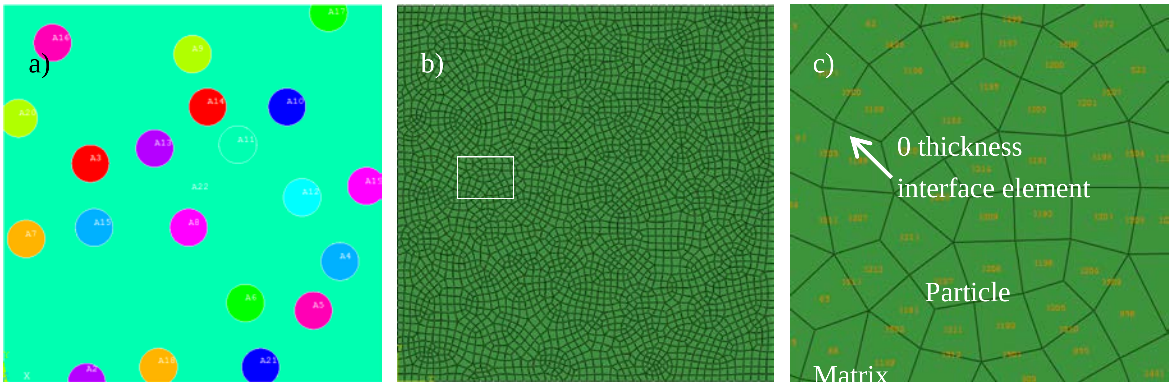

Fig. 1 (a) Unit cell model; (b) Finite element mesh for numerical calculations; (c) Local magnified.

The boundary conditions are defined as[10]: $u_x = 0$ at the left surface, $u_y = 0$ at the bottom surface without rotate; the displacement load u_x is applied at the right surface with max strain 5%; all nodes at the top surface have a common unknown u_y. The numerical true stress–strain curves in the tensile direction of the composites in the unit cell, which are compared with experimental results, are calculated by reaction force on right surface.

2.1. Material properties

In this work, the SiC particles have average diameters of 1μm, 2μm, 5μm, 10μm and 20μm. The matrix alloy is 6061 aluminum alloy. The SiC particles were modeled as perfectly elastic with a density of 3.2 g/cm^3, elastic modulus of 427 GPa and Poisson's ratio of 0.17. The material behavior of the 6061 aluminum matrix after T6 aging heat treatment was elastic–plastic, with a density of 2.67 g/cm^3, Young's modulus of 70 GPa, Poisson's ratio of 0.33 and initial yield strength of 269.1 MPa.

2.2. Progressive damage and failure mechanisms

Damage mechanisms in MMCs include void nucleation and growth in the matrix, interface decohesion and failure, and brittle fracture of the reinforcement particles. Matrix damage was included using the maximum principal stress criterion. Cohesive zone elements with zero thickness were inserted to model progressive damage and failure of the metal matrix–particle interface. The constitutive behavior of the cohesive elements was modeled using a biliner traction–separation law. In this work a quadratic nominal stress criteria was considered for damage initiation.

Particle fracture was included using the Griffith criterion to calculate the size dependent strength of the SiC particles in which the fracture stress is given by

$$\sigma_c^p = \frac{K}{\sqrt{d}}$$

where K is a constant related to the fracture toughness of the ceramic that takes into account geometrical factors. The K has liner relationship with the metal matrix strength [4]. The particle strength was calculated to be 800 MPa using the average particle diameter of 9um and 2.4 MPa$\sqrt{\text{m}}$ for SiC in A356-T4 matrix [7]. Then SiC strength in 6061-T6 maxtix can be calculated by metal matrix strength, 4.25 MPa$\sqrt{\text{m}}$.

3. RESULTS AND DISCUSSION

Fig. 2 shows the contour plots of Von Mises effective stress distribution. It can be seen that there is a great plastic stress gradient in the matrix. The plastic strain localizes into distinct bands that are oriented at approximately 45◦ to the loading direction. Compared with matrix, the distribution of Von Mises effective stress in particles are relatively homogeneous. From Fig. 2a~2d, high stress can be observed on the edge of particles. It is noted that stress on particle decreases with particle size increasing by comparing among these figures. It also can be observed that crack count and size increase with particle size increasing. When particle size increase to 20μm, particle fracture and interfacial decohesion can be seen and no crack yield in matrix. This phenomenon means damage mechanism is transformed from the nucleation and growth of voids in the matrix to interface decohesion and fracture of reinforcement particles with particle size increasing.

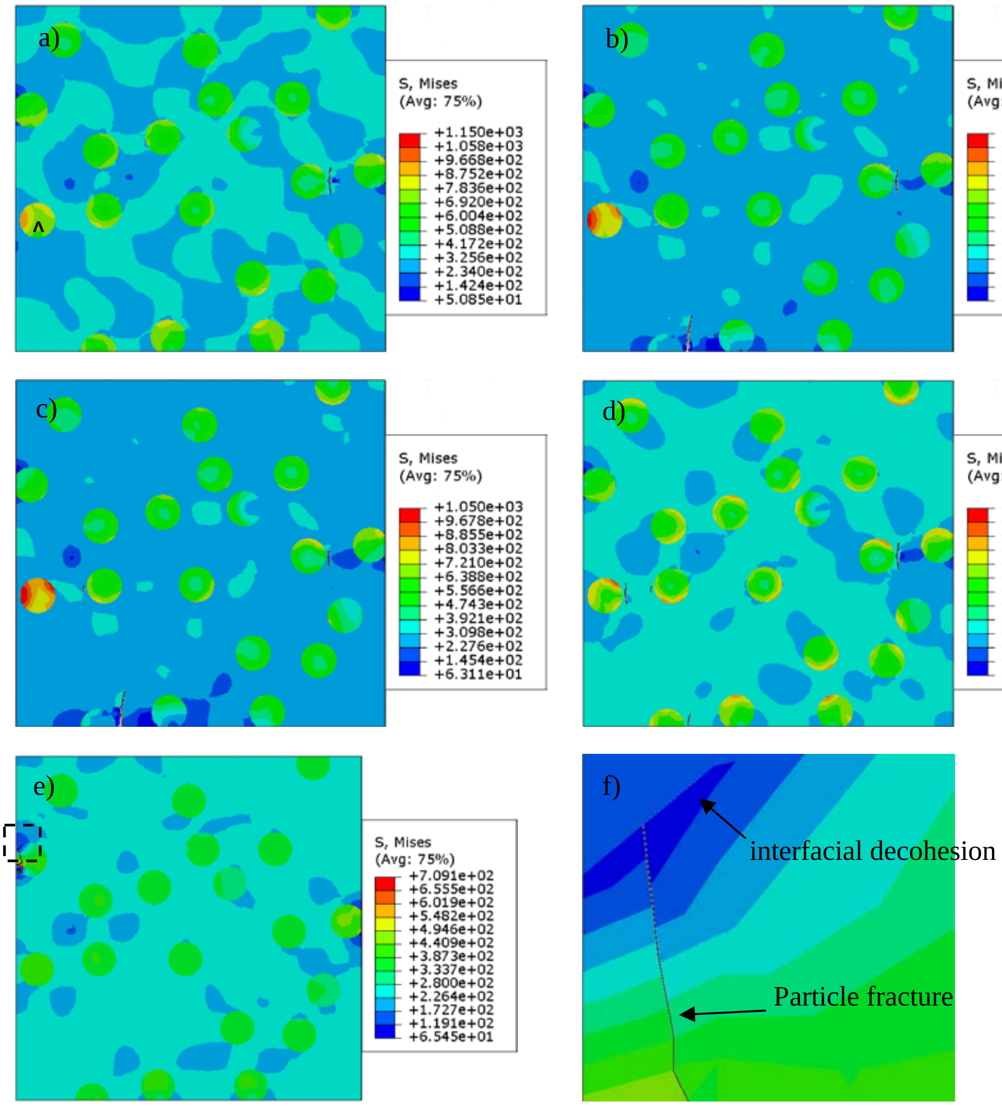

Fig. 2 Contours of von Mises equivalent plastic stress

(a) 1μm ε_{xx} = 3.5%; b) 2μm ε_{xx} = 3.5%; c) 5μm ε_{xx} = 3.25%;

d) 10μm ε_{xx} = 3.5%; e) 20μm ε_{xx} = 0.35%; f) 20μm local magnified.

Fig. 3 shows the comparison of the predicted stress–strain curves with different particle sizes. It can be seen that the calculated flow stresses are noticeably lower than experimental results, as shown in Table 1. The difference in stress between the simulation and the experiment is 16MPa at a strain of 0.2%. It can be seen on 10μm SiCp/Al curve that crack generates when global strain is about 3%. It is noted that this global strain value is similar with experimental elongation which is 3.2% [11]. With particle size increase, particle fracture would be the main damage mechanism. It can be observed that particle fracture occur at low global strain. It means that particle size increasing would be harmful for elongation.

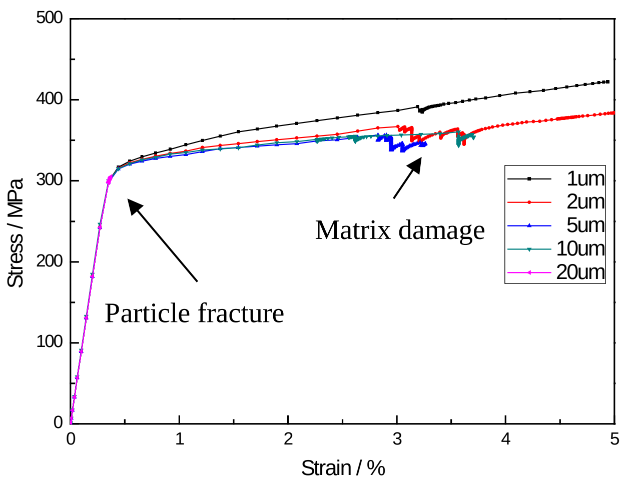

Fig. 3 Tensile stress–strain curves for the particles embedded in the unite cell.

Table 1 Properties of 10μm SiCp/Al composite from simulation and experiment

Method	Elastic modulus /GPa	Yield strength /MPa
Simulation	92	326
Experiment [11]	91	342

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