Materials Science & Engineering A 731 (2018) 351–359

Contents lists available at ScienceDirect

Materials Science & Engineering A

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

The influence of particles size and its distribution on the degree of stress concentration in particulate reinforced metal matrix composites

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ARTICLE INFO

Keywords:
Fracture toughness
Finite-element analysis
Particle size
Metal matrix composites

ABSTRACT

In this work, the degree of stress concentration in particulate reinforced metal matrix composites (PRMMCs) is investigated by finite element analysis method. It is found that, besides the particle morphology, particle size and its distribution can also remarkably influence the stress distribution of the composites, especially that in the matrix. The results indicate that the particles will bear more loads in the composites reinforced by irregular particles than those reinforced by spherical ones and the stress concentration in the matrix near the particle angularity is more serious. As to the particle size, the degree of stress concentration in the matrix will be reduced with the decrease of the size, while the size distribution has greater influence on that than the size itself. The calculated standard deviation of the stress indicates that the degree of stress concentration in matrix in multi-size particles reinforced models is obviously weaker than that in single-size particles reinforced models. Therefore, changing the size distribution is more effective to reduce the degree of stress concentration in the matrix and can be used to improve the fracture toughness of PRMMCs. It is considered that the results could be helpful for design better performance PRMMCs by controlling the ratio of particles with different sizes.

1. Introduction

Particulate reinforced metal matrix composites (PRMMCs), a subgroup of metal matrix composites (MMCs), have received substantial attention and widely applied in various fields in recent decades because of their excellent properties, such as high specific stiffness and strengths [1,2], outstanding frication [3] and high wear resistance [4–6], high electrical and thermal conductivity [7], and high temperature mechanical behavior [8–10]. Also, manufacturing flexibility and cost-effectiveness are two other powerful driving forces for widespreading industrial applications of PRMMCs since they can be machined with the majority of traditional manufacturing processes designed for metals [11]. However, the addition of the particles will also result in the degradation of ductility, fracture toughness and low-cycle fatigue properties, which limits its application [12].

For the time being, the fracture toughness and its improvement in PRMMCs has attracted much attention. The initial purpose to fabricate PRMMCs is combining the beneficial stiffness of ceramic with the superior ductility and toughness of metal. However, this combination produces relatively lower ductility and toughness in composites as compared to the matrix metal. The huge difference of mechanical parameters, such as elasticity modulus, between reinforced ceramic particles and matrix lead to uncoordinated deformation in composite, which promote stress concentrated area in reinforced particles, interface and near interface areas, for the reason of poor ceramic deformability, low interface combination strength and difference of material characteristics, respectively. In this case, three different types of fracture may be occurred in PRMMCs: reinforcement particle cracking, interface failure and near interface matrix failure [13–15]. Accordingly, fracture toughness will be influenced by particles volume fraction, size, shape, distribution and the interface character between particles and the matrix [15–18]. For example, the previous investigations on SiC and Al_2O_3 particulate reinforced Al composites have shown the decreasing trend of fracture toughness with increase of volume fraction of reinforcement particles [19,20]. Li and Zhou [21] devised a modified analytical model which allows the possible range of fracture toughness values to be predicted as function of microstructure and found that increase of interface debonding can result in higher fracture toughness. This fracture mechanism can be promoted by decreasing the reinforcement size and increasing its volume fraction in the dilute situation (volume fraction < 35%).

No matter which way, it is considered that the fracture of materials is due to the initiation and propagation of cracks, while the stress concentration is the key for the crack initiation and propagation. As for

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https://doi.org/10.1016/j.msea.2018.06.067
Received 19 April 2018; Received in revised form 13 June 2018; Accepted 16 June 2018
Available online 19 June 2018

PRMMCs, when the load is applied, it has been found that there will be serious stress concentration near interface between the reinforced particle and matrix, which will impose an adverse impact on interface and result in the cracks initiation and propagation. Therefore, figuring out the degree of stress concentration is important for understanding the fracture behavior of PRMMCs.

In this paper, based on the cohesive zone model, the widely used and studied SiC particle-reinforced Al matrix composite is chosen as the model system to study the stress distribution in PRMMCs by finite analysis. During studying the distribution of stress in PRMMCs, the models with particles randomly dotted in matrix are commonly used. As mentioned above, the particles size in particle reinforced composite is vital for the properties and have been investigated by many works. In addition, the particles size distribution which can change the distribution of stress and strain, and ultimately influence the properties, especially the fracture toughness, have also drawn wide attention [22–24].

Therefore, both single-size and multi-size particles reinforced models have been used in this study. And the influence of particle size and its distribution on the degree of stress concentration is primary investigated. It is considered that the results could be helpful for understanding how the fracture toughness be affected by the particles size distribution (PSD) and give some guidance for the design and manufacturing of better performance PRMMCs.

2. Modeling and simulation

In practice, PRMMCs are usually enhanced by particles with different sizes and morphologies. Fig. 1 shows the microstructures of several kinds of PRMMCs. Among them, TiB_2/Cu, TiC/Cu and TiC/Al composites shown in Fig. 1a, b and d are prepared by melt reaction method. During the preparation, the boron and carbon sources which are Cu-5 wt%B master alloy and graphite (< 15 µm, 99.5% pure) are added into the Cu-Ti or Al-Ti melts at 1150–1250 °C and then the melts are poured into the mold to obtain the composites. The SiC/Al composite shown in Fig. 1c is prepared by powder metallurgy method. Firstly, SiC and Al powder (SiC < 30 µm, 99.9% pure, Al powder < 30 µm, 99.9% pure) is mixed using powder mixing machine at 30 rpm for 30 min in order to make the mixture homogenous. Then, the SiC-Al powder mixture is sintered at 700 °C for 1.5 h under a pressure of 20 MPa in a vacuum hot pressure sintering furnace. It can be seen that the reinforced particles are distributed in the matrix disorderly, while the particle size is commonly inhomogeneous and the size distribution is varied in different samples. In this work, part of the sample shown in Fig. 1d is chosen as the prototype to build the simulation model and the details for establishing the models will be given in the following section.

Table 1
Material parameters of SiC particle and Al matrix.

	Elastic modulus (Gpa)	Poisson ratio	Density (g/cm^3)
Al	86	0.36	2.70
SiC	410	0.14	3.1

The two-dimensional model adopts the SiC/Al composite material system, and its material parameters are shown in Table 1. The eight-node quadrangle element (PLANE183, ANSYS) is employed to mesh models, and the element near the interface is divided as small as possible to improve the accuracy. Meanwhile, the calculation of convergence and operation time is taken into consideration after trial test and comparison, which aimed to set the mesh density more reasonable. The interface simulation adopts the widely used cohesive element, and the parameter setting of finite element INTER203 is shown in Fig. 2 [25].

The uniaxial tensile behavior of particle-reinforced composites is mainly studied in this paper. Considering the actual situation, boundary conditions (BCs) are set as follows:

$$u_x = -n^*L/2 \text{ on } x = 0, \quad u_x = n^*L/2 \text{ on } x = \text{L}. \tag{1}$$

where u_x is component of the displacement vector u along x-direction, n is the specific displacement coefficient to the x-direction, and it is set as 1% in all these simulations. L is the length of the cubic model, which is settled as 20 µm. In brief, the boundary conditions means that the lines x = 0 and x = L are maintained straight and move parallel with respect to its original shapes under loading.

3. Results and discussion

As mentioned above the sample shown in Fig. 1d is chosen as the prototype to build the simulation model as shown in Fig. 3, In order to establish the analysis model, the particle number and particle size of the prototype are firstly counted. The size distribution is shown in Fig. 4a and it is calculated that the particle volume fraction is about 27.58%. In order to study both the single-size particles and multi-size particles

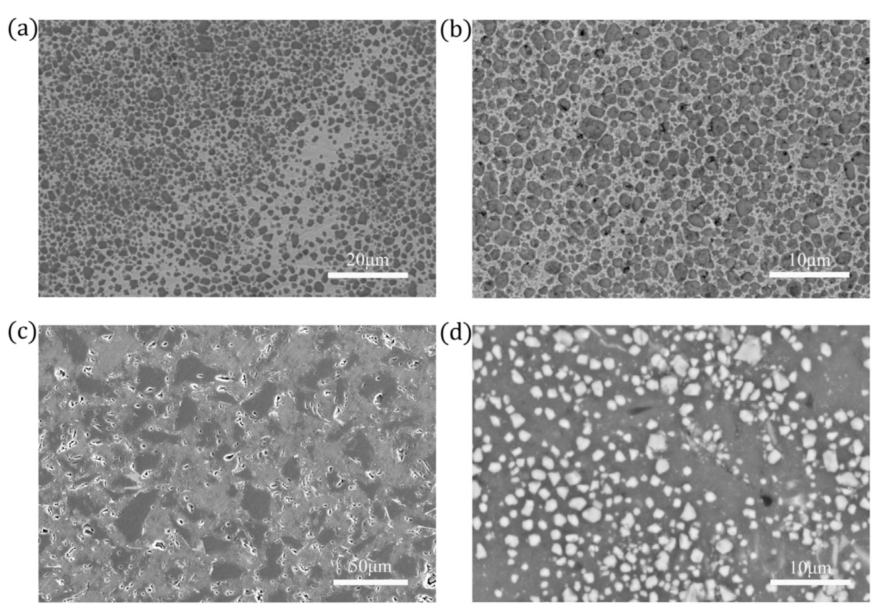

Fig. 1. Microstructure of different PRMMCs (a) TiB_2/Cu;(b) TiC/Cu;(c) SiC/Al;(d) TiC/Al.