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Prediction of interfacial strength and failure mechanisms in particle-reinforced metal-matrix composites based on a micromechanical model

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ABSTRACT

The interfacial strength and failure mechanisms of particle-reinforced metal-matrix composites were predicted using a micromechanical model. The micromechanical model was constructed based on the cohesive zone model, and the spherical particle was arranged on the body-centered cubic distribution. The SiC particle-reinforced Al matrix composite was chosen as the model system and its interfacial properties was predicted. It can be seen that a complete interfacial debonding all over the particle could never be reached, and the plastic strain of composite when the interfacial debonding begins to appear shows an increase trend with the increasing of interfacial strength.

1. Introduction

Particle-reinforced metal-matrix composites, especially aluminum matrix composites, have been widely used in aerospace and other industries as structural materials [1]. Ceramic particles, which are some of the most widely used materials for reinforcing aluminum matrix, improves the stiffness and strength of the reinforced matrix while conserving a quasi-isotropic nature and traditional manufacturing techniques for casting metal. In this way, the hardness can be improved considerably with direct impact and wear behavior. A widely used particle for reinforcing aluminum matrix is silicon carbide (SiC). Besides its density being slightly higher than the density of aluminum, it is among the widely used due to its low cost and its wide range of available grades [2]. The SiC reinforcement promotes an increase in the elastic modulus and tensile strength of the aluminum matrix composites, and another improvement of composites regarding the aluminum matrix is the behavior at high temperature. In addition, the mechanical properties of particle-reinforced composites are determined by the morphology [3,4], size [5], volume fraction [6] and distribution [7] of particles, and the materials characteristics of the matrix and particle. Numerical simulation based on the microstructure of composites has become increasing important tool to understand the mechanical behavior of particle-reinforced composites with the development of the finite element model and computation power [8]. Furthermore, the numerical simulation techniques are often more effective than analytical modeling for such multiphase materials since the complex structures of these materials are not suitable for closed-form theoretical analysis.

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Nomenclature

A	area
D	scalar damage variable
$\boldsymbol{D}$	stiffness tensor
E	elastic modulus
$\boldsymbol{K}$	elastic properties for the interface element.
V	volume fraction of particles
n	element number
r	particle radius
R	length of representative volume element
T	thickness of the interface element
t	surface traction
u	displacement vector
U	displacement constant
v	Poisson's ratio
σ	normal traction
τ	shear traction
δ	separation
ϕ	fracture energy

The interfacial debonding plays a key role in determining the ductility and toughness of a wide variety of particle-reinforced metal-matrix composites. Once the interfacial debonding occurs, small voids may nucleate, and subsequently the voids grow by plastic deformation of the surrounding matrix material until they eventually coalesce [9,10]. The complete experimental study of the effect of the material properties on the interfacial debonding process in particle-reinforced composites is unfeasible. A predictive modeling with interfacial debonding is becoming increasingly important as a cost-effective method for design of particle-reinforced composites. Since the particles are not uniform in size, and are dispersed in an irregular pattern throughout the matrix, a well established approach for predicting the macroscopic mechanical behavior of these morphologically complex three-phase systems relies on the introduction of a spatially periodic representative volume element. The interface or cohesive models are ideal tools to study the interfacial debonding progress in the composites. The basic idea for such models can go back to Dugdale [11] and Barenblatt [12]. These models relate traction to the relative displacement at an interface where a crack may occur and damage initiation is related to an interfacial strength. When the area under traction–separation curve is equal to the critical fracture energy, the traction is reduced to zero and complete crack surfaces are formed. Furthermore, various cohesive zone models have been proposed to study the growth of crack and the debonding of interface [13,14].

A few numerical micromechanical investigations have been carried out to interface properties and interfacial debonding in the particle-reinforced composites. Xu and Needleman [15] presented a numerical micromechanical study of interfacial debonding in the rigid particle-reinforced crystal matrix composites using the continuum-interface model. Based on the same interface model, Charles et al. [16] further analyzed the interface debonding in particle-reinforced metal-matrix composites. Segurado and LLorca [17] studied the interface properties in a model composite made of a random distribution of stiff spherical particles embedded in a ductile matrix based on a new cohesive crack model. Tsui et al. [18] used a three-dimensional unit cell model to predict the debonding damage process of particle-reinforced polymer composites. Kang et al. [19] discussed the effect of interfacial bonding state between particle and matrix on the ratchetting of SiC particle-reinforced composites in uniaxial cyclic stressing at room temperature. Romanova et al. [20] performed a finite difference modeling of interface strength effects on the deformation of a metal-matrix composite. While the researchers have made many efforts to study the interfacial debonding in the particle-reinforced composites, the interfacial strength and the debonding process have not been predicted very well. Therefore, it is required to develop an effective prediction model of the interfacial debonding in the particle-reinforced composites.

The objective of the present work is to predict the interfacial properties and the interfacial failure mechanisms of particle-reinforced metal-matrix composites using a micromechanical model. The micromechanical model is constructed based on the cohesive zone model (CZM) and the spherical particle is arranged on the body-centered cubic distribution. The SiC particle-reinforced Al matrix composite is chosen as the model system and its interfacial properties is predicted. In addition, the effect of interfacial properties on the interfacial debonding of composite is also investigated.

2. Numerical modeling

2.1. Micromechanical model

In the real particle-reinforced composites, the particle distribution is typically random in the filled matrix, although particles are expected to be distributed uniformly. For the micromechanical modeling of particle-reinforced composites, one can