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Analysis of the stress states and interface damage in a particle reinforced composite based on a micromodel using cohesive elements

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ABSTRACT

In this work, uniaxial tensile loading was simulated to explain the effect of the interface and varying particle shapes in particle reinforced composite models based on experiments. The cohesive element technique was applied alongside an ABAQUS user-subroutine UVRAM. The effect of the interface thickness and strength were also considered. The simulation results for various stress states (such as stress triaxiality, soft coefficient and Lode parameter) and the interface degradation Scalar Stiffness Degradation Variable (SDEG) were analyzed in detail. The particle shape and interface geometry strongly influenced the distribution of stress states, eventually influencing the integrity of the particle reinforced composites. Particles with a large aspect ratio that were also perpendicular to tensile loading direction were easy to crack, while those with a smaller aspect ratio were prone to interface debonding from particle poles.

1. Introduction

Particle reinforced composites are well known because they have promising features, such as high strength, low density and wear resistance [1–3], that have led to their widespread application. However, their low fracture toughness and ductility has hindered their extensive usage. The micro/macroscopic behavior of these composites is explained in detail in Refs. [4–7]. The mechanical properties of these materials are governed by factors including particle size [8–11], particle shape [12–15], particle orientation [16], local volume fraction [17], nearest neighbor particle distance [18], nearest neighbor orientation [19,20], spatial distribution [21,22], etc.

In contrast to macroscopic study, microscopic study has revealed that certain factors, including the particle, matrix and interface, are important when determining various key characteristics [7,23]. To date, different particle shape models have been applied during Finite Element Analysis (FEA). The most commonly used methods include the Representative Volume Element (RVE) [13,24], the Voronoi Cell method [14], Real Morphology model in 2D [22] and the Serial Section Technology (SST) that is also used to construct a three dimensional finite element model and is more similar to the real material [14,17,18,22,25,26]. As displayed in Fig. 1, the metal matrix composite (MMC) simulation model is plotted as a RVE model.

In the MMC of Al–SiC, the SiC particles are load bearing under certain loading conditions, including particle fracture, that are in accordance with the Weibull statistical distribution [11,12,19,26–29]. The higher the overall SiC particle content under the same applied stress is, the higher the particle fracture volume fraction is. Fracture toughness and ductility also correspond to the SiC particle volume fraction and the increasing SiC particle volume fraction, as well as decreased ductility and fracture toughness. Particle size also contributes to the aforementioned mechanical properties. Ductility and fracture toughness decrease when the SiC particle size decreases. Qin et al. [15] has reported that particle shape dramatically affects the thermal residual stress and strain fields in composites. Zhao et al. [12,28] have considered two types of partial debonding configurations: one on the top and bottom of the aligned oblate inclusion and one on the lateral surface of the prolate ones with a special reference for spherical inclusion. Using a Cohesive Zone Type model, Needleman [30,31] studied the process of void nucleation via inclusion debonding. Maire et al. [32] have revealed that initially elongated particles are easy to crack before debonding the particle matrix interface particles that are characterized by high aspect ratios, large sizes and low local volume fractions. Kim and Lee [33] have proposed a micromechanics-based elastic-damage model that accounts for cumulative damage and predicts the effective stress–strain response. A multi-step damage process is introduced to model accumulated damage induced by interfacial debonding in the particulate composites. Li [26] has found that larger particles in particle-rich regions are

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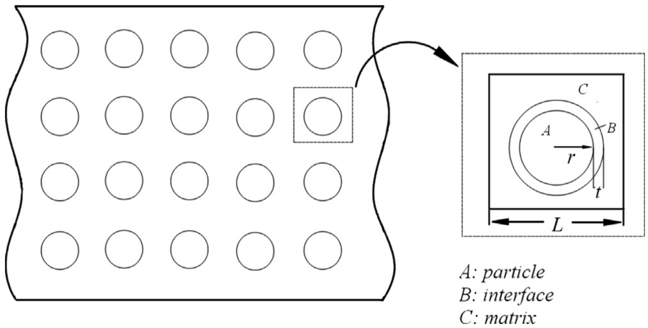

Fig. 1. The simulation model of MMC.

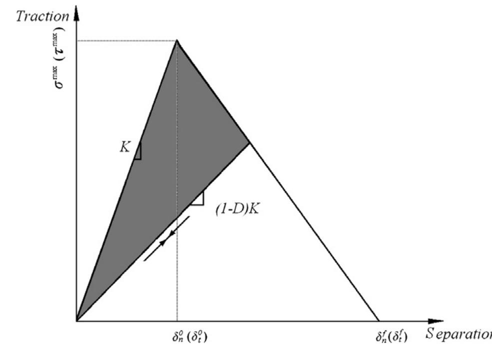

Fig. 2. The bilinear cohesive zone model [23].

more susceptible to cracking than those in sparse regions, while the spatial distribution of the particles is more important when assessing damage than particle size is for MMCs.

2. Theory and experiments

2.1. Cohesive zone models

Cohesive Zone models are used to explain the failure mechanism involved in MMCs. Cohesive damage–cracking processes use a traction–displacement relationship to describe the cohesive element model by applying the model forms (bilinear, trapezoidal, exponential and so on.) [21,29]; this Traction–Separation Law is presented in Fig. 2.

The traction–separation response is explained relative to the critical interface strength; this parameter is the free cohesive energy potential of separation per unit area, specifically cohesive energy ϕ, and equals the area enclosed by the cohesive curve and the horizontal axis.

$$\vec{T} = \frac{\partial \phi}{\partial \vec{\delta}} = \frac{\partial \phi}{\partial \delta_n} \cdot \vec{n} + \frac{\partial \phi}{\partial \delta_t} \cdot \vec{t} = T_n \cdot \vec{n} + T_t \cdot \vec{t} \tag{1}$$

here $\vec{n}$ and $\vec{t}$ represent the normal and tangential directions, respectively, while δ_n and δ_t are the corresponding directions for the opening displacements over the cohesion. An effective opening displacement can be defined as follows:

$$\delta = \sqrt{\delta_n^2 + \delta_t^2} \tag{2}$$

The bilinear traction–separation model can be described as follows:

$$T_n = \begin{cases} \frac{\sigma_{max}}{\delta_n^0}\delta & \text{for} \quad (\delta < \delta_n^0) \\ \frac{\delta_n^f - \delta}{\delta_n^f - \delta_n^0}\sigma_{max} & \text{for} \quad (\delta_n^0 < \delta < \delta_n^f) \\ 0 & \text{for} \quad (\delta_n^f < \delta) \end{cases} \tag{3a}$$

$$T_t = \begin{cases} \frac{\tau_{max}}{\delta_t^0}\delta & \text{for} \quad (\delta < \delta_t^0) \\ \frac{\delta_t^0 - \delta}{\delta_t^f - \delta_t^0}\tau_{max} & \text{for} \quad (\delta_t^0 < \delta < \delta_t^f) \\ 0 & \text{for} \quad (\delta_t^f < \delta) \end{cases} \tag{3b}$$

where T_n and T_t correspond to a separation distance δ when the separation is purely normal or tangential, respectively. The bilinear relations for solving the cohesive element softening relationship include the following: when the plastic zone crack tip displacement is below the damage threshold, i.e., the separation distance is expressed as $\delta < \delta^0$, and the applied stress is expressed as $\sigma = K\delta$; for $\delta^0 < \delta < \delta^f$ the applied stress is $\sigma = (1-D)K\delta$, where D is the scalar damage variable that is defined as follows [34]:

$$D = \frac{\delta_m^f(\delta_m^{max} - \delta_m^0)}{\delta_m^{max}(\delta_m^f - \delta_m^0)} \tag{4}$$

where δ_m^{max} refers to the maximum value of the effective displacement attained during the loading history and δ_m^f can be obtained through using the final separations. Within the cumulative damage variable D ranging from 0 to 1, the cohesive element represents a complete loss of traction at the critical separation distances δ_n^f and δ_t^f under normal and tangential cases. When the cohesive release energy reaches the energy damage threshold, local micro-damage will occur; the cohesive zone will enter the softening stage, and the overall stiffness weakening coefficient Scalar Stiffness Degradation Variable (SDEG), which describes the overall scalar damage variable D [34], will decrease gradually. When D equals 1, it is called the elemental loss of traction and the separation distance is expressed as $\delta > \delta^f$; SDEG is 1, corresponding to the maximum traction at the crack nucleation point σ^{max}.

2.2. State of stress parameters

To describe the deformation stress states, three parameters are adopted:

$$R_\sigma = \frac{\sigma_m}{\sigma_{eq}} = \frac{(\sigma_1 + \sigma_2 + \sigma_3)/3}{\frac{1}{\sqrt{2}}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}} \tag{5 – a}$$

$$R_\alpha = \frac{(\sigma_1 - \sigma_3)}{2[\sigma_1 - \nu(\sigma_2 + \sigma_3)]} \tag{5 – b}$$

$$\mu_d = \frac{2(\sigma_2 - \sigma_3)}{(\sigma_1 - \sigma_3)} - 1 \tag{5 – c}$$

where $\sigma_1 \geq \sigma_2 \geq \sigma_3$ are the three principal stress, σ_m and σ_{eq} are the hydrostatic stress and equivalent Von Mises stress, respectively, and ν is Poisson's ratio. According to the microscopic mechanism, stress triaxiality (R_σ) describes the advantages of the void mechanism over the shear mechanism during material deformation. For the high triaxiality stress, the void mechanism dominates such that the voids expand faster in deformed materials. When the triaxiality stress is low and the shear strain is high, the shear mechanism will dominate. When R_σ is positive, the deforming material tends to be in the tensile state, allowing the microcracks to grow; however, when R_σ is negative, it tends to be in a compressive state, causing the microcracks to close. R_σ ranges from $-\infty$ to $+\infty$, and its characteristic values are 1/3 for uniaxial tensile stress $(\sigma, 0, 0)$ with $\sigma > 0$, zero for pure shear $(\sigma, -\sigma, 0)$, and $-1/3$ for uniaxial compression $(\sigma, 0, 0)$ with $\sigma < 0$. For the entirely hydrostatic stress states (σ, σ, σ), $R_\sigma = \pm 1$ depends upon whether σ is greater or less than zero [35,36]. The soft coefficient R_α represents the 'soft' and 'hard' stress states. Larger R_α values