8th. World Congress on Computational Mechanics (WCCM8)
5th. European Congress on Computational Methods in Applied Sciences and Engineering (ECCOMAS 2008)
June 30 – July 5, 2008
Venice, Italy

THREE DIMENSIONAL (3D) MICROSTRUCTURE-BASED MODELING OF INTERFACIAL DECOHESION IN PARTICLE REINFORCED METAL MATRIX COMPOSITES (MMCs)

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Key Words: *Metal matrix composite, interfacial decohesion, finite element method, cohesive crack model.*

ABSTRACT

The design and development of high performance materials requires a thorough understanding and careful control of microstructure and its effect on properties. This is particularly challenging given the multiphase and heterogeneous nature of most high performance composite materials. Particle reinforced metal matrix composites (MMCs) are an important class of composite materials. These lightweight materials exhibit extremely high specific modulus, strength, and fatigue resistance, relative to conventional metals such as aluminum or titanium. Conventional analytical and numerical techniques have been developed and employed to understand the deformation behavior of particle reinforced composites. It is well known that microstructural complexities such as the inhomogeneous spatial distribution of particles, irregular morphology of the particles, and anisotropy in particle orientation after secondary processing, such as extrusion, significantly affect deformation behavior. Accurate prediction of macroscopic deformation behavior and an understanding of localized damage mechanisms can be accomplished by capturing the microstructure of the material as a basis for the model.

In this paper we examined the role of particle/matrix interfacial decohesion using actual microstructures, obtained from a 3D serial sectioning approach, Fig. 1. Simplified models, consisting of perfect ellipsoids and spheres (while maintaining the distribution of the particles constant) were also employed. It will be shown that 3D microstructure-based modeling approaches provide a quantitative understanding of localized damage phenomena, as well as excellent correlation to macroscopically-measured experimental behavior.

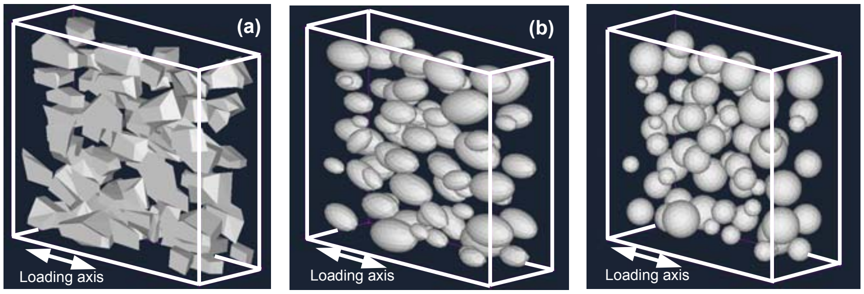

Figure 1. 3D models of SiC particle reinforced Al: (a) actual microstructure, (b) ellipsoid particles, and (c) spherical particles.

The tensile behavior of the three models was simulated using Finite Element Method (FEM). The model volume (matrix and reinforcing particles) was meshed using modified 10-node tetrahedral (C3D10M in Abaqus) using an adaptive automatic meshing algorithm. The modified elements contain an extra internal degree of freedom, and provide higher accuracy to reproduce the strain gradient in the matrix between closely-packed particles. Moreover, special care was taken to ensure that the matrix discretization between particles contained at least two element layers. 6-node interface elements, compatible with the C3D10M solid elements in Abaqus, were inserted at the surface of all the spherical particles to simulate interface decohesion. The particles behaved as elastic, isotropic solids characterized by their elastic modulus E_s= 410 GPa and Poisson's ratio ν_s= 0.20. The matrix was modeled as an isotropically hardening elastic plastic solid following the incremental (J2) theory of plasticity, and the total matrix strain was given by the sum of the elastic and plastic strain components. The matrix elastic constants were E_m = 74 GPa and ν_m = 0.30, and the isotropic matrix hardening during plastic deformation was given by the expression:

$$\sigma_m^{eq} = A\left[\varepsilon_m^p\right]^n$$

σ_m^{eq} is the Von Mises equivalent stress and ε_m^p stands for accumulated plastic strain. The constants A = 400 MPa and n = 0.15 are typical of an Al alloy matrix reinforced with ceramic particles. Interface decohesion was simulated using the interface elements through a cohesive crack model, where the normal and tangential stress transferred by the interface were derived from a potential Φ given by:

$$\Phi\left(\Delta u_n, \Delta u_{t1}, \Delta u_{t2}\right) = \Delta u_c \int_0^{\lambda} \sigma\left(\lambda'\right) d\lambda'$$

where Δu_n, Δu_{t1} and Δu_{t2} stand for the normal and tangential relative displacements between the crack faces, and Δu_c is the critical normal (or tangential) displacement between the crack faces at which all interaction vanishes. λ is the generalized crack opening displacement expressed as:

$$\lambda = \sqrt{\left(\frac{\Delta u_n}{\Delta u_c}\right)^2 + \left(\frac{\Delta u_{t1}}{\Delta u_c}\right)^2 + \left(\frac{\Delta u_{t2}}{\Delta u_c}\right)^2}$$

The function $\sigma(\lambda)$ (which stands for the normal stress transferred through the crack in the absence of tangential displacements) is plotted in Fig. 2. The interface behavior is given by the interface strength, t_c, and the fracture energy, Γ_i, which is the area enclosed under the $\sigma(\lambda)$ function:

$$\Gamma_i = \frac{1}{2} t_c \Delta u_c$$

Results of the simulations using the cohesive zone elements to model interface decohesion will be presented. The effect of particle shape and distribution will be discussed.

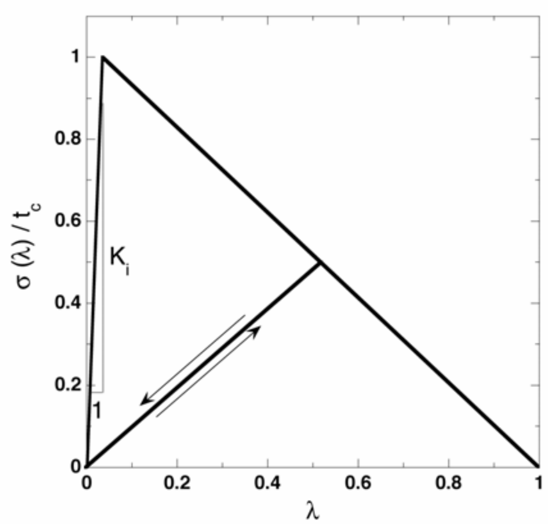

Figure 2. Cohesive traction law in terms of normal stress versus crack opening displacement.