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The effect of microstructural morphology on the elastic, inelastic, and degradation behaviors of aluminum–alumina composites

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ABSTRACT

Micromechanical models with idealized and simplified shapes of inhomogeneities have been widely used to obtain the average (macroscopic) mechanical response of different composite materials. The main purpose of this study is to examine whether the composites with irregular shapes of inhomogeneities, such as in the aluminum–alumina (Al–Al_2O_3) composites, can be approximated by considering idealized and simplified shapes of inhomogeneities in determining their overall macroscopic mechanical responses. We study the effects of microstructural characteristics, on mechanical behavior (elastic, inelastic, and degradation) of the constituents, and shapes and distributions of the pores and inclusions (inhomogeneities), and thermal stresses on the overall mechanical properties and response of the Al–Al_2O_3 composites. Microstructures of a composite with 20% alumina volume content are constructed from the microstructural images of the composite obtained by scanning electron microscopy (SEM). The SEM images of the composite are converted to finite element (FE) meshes, which are used to determine the overall mechanical response of the Al–Al_2O_3 composite. We also construct micromechanics model by considering circular shapes of the inhomogeneities, while maintaining the same volume contents and locations of the inhomogeneities as the ones in the micromechanics model with actual shapes of inhomogeneities. The macroscopic elastic and inelastic responses and stress fields in the constituents from the micromechanics models with actual and circular shapes of inhomogeneities are compared and discussed.

1. Introduction

The overall response of aluminum (Al)–alumina (Al_2O_3) composites depend on the microstructural characteristics of the composites, such as composition and distribution of the constituents, amount of the porosity, size and shape of the micro-constituents, which are strongly influenced by the processing methods. Another factor that could influence the mechanical properties and performance of Al–Al_2O_3 composites is the residual stress. The residual stresses can arise due to temperature changes during the composite processing, which in this case are known as thermal stresses. High thermal stresses can cause yielding in ductile constituents such as in the aluminum, while high tensile thermal stresses can induce cracking in the brittle constituents such as alumina. Both plasticdeformation and cracking of micro constituents can affect the overall mechanical properties and performance of the composites.

In order to understand the effects of different microstructural characteristics and behaviors of different constituents on the overall performance of composites, micromechanical models are often used. There have been several micromechanical models formulated for predicting the overall mechanical properties of metal–matrix composites. Most of these micromechanical models are derived based on a volume-averaging scheme on idealized composite microstructures, e.g., Aboudi (1985), Eischen and Torquato (1993), Dvorak and Srinivas (1999), Khan et al. (2011). Several micromechanical studies (Rasool and Böhm, 2012; Qin et al., 1999) have considered the effects of particle shapes on the overall thermo-mechanical properties of ceramic-metal composites, with a relatively low volume content of ceramics (20% or less). They considered composites with spherical, cubical, octahedral, and tetragonal shapes, and showed that the particle shapes have rather insignificant effect on the overall linear thermo-elastic mechanical properties of the composites. Rasool and Böhm (2012) also showed that the particle shapes have more effects on the conduction properties. Composites with sharp edged particles lead to

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higher micro-fields, i.e., stresses, near the particle-matrix interfaces, which potentially cause debonding. Williams et al. (2012) examined the effects particle shapes and interfacial decohesion on the overall tensile stress-strain responses of ceramic-metal composites with 20% ceramic volume contents. They showed that in absence of the interfacial decohesion the effect of particle shapes is quite insignificant when the strain is relatively small, and deviations are observed under a relatively large strain. However, when interfacial decohesion is considered, the effect of particle shapes on the overall stress-strain responses are pronounced. There are a limited number of micromechanics models of composites that incorporate the detailed microstructural morphologies of the metal matrix composites. Of these, image based finite element software OOF (Langer et al., 2007) is one of the latest techniques to incorporate detailed microstructural morphologies of the composite. OOF was used to determine thermal residual stress, for e.g., in polycrystalline alumina by Zimmermann et al. (1999), in alumina phase of borosilicate–alumina composite by Cannillo et al. (2002). Chawla et al. (2004) used OOF to determine Young's modulus and thermal expansion coefficient of SiC reinforced Al matrix composites. Gudlur et al. (2012, 2014) conducted a numerical study to examine the effects of microstructural morphologies, plastic deformations in the aluminum constituent, and 'stress-free' temperature on the overall elastic modulus, Poisson's ratio, and thermal expansion coefficient of the Al–Al_2O_3 composites. There are several advantages of using the micromechanical models with microstructural details in modeling the overall mechanical response of the composites. First, it allows incorporation of different distribution of constituents in the composite and their behaviors. Second, micromechanical models can capture the stress and strain concentrations (or discontinuities) at various locations within the microstructures of the composites and also take the residual stresses into account in predicting the overall response of the composites. However, they are generally computationally expensive, which make them impractical to be incorporated in performing large scale structural analyses.

In this study, we examine the effects of shapes of the inhomogeneities (inclusions and pores) that are randomly dispersed in the homogeneous ductile matrix on the overall mechanical response of Al–Al_2O_3 composites. The study is done on the composites with 20% alumina volume content. The first micromechanical model is constructed from the microstructural images of the composite obtained from the scanning electron microscope (SEM). The SEM images of the composite are converted into finite element (FE) meshes using software OOF_2[1] and ABAQUS FE code is used to analyze the overall mechanical response of the Al–Al_2O_3 composite. Fig. 1 shows the SEM image of 20 vol% composite, where the alumina particles appear light in color, aluminum matrix in gray, and voids/pores appear dark in color. The second micromechanics model is constructed by considering idealized shapes of the inhomogeneities, while maintaining the same volume contents and locations of the inhomogeneities as the ones in the first micromechanics model. The alumina constituent is modeled as linear elastic, while the aluminum constituent follows an elastic–plastic response. The overall response from the detailed microstructural characteristics is compared to the ones determined with idealized microstructures. We also investigate the thermal stress effects using the two micromechanics models discussed above. The purpose of this study is to examine the feasibility in using idealized and further simplified micromechanics model for determining the macroscopic mechanical properties of the composites.

[1] http://www.nist.gov/mml/ctcms/oof/index.cfm.

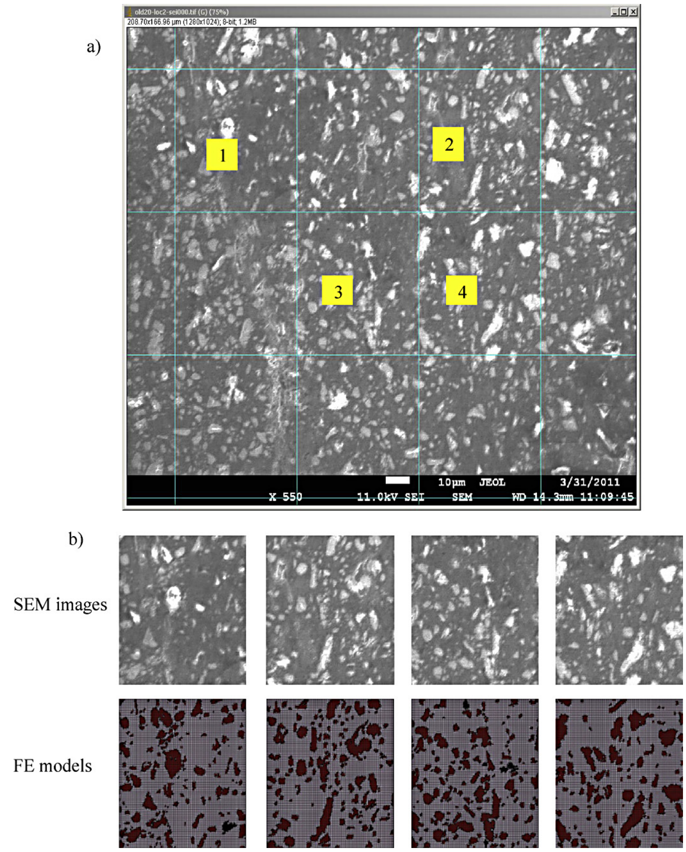

Fig. 1. (a) SEM image of A-20 composite sample; (b) four random square micrographs of A-20 composite sample and their corresponding FE microstructural models 1, 2, 3, and 4 (from Gudlur et al. 2014).

2. Micromechanical models

The microstructural models of the Al–Al_2O_3 composites with 20% alumina volume content are generated from the SEM microstructural images, as shown in Fig. 1. The size of the microstructural image is 217 μm × 173 μm. This micrograph image is divided into uniform sub-images (regions). As an example, the image is divided into 12 uniform regions with 50 μm × 50 μm. Four different 50 μm × 50 μm square regions having different microstructures are randomly chosen as representative microstructures of the composite. Using software OOF_2, the aluminum matrix, the pores and the alumina particles in each of the selected microstructure are determined based on their color contrast. After defining the geometry and boundaries of the different pixel groups, meshes are generated and converted to two-dimensional (2D) finite elements. The continuum plane stress element (CPS4) is used in the ABAQUS FE analyses. These four representative volume elements (RVEs) are referred as FE meshes 1, 2, 3, and 4. We first determined the overall linear elastic modulus of the composites from the selected RVEs. We have also conducted convergence studies in terms of number of elements used in FE analyses and also the sizes of RVE, in which we varied the RVE sizes by selecting two regions with 100 μm × 100 μm. The two RVEs are referred as FE meshes 5 and 6. The elastic moduli, determined from different RVE sizes and number of elements, are compared.

The reinforcement and pores in Al–Al_2O_3 composites, manufactured using powder metallurgy method, have irregular shape as shown in Fig. 1. Analytical and numerical studies on micromechanics of composites are often done on idealized microstructures, i.e., assuming circular or spherical particles dispersed in homogeneous matrix, in order to reduce complexity in obtaining the