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Effective thermo-mechanical properties of aluminum–alumina composites using numerical approach

Pradeep Gudlur [a], Anastasia Muliana [a,*], Miladin Radovic [a,b]

[a] Department of Mechanical Engineering, Texas A&M University, United States
[b] Materials Science and Engineering Program, Texas A&M University, United States

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ABSTRACT

This study examines the effect of microstructural characteristics on the effective thermo-mechanical properties, i.e., elastic moduli, Poisson's effect, and coefficient of thermal expansion (CTE), of ceramic particle-reinforced metal–matrix composites. Two-dimensional (2D) micro-structures for composites with 10% and 20% alumina volume contents dispersed in aluminum matrix are constructed from the micrograph images of the composite samples taken at various locations. A representative area element approximately of size 50 μm × 50 μm is chosen to represent the microstructure of the composite. For each of the selected square regions, ceramic content and porosity are first determined in order to examine the validity of the represented microstructure. These microstructures are implemented in finite element (FE) in order to numerically characterize the effective thermo-mechanical properties of the composites. The alumina constituent is assumed to behave as linearly elastic solid, while the aluminum constituent is modeled as an elastic–plastic solid with material parameters varying with temperatures. The effect of loading directions, porosity, properties of the constituents, particle sizes, and thermal (residual) stresses developed during cooling from the sintering temperature to room temperature, on the overall thermo-mechanical properties of the composites are further discussed.

1. Introduction

Aluminum–alumina composites have been the subject of many study recently [1–5], because of their increasing usage in high temperature and high wear applications. The aim of this study is to examine the effect of microstructural characteristics and thermal (residual) stresses on the overall thermo-mechanical properties of alumina (Al_2O_3) reinforced aluminum (Al) matrix composites, manufactured using powder metallurgy method. The overall physical and mechanical properties of composites depend strongly on the microstructural morphologies, compositions of the constituents, and processing methods. The effect of alumina volume content on the porosity and density of the composite was studied by Kok [6]. He showed that the density of the composites increased linearly with increasing alumina content. The measured density was smaller than the one predicted by rule of mixtures due to the presence of porosity in the composite, which increased with increasing alumina content. McCormick et al. [7] studied the effect of the size of alumina particles on the tensile strength, flexural strength and fracture toughness of Al–Al_2O_3 composites manufactured using a liquid metal infiltration method. They found that these properties increase with a decrease in the particle size. On the other hand, the particle content did not affect the tensile strength, flexural strength and fracture toughness significantly, however the elastic modulus of the composite increased with an increase in Al_2O_3 particle contents. The overall yield stress of the Al–Al_2O_3 composite was shown higher than that of pure aluminum because of the strengthening effect in the aluminum matrix, which is mainly due to an increase in the dislocation density. Arsenault and Haasen [8] showed that high coefficient of thermal expansion (CTE) mismatches between the constituents increased the yield stress of the composite. Mazen and Ahmed [9] showed that Al–Al_2O_3 composites manufactured using the powder metallurgy method had higher yield strength, tensile strength and% elongation than those manufactured using a conventional casting technique.

Residual stresses develop in Al–Al_2O_3 composites during the cooling down process from the sintering temperature to room temperature. This is because of the CTE mismatch between the aluminum and alumina constituents. The residual stresses can also develop due to inelastic deformations in the composites during the processing [10,11]. Bruno et al. [12] and Fitzpatrick et al. [13] used neutron diffraction methods on Al–SiC composites to determine the residual stresses that develop during the fabrication process of the composite. They found that because of this thermal residual stresses, there was net tension in the matrix and compres-

* Corresponding author.
E-mail address: amuliana@neo.tamu.edu (A. Muliana).

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sion in the reinforcement. They performed a tensile test on the composite and found that plastic deformation actually relaxes the residual stresses effectively to zero in both matrix and particle phases. Further they found that any additional increase in strains of more than 0.2% can even reverse these residual stresses, i.e. compression in matrix and tension in reinforcement. Another set of tests conducted by them revealed that if the samples were first plastically deformed and then heat treated, the residual stress increased giving an opposite effect. From these observations they concluded that plastic deformation and heat treatment have opposite effects on residual stresses.

Several micromechanical models have been developed to predict the overall behavior of metal matrix composites. The first class of micromechanics models consider simpler microstructural geometries of the composites, such as assuming dilute or periodic distributions of particles, of spherical or ellipsoidal shape, in the homogeneous matrix. Examples are Aboudi [14], Eischen and Torquato [15], Dvorak et al. [16], Torquato [17], Dvorak and Srinivas [18], Yin and Sun [19], and Muliana [20]. The second class of micromechanical models uses finite element (FE) method to obtain the effective thermo-mechanical properties of composites, in which the microstructures of composites having ordered or random distribution of particles are meshed using finite elements. Examples of such micromechanical models are Kari et al. [21], Pierard et al. [22], Barello and Levesque [23], and Khan et al. [24]. The actual microstructures of composites often contain constituents with complex shapes and various sizes distributed randomly and depend strongly on their manufacturing methods. Scanning Electron Microscope (SEM) is commonly used in order to provide microstructural images of the studied composites. These images are then used to generate finite element meshes of the composite microstructures. The advantage of using this method is that it allows incorporating the details of the microstructure in predicting the overall response of the composites. Wojnar [25], Langer et al. [26] and Chawla et al. [27,28] discussed the basic steps involved in performing image analysis, creating different pixel groups for different constituents based on the difference in contrast in the SEM micrograph, assigning material properties to pixel groups and generating finite element meshes. Software OOF was used to transform the SEM images into finite element meshes. These micromechanical models can incorporate detailed information on the effect of microstructural morphologies on the overall performance of composites; however, this approach has not been fully explored. Only limited number of studies has been conducted using this approach, for examples Chawla et al. [27,28] determined the modulus and CTE of SiC reinforced Al matrix composites, Bakshi et al. [29] studied the thermal conductivity of carbon nanotube reinforced aluminum composites, Dong et al. [30] determined the tensile modulus of polypropylene–organoclay nanocomposites and Wang et al. [31] characterized the modulus and thermal conductivity for plasma sprayed zirconia coatings.

Several micromechanical models have also been used to determine the thermal residual stress in metal matrix composites. Arsenault and Taya [32] used a model based on Eshelby's theory and predicted the magnitude of thermal residual stress developed in Al–SiC composites, when they are cooled from fabrication temperature. They compared these theoretical results with experimental data obtained in tension and compression testing of Al–SiC and found them to be in close agreement with each other. Muliana [20] used a simplified micromechanical model to incorporate the effects of viscoplastic aluminum matrix and degradation in the alumina and aluminum constituents on predicting the deformation in aluminum/alumina functionally graded composites during transient heat conduction. Khan et al. [24,33] studied the effect of thermal stresses in particulate composites during nonlinear transient heat conduction. They found that the discontinuities in the thermal stresses at the interfaces between particles and matrix increase with increasing temperature changes and number of particles. Shabana and Noda [34] used finite element method to study the thermo-elasto-plastic stresses in particle reinforced functionally graded composites, taking residual stresses of the fabrication process into consideration. Micromechanical models generated from the microstructural images of the composites have also been used to study thermal residual stresses, e.g., in polycrystalline alumina by Zimmerman et al. [35] and in alumina phase of borosilicate–alumina composite by Cannillo et al. [36]. But only limited number of studies has been conducted to determine the effect of thermal residual stresses on the overall response of metal matrix composites using this approach.

In this manuscript, we examine the effects of microstructural morphologies, i.e., the size, shape, distribution, and properties of the constituents, interactions between the constituents, existences of porosity, loading direction, and residual (thermal) stresses, on the effective CTE, elastic modulus, and Poisson's ratio of Al–Al_2O_3 composites manufactured using powder metallurgy method.[1] For this purpose the micromechanical models are generated from the detailed microstructural images of the composite samples. Two composite systems with different sizes of aluminum particles are considered. The micro-structural models for the composites with 10% and 20% alumina volume contents dispersed in aluminum matrix are constructed from the microstructural images of the composite samples obtained from SEM, shown in Fig. 1. Next, the SEM images of the composite are converted into FE meshes using software OOF [37] and ABAQUS FE code is used to analyze the overall properties of the Al–Al_2O_3 composites. The numerically calculated properties are compared with the experimental data reported by Gudlur et al. [38].

2. Experiment

Two alumina–aluminum composite systems with different sizes of aluminum particles were manufactured using powder metallurgy method. The first system, labeled as system A, consists of 99.5% pure aluminum powder of −100 +325 mesh size (Alfa Aesar, MA) and 99.7% pure alumina (Sigma–Aldrich, MO) with average particle size of 10 μm. The above Al–Al_2O_3 composites are labeled as A-XX, where XX is the nominal volume percentage of Al_2O_3. The Al–Al_2O_3 composite system B, further labeled as B-XX, where XX is the nominal volume content of Al_2O_3, consists of 97.5% pure aluminum powder with smaller particle size, i.e. 3–4.5 μm (Alfa Aesar, MA) and the same alumina powder as that of the composite system A. The purpose of manufacturing and studying Al–Al_2O_3 composites with two different sizes of aluminum particles is to examine the effects of particle size and relative density on the overall thermo-mechanical properties of the composites.

The composite specimens were fabricated with different volume contents of alumina: 10 and 20 vol% for both composite systems A and B. To achieve a specific volume content of a composite sample, proper amounts of Al and Al_2O_3 powders were mixed, ball milled, and put in a cylindrical die of 25 mm diameter and a hydraulic press was used to cold press the powders for 30 min at room temperature and at a compacting pressure of 502 MPa. The cold pressed pallets were further sintered in a quartz

[1] As powder metallurgy method involves high pressures and temperatures and as we are dealing with ceramics and metals, which have significant differences in the thermo-mechanical properties, residual stresses, also known as pre-stress, are developed during sintering the composite samples at elevated temperatures and cooling down the samples to room temperature. Depending on their magnitudes, these residual stresses could induce yielding in the aluminum matrix or cracking in the alumina, affecting the overall performance of the composites and could even lead to premature failure of the component. In addition, at elevated temperatures metallic constituents experience creep (and stress relaxation); thus an exposure to high temperature can relax some of the residual stresses built in the composites.