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Effect of particle orientation anisotropy on the tensile behavior of metal matrix composites: experiments and microstructure-based simulation

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Abstract

Deformation processing of particle reinforced metal matrix composites induces preferential orientation of the reinforcement particles. Thus, the orientation anisotropy of the reinforcement will strongly influence the mechanical behavior of the composite. In this study, the effect of reinforcement orientation anisotropy on the mechanical behavior of extruded 2080 Al matrix composite was examined. Microstructure characterization showed a preferred orientation of the reinforcement particles parallel to the extrusion axis, although the degree of orientation decreased with increasing reinforcement volume fraction. Young's modulus and tensile strength in the longitudinal orientation (parallel to the extrusion axis) were higher than that in the transverse orientation (perpendicular to the extrusion axis). The particle orientation-induced changes in stress–strain behavior were modeled using a microstructure-based finite element method approach, yielding good agreement with experimental results. The relationship between tensile behavior of the composites, especially elastic modulus, to the degree of anisotropy in orientation of the reinforcement particles is discussed.

Keywords: Aluminum composites; Anisotropy; Elastic modulus; Deformation behavior; Microstructure-based finite element modeling

1. Introduction

Metal matrix composites (MMCs) are attractive materials for many structural applications due to their lightweight and superior mechanical and thermal properties [1–6]. Among the various types of MMCs (fiber, short fiber, particle reinforced), particle reinforced MMCs are quite attractive because of their relatively isotropic properties (compared to continuous fiber reinforced composites), ease of fabrication, and low cost. Particle reinforced MMCs are processed primarily by liquid [6–10] or solid state processing techniques [7,11,12]. Liquid phase processing techniques include casting and infiltration [6,8–10]. The main advantages of liquid phase processing are the high speed and low cost of fabrication. The drawbacks of liquid phase methods include inhomogeneous distribution of particles and interfacial reaction between matrix and reinforcement. Interfacial reaction, in particular, can adversely affect the mechanical properties of the composite. In solid phase processing techniques, such as powder metallurgy processing, interfacial reactions are minimized and a relatively homogeneous and refined particle distribution can be achieved [11,12]. One of the most effective methods for processing particle reinforced MMCs involves consolidation of the particle and matrix by hot pressing, followed by a secondary operation such as extrusion, forging, or rolling [13]. Secondary deformation processes result in a strong mechanical bond between the reinforcement and matrix, along with refinement of the matrix grain size [14]. In some cases, however, particularly where relatively large reinforcement particles (∼20 μm) are involved, processing-induced particle fracture may take place [15–17]. A very important attribute of deformation processing is the preferred orientation of the reinforcement particles along the extrusion axis [18–22]. While the existence of preferred orientation after extrusion has been noted, the effect of reinforcement volume fraction and particle size on the degree of orientation has not been examined in detail [23]. Indeed,

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the effect of anisotropy on tensile and fatigue behavior of these composites is not well understood because most studies report tensile properties measured parallel to the extrusion axis.

The anisotropy in composite microstructure also poses a challenge for modeling of the deformation behavior. The unit cell modeling approach [24], where a single particle of simple geometry is modeled, is clearly not adequate for quantifying microstructural anisotropy in the form of particle orientation characteristics. Recently, multiparticle-based models have been proposed, once again by simplifying the particle morphology to that of an ellipse or rectangle [25,26], but these models also do not quite capture the angular nature of the SiC particles. Thus, what is required is a microstructure-based model that encompasses the actual microstructure and, thus, accounts for the actual morphology, distribution, and orientation of the reinforcing particles. Recently, Chawla and coworkers [27–29] used this novel approach and successfully predicted the elastic, elastic–plastic and thermal properties of particle reinforced MMCs by using two- and three-dimensional microstructure-based models. They also demonstrated the effectiveness of microstructure-based models in predicting localized stress and strain in the material due to microstructural inhomogeneities, such as particle clusters.

In this study, we have conducted a systematic investigation of the degree of orientation anisotropy of SiC particles, for a range of reinforcement volume fractions, in extruded SiC particle reinforced Al alloy composites. The influence of preferred orientation of reinforcement particles on tensile behavior was examined parallel (longitudinal) and perpendicular (transverse) to the extrusion axis. Two-dimensional microstructure-based modeling was conducted using finite element method (FEM) to understand the deformation behavior of the composites. It will be shown that the degree of particle orientation anisotropy is significant and that it is directly dependent on the reinforcement volume fraction of the composite. This anisotropy has a significant effect on the anisotropy in tensile behavior, which is captured very well by the microstructure-based models presented here.

2. Materials and experimental procedure

The material used in this study was a 2080 aluminum alloy (3.6% Cu, 1.9% Mg, 0.25% Zr) reinforced with 10, 20, and 30 vol.% SiC particles (average particle size of 8 μm). The materials were processed by blending SiC and Al powders, compaction of the powder mixture, hot pressing, and hot extrusion (Alcoa Inc., Alcoa, PA). Details of the powder metallurgy process for fabrication of these composite materials can be found elsewhere [30]. After extrusion, the composites were electro-discharge machined (EDM) into rectangular blanks, solution treated at 493 °C for 2 h, water-quenched, and peak-aged at 175 °C for 24 h.

Optical and scanning electron microscopy (SEM) was used to analyze the microstructure of the composite. The composite samples were polished along the longitudinal (parallel to extrusion axis), transverse (perpendicular to extrusion axis), and short transverse (parallel to the longitudinal–transverse plane) axes, to examine the orientation anisotropy of the reinforcement particles and the matrix microstructure. The micrographs were segmented using conventional image analysis software and the particles fitted to an ellipse to quantify the particle size and aspect ratio. The distribution in particle size, aspect ratio, and relative orientation of particles with respect to the extrusion axis was then obtained. The relative orientation was measured by the angle between the major axis of the particle and that of the longitudinal or transverse axis. Matrix grain characteristics were analyzed by etching the polished surface with Keller's reagent (0.5 HF (49%) + 1.5 HCl + 2.5 HNO_3 + 95.5 H_2O) to reveal the matrix grain structure. The matrix grain size and aspect ratio were calculated using techniques described above.

Uniaxial tensile tests were carried out on dog-bone cylindrical smooth bar specimens with a gauge length of 15 mm and diameter of 4 mm. Specimens were machined parallel and perpendicular to the extrusion axis. Final machining of the tensile specimens was carried out using low stress grinding. All tensile tests were carried out on a precision aligned servo-hydraulic load frame, at ambient temperature, in strain control at a strain rate of 10^{-3} s^{-1}. The strain was measured using a clip-on extensometer. Fracture surfaces of the tensile specimens were characterized using SEM. Mirror images of the mating fracture surfaces were then obtained to quantify the degree of particle fracture.

3. Results and discussion

3.1. Microstructure characterization

The microstructure of the composites of all volume fractions is shown in Fig. 1. A clear preferred orientation of reinforcement particles along the extrusion axis was observed for all SiC volume fractions. The average size of the SiC particles, for all volume fractions, was about 8 μm with an aspect ratio of approximately 2 (Table 1). The measured aspect ratio and size of particles in the longitudinal plane was

Table 1
Size and aspect ratio distribution of SiC particles

Composite and orientation	Particle size (μm)	Particle aspect ratio (D_{max}/D_{min})
2080/SiC/10_p longitudinal	8.57 ± 2.39	2.32 ± 0.98
2080/SiC/10_p transverse	7.25 ± 2.12	2.13 ± 0.87
2080/SiC/20_p longitudinal	8.33 ± 2.88	2.25 ± 0.94
2080/SiC/20_p transverse	7.24 ± 2.09	2.04 ± 0.84
2080/SiC/30_p longitudinal	7.87 ± 2.45	2.19 ± 0.83
2080/SiC/30_p transverse	7.09 ± 2.11	2.00 ± 0.71