Materials Science & Engineering A 650 (2016) 323–334

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

Numerical and theoretical modeling of the elasto-plastic response of aluminum–graphite composites during straining

J.L. Hernández-Rivera, H.I. Medellín-Castillo *, D.F. de Lange

Facultad de Ingeniería, Universidad Autónoma de San Luis Potosí, Av. Manuel Nava No. 8, Zona Universitaria, 78290 San Luis Potosí, S.L.P., México

ARTICLE INFO

Article history:
Received 13 May 2015
Received in revised form
15 October 2015
Accepted 17 October 2015
Available online 19 October 2015

Keywords:
Metal matrix composites (MMC)
Aluminum–Graphite (Al–Gr)
Finite Element Method (FEM)
Elastic response
Plastic response
Plastic response model

ABSTRACT

One of the ways to improve the mechanical properties of Aluminum alloys is by dispersion of the metal matrix with small particles, such as Aluminum–Graphite (Al–Gr) composites. The elasto-plastic response of Aluminum–Graphite composites has not been fully understood. Hence, in this paper a numerical analysis of the elasto-plastic structural response of Al–Gr composites is presented. FEM models based on unit cells are proposed by considering two different Al/Gr interface conditions: (1) strongly bonded interface and (2) friction–sliding interface. The results from the numerical simulation in the elastic region are evaluated in terms of the effective elastic modulus and compared with existing theoretical models. On the other hand, the results from the numerical simulation in the plastic region are compared with experimental data obtained from compression tests, and with existing theoretical models that are based on the rule of mixtures. The results have shown that FEM models, based on conventional continuum theory, and existing theoretical models, based on the rule of mixtures, are not capable to predict with accuracy the plastic behavior of the composite. Therefore, a new empirical model is proposed instead, which is compared to the experimental results. After a calibration process of the model with a limited set of experimental data input, the new proposed model has shown a high accuracy in predicting the effective plastic response of the Al–Gr composite for different volume fraction of reinforcing particles.

1. Introduction

Metal matrix composites (MMC) emerged initially as a distinct technology in an era when improved performance for advanced military systems provided a primary motivation for materials development [1–6]. Several investigations employing aluminum (Al) as a matrix have been carried out so far. For instance, Surappa et al. [7] found that the cast Al–11.8Si alloy reinforced with 3 wt% of graphite (Gr) particles, increased its Ultimate Tensile Strength (UTS) from 130 MPa to 208 MPa after hot extrusion. They argued that graphite particles were deformed during plastic processing since they experienced a combination of shear and compressive loads that caused these particles to form strings along the extrusion axis, this in turn was taken as one of the main hardening mechanisms. Xu et al. [8] studied the stresses developed in the matrix as well as in the reinforcement in AA-2618 reinforced with different volume fractions (10% and 20%) of SiC and Al_2O_3 particles by employing an Eshelby particle-compounded mechanical model. They found that the stresses in the reinforcing particles were much higher than those in the matrix during straining, which was interpreted as a major load transfer from the aluminum matrix to the reinforcement. In addition, it was concluded that the mismatch strain (difference in the strain response between matrix and reinforcement during straining of composite) played a more important role in the load transfer in a soft matrix than in a hard matrix. Peng et al. [9] proposed a microunified model based on microstructural information of Aluminum reinforced with SiC particles to predict the stress–strain curves. These curves were compared with continuum composite model predictions and it was found that the stresses and strains in the microunified model were higher than those corresponding to the continuum model.

Graphite (Gr) is an important reinforcement used in Al based MMC because it provides an important hardening mechanism during hot processing due to the high difference in the thermal expansion coefficient between both the materials. It has been reported that during thermomechanical processing, elasto-plastic strains and stresses can occur in matrix areas close to the reinforcement due to this difference [2,10–12]. Hu et al. [10] used a method based on a secant moduli approximation for the evaluation of the thermal residual stresses in Aluminum matrix reinforced with SiC particles. The analytical results showed that the induced plastic strain (after a temperature change) depended significantly on the reinforcement shape. For example, the thermal

* Corresponding author. Fax: +52 444 8262330.
E-mail addresses: jlhri10@yahoo.com.mx (J.L. Hernández-Rivera), hugoivanmc@uaslp.mx (H.I. Medellín-Castillo), dirk.delange@uaslp.mx (D.F. de Lange).

http://dx.doi.org/10.1016/j.msea.2015.10.063
0921-5093/

residual stresses induced a tensile hardening curve higher than the compressive one for particle reinforced composite with an aspect ratio of 1; observations that were confirmed with experimental results. On the other hand, Chou et al. [11] analyzed the residual thermal stresses in an A356–Al_2O_3 composite by using high angle X-rays. They reported residual thermal stresses close to 200 MPa when the reinforcement content was 70 vol%. Recently, Lu et al. [12] determined thermal stresses acting on unidirectional fiber-reinforced SiC/Al composite by means of X-ray diffraction. The experimental results were compared with theoretical models based on the rule of mixtures (ROM) and taking into account the residual stresses. A good agreement was found between both the results. In addition, it was concluded that the effect of the residual stresses on Young's Modulus of the composite is very small.

It has also been observed that the Al–Gr MMC properties such as ultimate tensile strength (UTS) and yield strength (YS) are increased in matrix regions close to reinforcement by approximately 50–200 MPa in an extension close to 0.5 μm [2,13]. On the other hand Gr provides attractive tribological properties to Al matrix by reducing the wear and abrasive loads that cutting and die tools experiment during machining or forging of these materials [14]. In addition, Gr has a low solubility in Al and therefore the tendency for chemical reaction between both materials is low [1,2]. Furthermore, in a recent report Achutha et al. [15] have compared the stress-life (S-N) performance of a cast Aluminum with the same Aluminum matrix reinforced with Gr particles. A rotating beam fatigue testing machine with different stress levels was used. The results showed that the fatigue performance of the composite was superior to the matrix without prticles, which was associated to the excellent anti-seizing and tribological properties of graphite.

Several works have been published regarding the simulation of the elasto-plastic deformation mechanism of composite materials using the Finite Element Method (FEM) and unit cells models. The unit cells are commonly considered to be periodic and regular. Unit cells are used to get an insight into microscale stress states generated during straining processes, and to relate the composites micro-structural features to their macroscopic mechanical performance in terms of the deformation mechanisms, strengthening mechanisms and failure mechanisms. Watanabe et al. [16] established a numerical method for predicting the macroscopic yield strength of polycrystalline metals after plastic deformation by employing unit cells in combination with homogenization techniques. The theoretical results were compared with the experimental results obtained from rolling tests. It was concluded that the proposed method was capable to predict with enough accuracy the macroscopic yield strength for any arbitrary forming process, even though the plastic deformation is so severe that texture is developed.

Wang et al. [17] modeled the elastic properties of porous materials by using a 2D plane strain unit cell model with a double random distribution of void size and position. Since a circular geometry of voids normally involves a more computational work due to the curved boundaries, a square representation for voids was proposed. This approach allowed them to model a large number of voids. The results showed a good agreement between the numerical and the literature values when a square-shaped voids were considered in the numerical model. They claimed that this square-shaped approximation had the potential to be extended to 3-dimensional modeling of engineering materials due to the reduced requirement for Finite Element Analysis. On the other hand, Sierra et al. [18] studied the plastic response of transformation induced plasticity (TRIP) steels by using a 2D unit cell model in which the matrix was composed of ferrite and bainite, and the retained austenite phase which was considered as the reinforcement. The austenite content was varied (6, 12, and 22 vol%) in order to study its transformation to martensite under load, and also to observe its effect in the mechanical properties of the steel. It was found that the maximum volume fraction of retained austenite coincides with an increase in the work hardening, ductility formability index and ultimate tensile strength. The results showed that there was a 24% increase in formability when a TRIP steel microstructure was compared with a non-TRIP steel microstructure. Also, the high fractions of austenite and bainite contributed to the suppression of voids initiation at the austenite–matrix interface.

Alternatively, Illie et al. [19] modeled an AA2009 reinforced with SiC particles by using a micromechanical model based on a 2D unit cell. The aim was to obtain the stress and strain distributions and to predict the tensile strain–stress behavior of the MMC. A brittle particle fracture criteria was incorporated to the micromechanical model. The micromechanical model was shown to predict very well the stress–strain curves of the MMC when particle fracture was incorporated at room temperature and not incorporated at high temperature. Balasivanandha et al. [20] modeled a 3D unit cell of a MMC of 6061 aluminum alloy reinforced with different volume fractions of SiC fibers in order to study the influence of fiber diameter and volume fraction of the fiber on the debonding event at the interface. The results indicated that the shear stresses at the interface were higher when the diameter of the fiber was increased; reaching values close to 700 MPa. Also it was reported that the debonding was more pronounced in the interfacial elements near the axis of symmetry where the stresses reach the above value.

In the previous Refs. [18–20], continuity conditions have been completely assumed in the interface between the reinforcement and the matrix; however, other works have used contact elements to model the friction between the interface matrix/reinforcement because this fact affects significantly the load transfer between them. Zeng et al. [21] incorporated contact elements in the interface of a Ti based composite with SCS-6 fibers to predict interfacial shear strengths and compared them with pull-out experimental tests. The maximum load measured in the push-out experiments was used as a criterion to determine the properties of the matrix/fiber interface. FEM results showed shear stresses as high as 500 MPa at room temperature and 140 MPa at 150 °C. They concluded that the FEM analysis and the experimental tests lead to a similar load-debond length behavior at and after the maximum load. Lee et al. [22] modeled the interface of an Al composite by considering relative slipping between the reinforcement and the matrix. This condition was named as weak interface. On the other hand, a rigid interface was also considered by assuming an infinite bonding strength with no sliding or decohesion. They found that the hardening of the composites with rigid interface was higher, or similar in some cases, than the composites with weak interface. The results were attributed to the decohesion that was more prone to occur in the weak interface. More recently Rodríguez-Ramos et al. [23] studied the effective properties of fiber-reinforced periodic piezoelectric composites by using an asymptotic homogenization approach and cell models with different fiber orientations. It was also considered an imperfect mechanical contact in the models by using a linear spring model, which is an idealization of a layer of mechanical springs of zero thickness. Approximate analytical solutions for the effective moduli on microlevel depending on the degree of the interfacial debonding were obtained. The results also showed that the presence of normal imperfect contact enhanced the effective hydrostatic performances of the 1–3 piezoelectric composites.

The literature review reveals that there has been many research works focusing on the analysis of the mechanical properties of MMC. However, in these works several discrepancies can be observed when predicting the mechanical response of this type of composites. Therefore there is still much work to be done in order