Effect of the particle shape in the Young modulus of SiC particle reinforced Al matrix composite

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Abstract: Particulate reinforced metal matrix composites (PRMMC) show good combination of strength-to-weight ratio, as a result they are used commonly in fields such as the automotive, aerospace, electronics, among others. Typical PRMMC are made of metal matrixes such as aluminium and magnesum, whereas reinforcement particles are silicon carbide, alumine, among others. Particle reinforcements exhibit angular and circular shapes. Young moduli of PRMMC depend strongly on factors such as the reinforcement volume fraction, particle shape, particle size as well as particle orientation and cohesive forces at the particle-matrix. The experimental development of PRMMC is time consuming and cost effective. For desing purpose analytical models have been development, however, they exhibit a different degree of reability depending on the Young modulus strength ratio for example, hence they are limited to certain applications. In recent decades the finite element analysis (FEA) of microstructures have shown to be an accurate approach to determine the elastic modulus of PRMMC as function of particle shape, particle size, particle volume fraction, etc. In this work a micromechanical model was developed and solved using COMSOL Multiphysics. The Solid Mechanics module is used for the stationary study of two-dimensional microstructures, where the effects of particle shape, particle volume fraction and particle size on the elastic modulus. The MMC studied is a silicon carbide particle reinforced aluminium-based matrix composite. The finite element outcome is validated by comparing the numerical predictions against several experimental data ranging in low and high-volume fraction and good agreement is found. The elastic modulus of aluminium reinforced silicon carbide increases as volume fraction reinforcement increases. The smaller cicular particles considered in the study act as stress concentrator, whereas, stress is concentrated in sharped corners of angular particles. The elastic modulus is sensitive to the particle morphology, where angular particles exhibit better stregthening effect for a given volume fraction when compared to cicular particles.

Keywords: SiC-Al composite, shape particle, numerical analysis

1. Introduction

Particulate reinforced metal matrix composites (PRMMC) are widely used in various areas such as the automotive, aeronautical, energy and defense industries, among others, due to the properties they present. Some of them are the combination of high resistance, elastic modulus, specific rigidity and strength-to-weight ratio [1]. These properties can be obtained by adding ceramic particles (silicon carbide, alumina, tungsten carbide, or others) to a matrix of light metals such as aluminum and magnesium [2]. Young's modulus depends on certain characteristics like the reinforcement volume fraction, particle shape, particle size, particle orientation and cohesion forces on particle-matrix [3]. The only use of experimental methods to establish a quantitative relationship between properties at the macroscopic level and the microstructure requires large amounts in terms of cost, time and material testing. For this reason, many times these properties are theoretically analyzed. Finite element analysis (FEA) allows the study of mechanical properties of compounds with greater efficiency, and lower cost. FEA is carried out using two approaches: the unit cell (UC) and the representative volume element (RVE). The first one consists of a particle embedded in a metal matrix which represents a periodic matrix. RVE, on the other hand, assumes random microstructures, it is the smallest volume capable of characterizing its microstructure in a global way, that is, it allows representing the characteristics of the composite material at a higher level, it is a true representation of the composite material at macroscopic level [4,5].

This analysis has proven to be a precise approach to determine the elastic modulus of PRMMC as a function of particle shape, particle size, particle volume fraction. Chawla et al. [6] studied the effect of the particle shape on Young's modulus for an Al-SiC system. They determined that using a real morphology of the compound provides more precise results because they fit better to the experimental data, but not when using circle and square particle shapes, through a three-dimensional model based on microstructure. Rivera et al. [3] also investigated the effect of particle shape and particle fraction on the elastic modulus by using a UC effect for circular and square particles, indicating that as the reinforcement volume fraction increases, angular particles strengthen the compound better than circular ones.

On the other hand, the effect of the volume fraction, size, distance and shape of the particles on the distribution of stresses and deformations has been analyzed. Lui et al. [7,8] have studied the effect of particle size, particle shape and distance between particles. They concluded that particles provided more charge in compounds reinforced with irregular particles than those reinforced with spherical particles, and that the degree of stress concentration increased as particle size decreased.

The aim of the present work is to study the effect of particle shape in the Young's modulus of an aluminium system reinforced with silicon carbide particles, considering circular and angular particles. A numerical model of micromechanics was developed using COMSOL Multiphysics. The Solid Mechanics module is used for the stationary study of 2D microstructures, to study the effects of particle shape and size, as well as the reinforcement volume fraction on the elastic modulus of the compound. The model is validated by comparing the results obtained with experimental data reported in the literature and the Hashin-Shtrickman model, at different volume fractions, concluding that it is in good concordance.

2. Methods and material

2.1 Microstructure

Circular and angular particles were considered for the Al-SiC system for volume fractions of 10, 20, 30, 40, 50, 60 and 70%.

The following procedure was used to generate the microstructures containing angular particles:

First, a digital micrography was taken, extracted from a scanning electron microscopy (SEM image) that included scanning for capturing the real morphology of the reinforcing particles. After that, the point field was generated in the vertices for those particles, considering 50 different shapes, then, using the extracted points, the computational domain was generated in COMSOL providing different particle sizes.

For the microstructures reinforced with circular particles, the area of each angular particle was considered and used to obtain the diameter of each circular particle. Each circle was carefully placed on a similar location to the corresponding angular particle. Figure 1 shows the microstructure for a volume fraction of 20% for the compound reinforced with angular and circular particles.

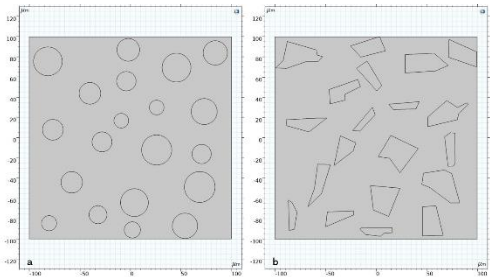

Figure 1 Microstructures reinforced with a) circular particles, and b) angular particles

In both cases, the volume fraction was given by the relationship of the particle areas with the total matrix area.

The image used to build the model provides a particle size distribution so, to eliminate size distraction, models with a single size distribution were made.

2.2 Governing equations

The governing equations of the mechanics problem are given by the balance equation

$$\nabla \cdot \sigma + f = 0$$

Where σ is the stress tensor and *f* is the force. A flat deformation is assumed for the stress-strain ratio. On a macroscopic scale, a heterogeneous material can be considered as a homogeneous medium. The mean fields of stress and strain are related to the RVE displacements through the Gaussian theorem.

$$\bar{\sigma}_{ij} = \frac{1}{A}\int_{A} \sigma_{ij}(x,y)dA = \frac{1}{A}\int_{\Gamma} \left(Eu_in_j + Eu_jn_i\right)d\Gamma$$

$$\bar{\varepsilon}_{ij} = \frac{1}{A}\int_{A} \varepsilon_{ij}(x,y)dA = \frac{1}{A}\int_{\Gamma} \left(u_in_j + u_jn_i\right)d\Gamma$$

The Young´s modulus calculation was based on Hook´s law, $\bar{\sigma}_{ij} = E_c\bar{\varepsilon}_{ij}$.

Table 1.Material parameters of SiC particle an Al matrix

	Elastic modulus (Gpa)	Poisson ratio	Density (g/cm^3)
Al	73.9	0.33	2.67
SiC	410	0.14	3.21

2.3 Numerical model

A micromechanics model based on a microstructure for an aluminum composite reinforced with silicon carbide particles was established at different volume fractions. The representation of a statistical microstructure of the matrix-particle system was defined through the RVE approach. The model assumed perfect bonding and isotropic behavior. Figure 2 presents a 2D model scheme and the boundary conditions, for a 200 x 200 µm square matrix, with an effort of 0.1 Pa.

Along the left edge the constraint is fixed, this means that it is not allowed to move on any of the axes. This constraint is governed by the following equation:

$$u_x = 0$$

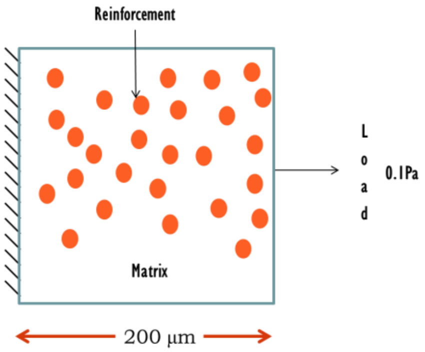

Figure 2 Scheme of model and boundary conditions used on numerical simulation.

3. Results and Discussions

3.1 von Mises stress distribution

The differences between the particle and the matrix also make the distribution of the stress and strain field different in various parts of the compounds. This section presents the effect of particle shape and particle size on stress concentration distribution.

Particle Size: As mentioned above, the effect of particle size was observed from microstructures. The study took a volume fraction of 10%, with different size distributions. Figure 3 presents the von Mises stress distribution for a particle size varying in the range of 10-40 µm, at a volume fraction of 10%.

In all cases, it is observed that for a constant volume fraction, the behavior of the stress concentration is similar. The stresses are concentrated mainly on the reinforcing particles, and they are uniformly distributed within the particle. For the matrix, the distribution is less uniform, with a stress concentration around the particles, mostly towards the direction of the charge axis. At the ends of the particles the stress concentration is minimal for all cases.

Furthermore, some 10 µm particles have a higher stress concentration, this is mainly found in particles that are located close to the charge condition. That concentration decreases as particle size increases, this behavior is confirmed with [7,10-12].

It is observed that the distance between the particles influences the stress distribution, as can be seen at a particle size of 20µm, in the coordinates (45, 35), where it is observed that the distance between the particles is relatively small, compared with the rest, this distance causes that the stresses were distributed in a different way inside the particle, and that there was a high stress concentration in the matrix. This behavior is consistent with that described by Liu et al., Liu et al. and Paknia et al. [7,8,12], indicating that towards the direction of charge, not only the proximity of the particles, but also the angle, affect the stressed distribution.

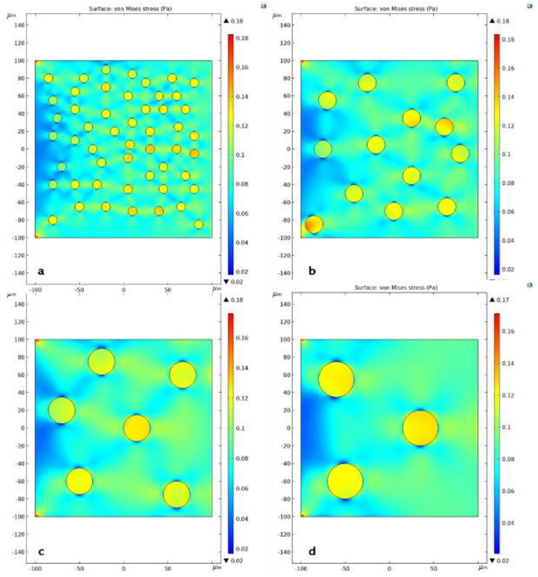

Figure 3 von Mises stress distribution with particle size of a)10µm, b)20µm, c)30µm and d)40µm at volume fraction 10%.

Particle Shape: In order to observe the effect of particle shape on stress distribution, the microstructures for angular and circular shapes are presented. Figure 4 shows the stress concentration distribution of von Mises in the microstructures reinforced with circular particles, for volume fractions of 10-70%. At low volume fractions it is clearly observed that the stress concentration in the matrix is around the particles, which suggests that matrix and particles share those stresses.

In the spaces for the short distances among particles, there is a higher stress concentration, behavior that agrees with that reported by Liu et al., [7]. It is observed that the stress distribution within the particles is not uniform, because the behavior is influenced by the distance between the particles at high volume fractions (40-70%), especially where there is a clustering of particles. For smaller particles, the loads supported are greater than the rest, this could be due to the size of these, since as mentioned above the stresses are concentrated in smaller particles. In this case it is also necessary to notice the proximity to the load axis which increases the concentration of effort as reported by Peng et al.,[10].

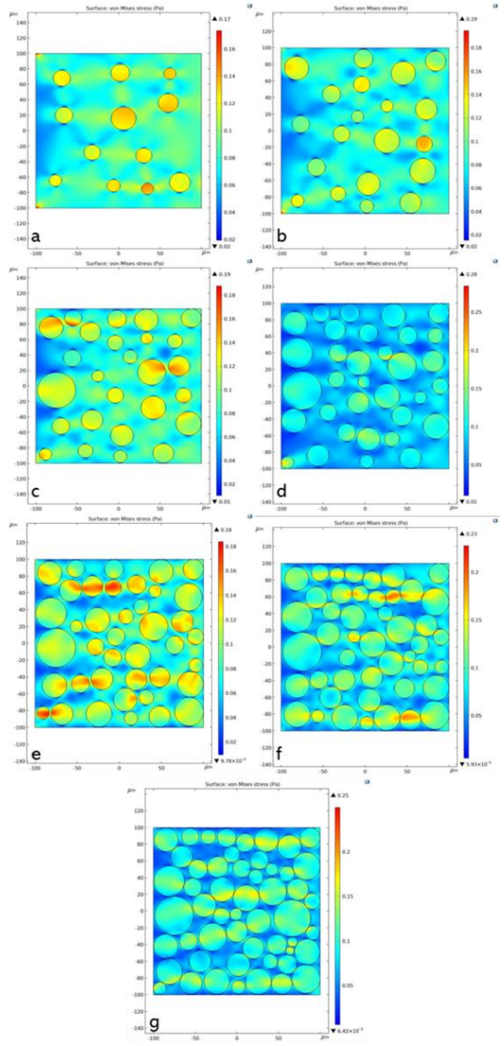

Figure 4 von Mises stress distribution for reinforcement with circular shape particles at volume fraction of a)10%, b)20%, c)30%, d)40%, e)50%, f)60% and g)70%.

Figure 5 presents a distribution of the von Mises stress concentration in the microstructures reinforced with angular particles for volume fractions of 10-70%. It is seen that the distribution in the particles is not uniform, in comparison with that on circular particles. However, the stresses are concentrated in the sharp edges of the same ones, due to the area of the particles is not constant, causing this behavior of stress concentration, which finally would present the zones where a greater elastic deformation would exist. That behavior has been previously reported by Chawla et al., Liu et al., Peng et al., [6,7,10] for angular particles.

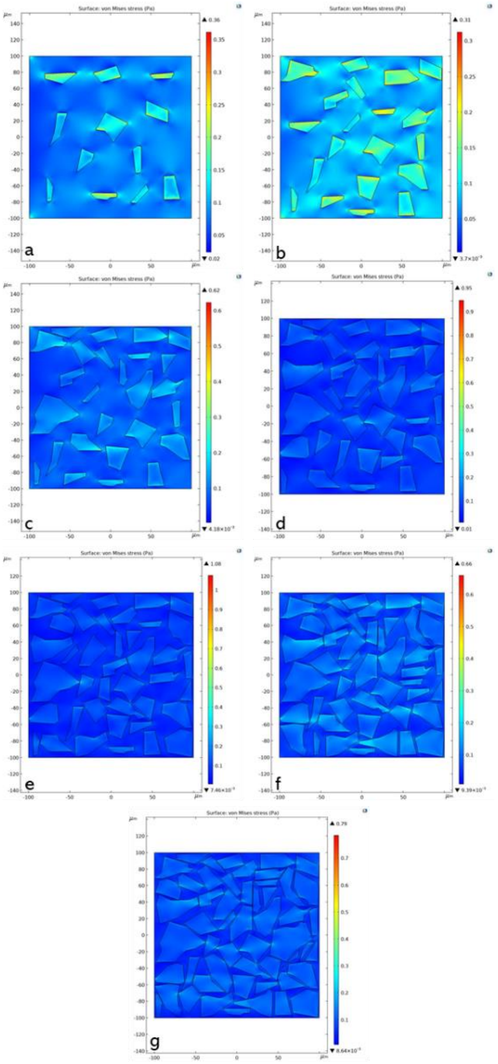

Figure 5 von Mises stress distribution for reinforcement with angular shape particles at volume fraction of a)10%, b)20%, c)30%, d)40%, e)50%, f)60% and g)70%

The influence of the particle shape on the stress distribution can be noticed for those whose shape is close or similar to a rectangle, in which the distribution is quite irregular. Moreover, this stress concentration is greater where the distance between the particles is smaller, this is consistent with what was found by Chawla et al., Liu et al., Paknia et al., [6,7, 12].

3. 2 Young’s Modulus

The model was validated by comparing the results of Young's modulus against experimental data reported in the literature, and the Hashin-Shtrikman model. The H-S model is one of the most widely used due to its accuracy.

$$E^{\pm} = E_2 + \frac{\phi_1}{\frac{1}{(E_1 - E_2)} + \left(\frac{3\phi_2}{3E_2 + 4G_2}\right)}$$

where E is the Young modulus, φ is the volume fraction, and G is the shear modulus. For the calculation of the upper limit $E_2 > E_1$, while for the calculation of the lower limit the subscripts (1, 2) are exchanged.

In figure 6, a comparison of Hashin-Shtrikman's limits among experimental data [13-18], numerical predictions [3] obtained from the literature, and data obtained from the simulations of the present study is presented. The data obtained in the numerical simulations for a synthetic microstructure, are quite close to the experimental data reported in the literature for an Al-SiC system. It is observed that for low volume fractions (10 to 40%), both, the experimental data and the numerical predictions, are close to the lower limit of Hashin-Shtrikman, so it is possible to make the prediction about the resistance of Al-SiC compounds using the lower limit of the Hashin-Shtrikman model with a high level of concordance [3]. Regarding the simulations performed in this study, it was observed that Young's modulus at low volume fractions (under 11%) is almost identical for both, idealized and angular particles, suggesting that at these volume fractions the shape of the particle has no effect on Young's modulus, which is consistent with that found by Rivera et al., [3]. However, as the volume fraction of the SiC particles increases, the composites reinforced with angular particles strengthen better than the composites reinforced with circular ones.

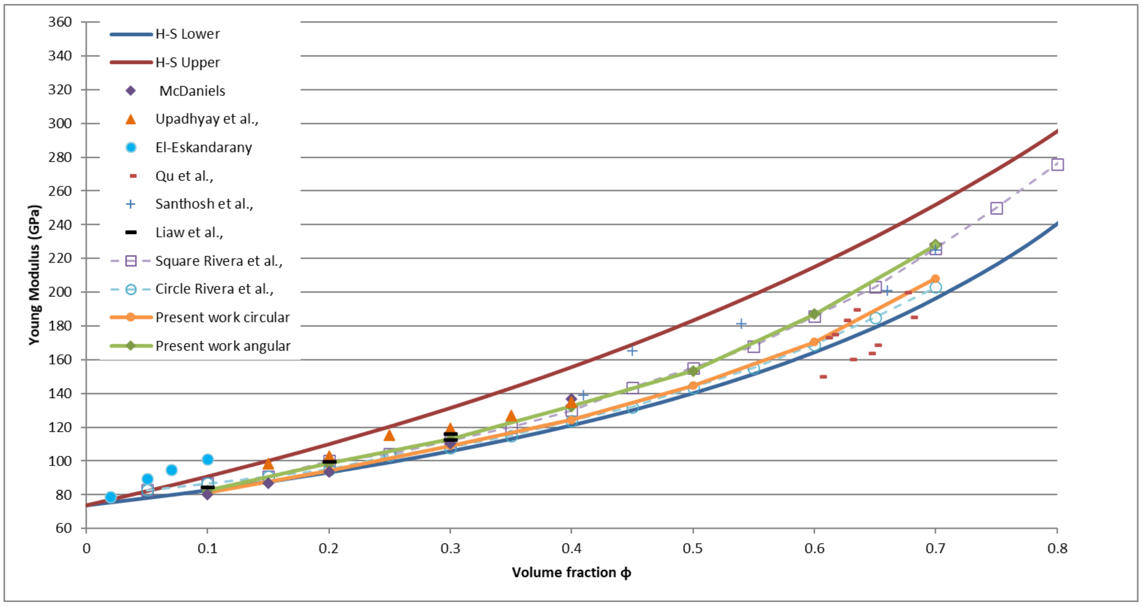

Figure 6 Effect of reinfocement content on the Young modulus of Al-SiC composite.

Furthermore, it can be seen that increasing the reinforcement volume fraction for both cases (with angular and circular shapes), increases the degree of reinforcement for the material, being consistent with the experimental data.

4. Conclusions

The present study provided the development of a two-dimensional micromechanical model for the finite element modeling of the uniaxial behavior of aluminum composite material, reinforced with silicon carbide particles, using the representative volume element approach, for circular and angular particles. The results were validated by comparing the numerical predictions against experimental data.

1. The smaller circular particles considered in the study act as stress concentrators.

2. In angular particles, the stress is concentrated in the sharp corners.

3. The Young´s modulus increases as the reinforcement volume fraction increases.

4. The particle shape has an evident effect at high reinforcement volume fractions, resulting in a higher modulus of elasticity for irregularly shaped particles.

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