Wear and Mechanical Behavior of Bottom-Up Poured AA4015/Graphite Particle-Reinforced Metal Matrix Composites

A. Chennakesava Reddy

[2]Professor, Department of Mechanical Engineering, JNT University, Hyderabad, India
dr_acreddy@yahoo.com

Abstract: *AA4015/graphite metal matrix composites were fabricated by stir casting practice and bottom-up pouring technique to explore the effect of clustering and porosity on their mechanical and wear properties. Tension and wear tests were conducted on specimens reinforced with different volume fractions of graphite. Two types of finite element models were used to estimate the strength of the MMCs. The models have been successful in predicting the experimentally observed strength the AA4015/graphite metal matrix composites. The microstructures of AA4015/graphite composites have revealed the occurrence of particle clustering and porosity. The normalized tensile strength and elastic modulus decrease with porosity and clustering of graphite nanoparticles. AA4015/graphite composites can be attractive candidates for automotive applications .*

Keywords: *AA4015 alloy, graphite, unit cell, finite element analysis, clustering, porosity, wear.*

1. INTRODUCTION

In recent years the aerospace, military and automotive industries have been promoting the technological development of composite materials to achieve good mechanical strength/density and stiffness/density ratios. Graphite is well known as a solid lubricant and its presence in aluminum alloy matrices makes the alloy, self-lubricating. Aluminum alloys reinforced with graphite fibers are emerging as potential structural materials for aerospace needs and their outstanding mechanical properties have drawn considerable scientific attention to the exploration of their possible applicability to high-technology naval applications [1]. The reason for the excellent tribological properties of graphitic aluminum is that aluminum alloy matrix yields at low stresses and deforms extensively, which enhances the deformation and fragmentation of the surface and sub-surface graphite particles even after short running-in period. This provides a continuous film of graphite on the mating surfaces which, essentially, prevents metal to metal contact and hence prevents seizure. Several processes involving incorporating graphite particles in aluminum-base alloy to produce particulate composites have been developed [2]. The most economical production of such composites is by stir casting; nevertheless, this is associated with some problems arising mainly from the apparent non-wettability of graphite by liquid aluminum alloys [3] and density differences between the two materials [4]. As a result, the introduction and retention of graphite particles in molten aluminum is extremely difficult.

In order to explore the possibilities of using Al/graphite composites as structural materials, mechanical properties need to be enhanced by controlling the nature of the distribution of the graphite particles and the interface that exists between the graphite and the matrix. Despite the growing popularity of these cast metal-graphite particle composites, no study on characterization of reinforcement distribution influenced by processing parameters has been reported as yet. Defects such as clusters, agglomerates, and segregation of graphite particles play a dominant role in accelerating the fracture process [5-30].

In view of the above mentioned problems, this study was undertaken to produce AA4015/graphite composites by bottom-up pouring technique to get good mechanical properties of the final product. In this connection, the effects of particle clustering and porosity on micromechanical behavior were analyzed using experimental procedure and finite element method (FEM). Two models were used in the computational framework. The first one is uniform distribution of nanoparticles without clustering and porosity. The second one is with clustering and porosity.

2. MATERIALS METHODS

The matrix material was AA4015 alloy. The reinforcement material was graphite nanoparticles of average size 100nm. AA4015/graphite metal matrix composites were fabricated by the stir casting process with bottom-up pouring technique (figure 1). Magnesium was added at 1%.wt to the liquid melt to improve wettability of graphite nanoparticles. The test samples were machined to get flat-rectangular specimens (figure 2b) for the tensile tests. The tensile specimens were placed in the grips of a

Universal Test Machine (UTM) at a specified grip separation and pulled until failure (figure 2a). The test speed was 2 mm/min. A strain gauge was used to determine elongation (figure 2c). The wear test was conducted on pin-on-disc machine. In the current work, a unit cell comprising of nine particles was implemented to analyze the tensile behavior AA4015/ graphite metal matrix composites at three (10%, 20% and 30%) volume fractions of graphite with and without clustering and porosity. The large strain PLANE183 element was used in the matrix in all the models. In order to model the adhesion between the matrix and the particle, a CONTACT 172 element was used. The shape of graphite nanoparticle considered in this work is spherical. The periodic particle distribution was a square array. The tensile stress, elastic modulus and shear modulus are, respectively, normalized with tensile strength, elastic modulus and shear modulus of the matrix alloy.

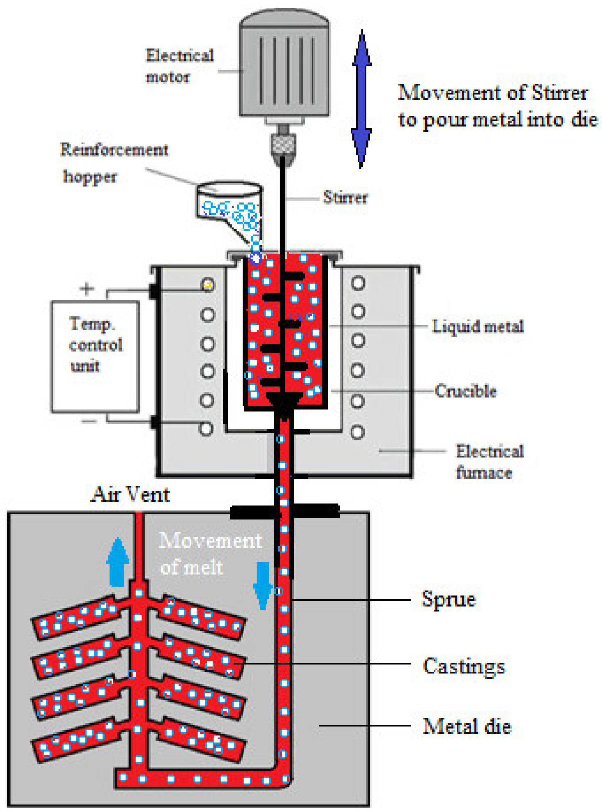

Figure 1: Concept of bottom-up pouring of composite metal.

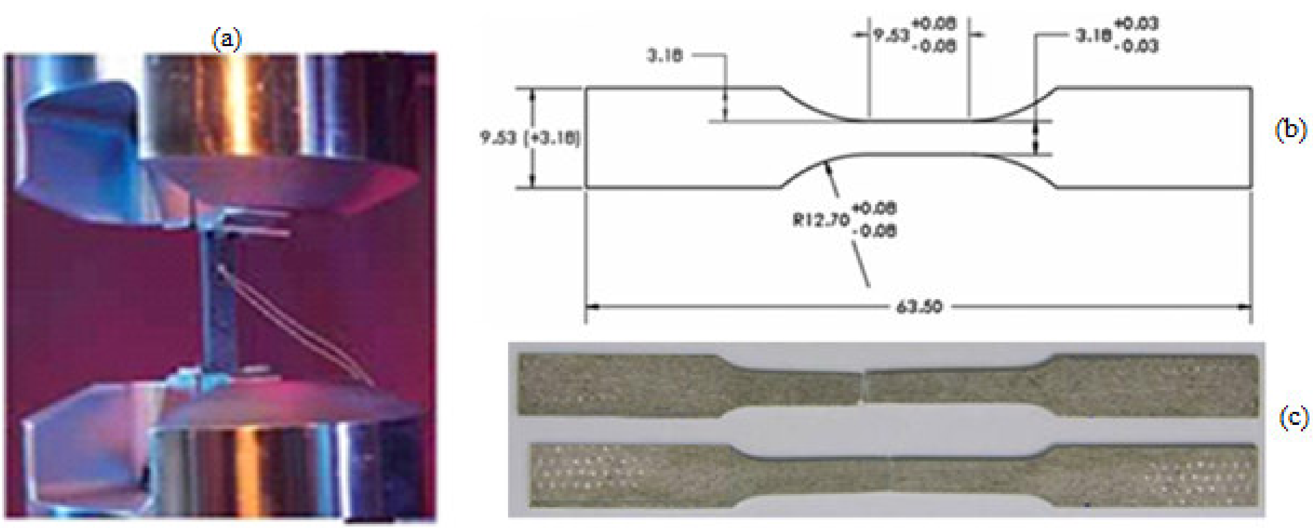

Figure 2: Testing of composites: (a) tensile testing, (b) dimensions (mm) of tensile specimen and (c) tensile specimens.

Considering adhesion, formation of precipitates, particle size, agglomeration, voids/porosity, obstacles to the dislocation, and the interfacial reaction of the particle/matrix, the formula for the strength of composite is stated below:

$$\sigma_c = \left[\sigma_m \left\{\frac{1-(v_p+v_v)^{2/3}}{1-1.5(v_p+v_v)}\right\}\right] e^{m_p(v_p+v_v)} + kd_p^{-1/2} \quad (1)$$

$$k = E_m m_m / E_p m_p$$

where, v_v and v_p are the volume fractions of voids/porosity and nanoparticles in the composite respectively, m_p and m_m are the possion's ratios of the nanoparticles and matrix respectively, d_p is the mean nanoparticle size (diameter) and E_m and E_p is elastic moduli of the matrix and the particle respectively. Elastic modulus (Young's modulus) is a measure of the stiffness of a material and is a quantity used to characterize materials. Elastic modulus is the same in all orientations for isotropic materials. Anisotropy can be seen in many composites.

The upper-bound equation is given by

$$\frac{E_c}{E_m} = \left(\frac{1-{v_v}^{2/3}}{1-{v_v}^{2/3}+v_v}\right) + \frac{1+(\delta-1){v_p}^{2/3}}{1+(\delta-1)({v_p}^{2/3}-v_p)} \quad (2)$$

The lower-bound equation is given by

$$\frac{E_c}{E_m} = 1 + \frac{v_p - v_p}{\delta/(\delta-1)-(v_p+v_v)^{1/3}} \quad (3)$$

where, $\delta = E_p/E_m$.

3. RESULTS AND DISCUSSION

The optical microstructures of the cast samples are shown in figure 3. The clustering of particles (green circles) and porosity (red arrows) are seen in the microstructures. The clustering of nanoparticles increased with increase of volume fraction. Porosity voids can be seen in the matrix and inter-nanoparticle regions.

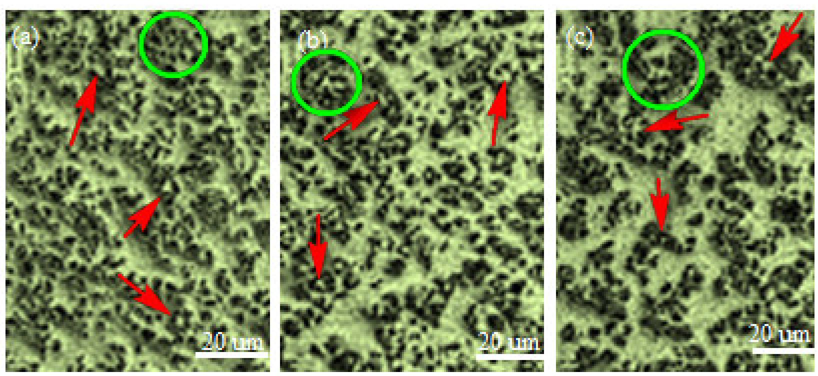

Figure 3: Microstructure showing distribution of graphite nanoparticles, clustering and porosity in AA4015 alloy matrix.

The density of AA4015/graphite metal matrix composites decreased as shown in figure 4a with increase of volume fraction of graphite nanoparticles in AA4015 alloy matrix. The densities of AA4015 alloy matrix and graphite nanoparticles are, respectively, 2.71 g/cc and 2.51 g/cc. In order to characterize the mechanical properties of AA4015 alloy/graphite composites, the strengths have been normalized with respect to the base matrix. The tensile stresses obtained from the finite element analysis (FEA) were higher than those obtained from the mathematical expression mentioned in Eq.(1) and the experimental procedure as shown in figure 4b. This is owing to the occurrence of stress concentrations at voids and clustered regions. The tensile strength was increased without porosity and clustering in AA4015/graphite metal matrix composites. It is significant to note that the graphite particulate clusters have a major effect on the tensile properties of the composites. As shown in figure 4b, the normalized tensile strength was very low at higher graphite contents, mostly due to the increased amount of clustering and voids. The normalized elastic modulus increased with increase of volume fraction of graphite nanoparticles in AA4015 alloy matrix without porosity and clustering in the composites; while it was low with porosity and clustering (figure4c). The normalized shear modulus is constant with increase of volume fraction of graphite with and without porosity and clustering (figure 4d).

In all the finite element models (figure 5), the amount of porosity and volume of clustering were maintained constant. With or Without porosity in the composites, the stress intensity decreased with increase of volume fraction of graphite in AA4015 alloy matrix. However, the stress intensity levels were higher in the composites having porosity and clustering than those in the composites without porosity and clustering. This is attributed to the fact of the stress concentration in the vicinity of the porosity and clustering. This trend is in agreement with the results obtained from experimental procedure and mathematical computation.

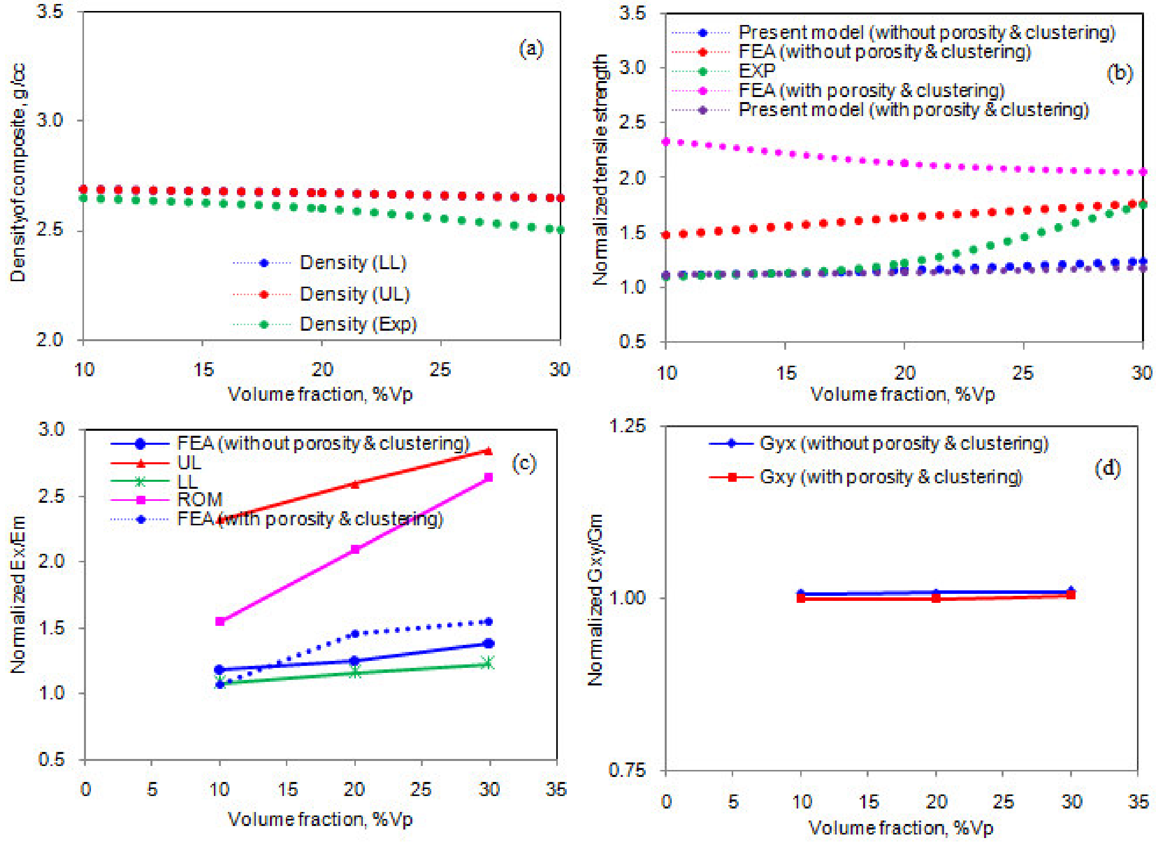

Figure 4: Effect of volume fraction on (a) density (b) normalized tensile stress, (c) normalized tensile elastic modulus and (d) normalized shear modulus of AA4015/ graphite composites.

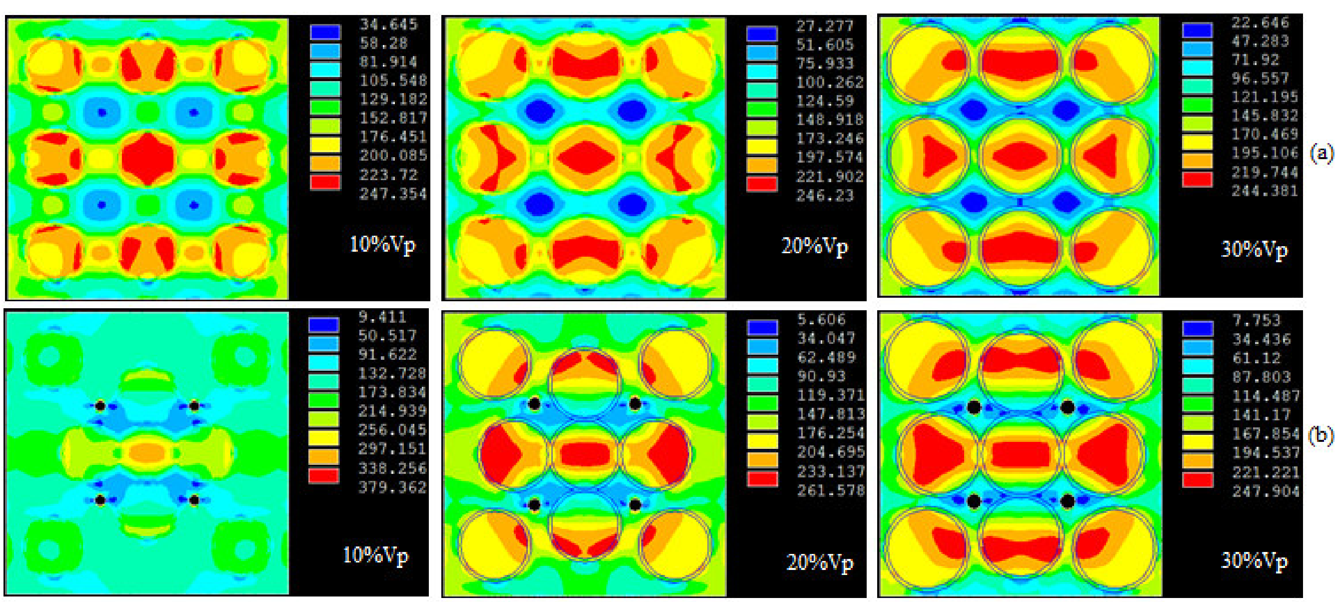

Figure 5: Images of von Mises stresses obtained from FEA: (a) without clustering and porosity and (b) with clustering and porosity.

A comparison of wear rate between 10%, 20% and 30% graphite composites is shown in figure 6. It can be seen that the wear loss of the matrix alloy and composites increased linearly with sliding distance. The wear loss decreased with increase of volume fraction of graphite. As expected, the high wear resistance of Al-graphite composites is primarily to due to the presence of graphite particles which act as a solid lubricant. Figure 7 revealed well-dispersed graphite particles on the worn surface of 30%graphite composite. The improved wear resistance of graphite composite is attributed to the uniform dispersion of graphite particles in the matrix. In view of these superior mechanical properties of AA4015/graphite composites, they could be attractive candidates for automotive applications.

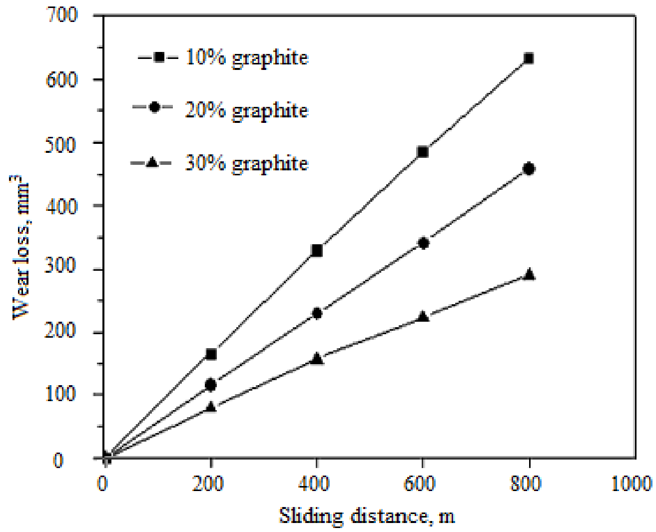

Figure 6: Wear analysis of AA4015/graphite composites.

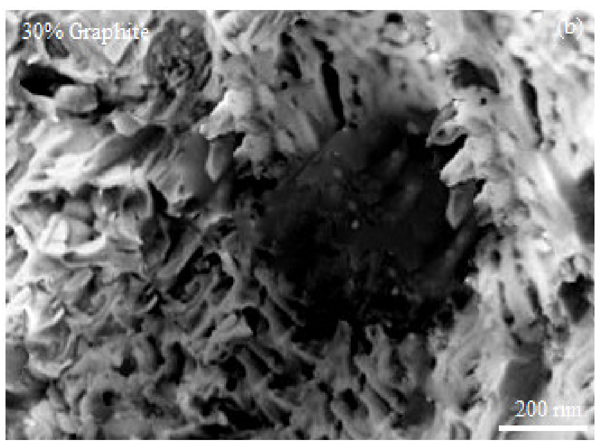

Figure 7: Micrographs of worn surfaces.

4. CONCLUSION

AA4015/ graphite metal matrix composites had clusters and porosity voids. The voids are typically located at the interface of clustered particles. The stress intensity was increased with porosity and clustering of graphite nanoparticles. The wear loss has decreased with increase of volume fraction of graphite in AA4015 alloy matrix. AA4015/graphite composites can be attractive candidates for automotive applications.

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