Finite Element Analysis Study of Micromechanical Clustering Characteristics of Graphite/AA7020 Alloy Particle Reinforced Composites

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Abstract: *In the present work, Gr/AA7020 alloy metal matrix composites were fabricated at 10%, 20% and 30% volume fractions of* Gr. *These composites were also analyzed with finite element analysis software with and without clustering of* Gr *particles. The number of Gr particles per cluster increases with increase in volume fraction of Gr particles. In the clustering regions, the stress induced was found to be high. The tensile strength and elastic modulus decrease with clustering of* Gr *particles in AA7020 alloy matrix.*

Keywords: *AA7020, graphite, spherical nanoparticle, unit-cell, finite element analysis, clustering.*

1. INTRODUCTION

The increasing need for metal matrix composites to be cost effective and at the same time have an optimum level of performance have led to particle reinforced metal matrix composites receiving considerable attention in recent years. Particle reinforced metal matrix composites have excellent mechanical properties, such as high specific stiffness and strength and low weight. The particle reinforced metal matrix composites are relatively isotropic compared to the whisker and fiber reinforced composites. The mechanical properties of particle reinforced metal matrix composites are strongly influenced by the heterogeneity of the microstructure. Reducing particle size significantly benefits overall mechanical properties so current trends in MMC production mostly include use of nanoparticles creating thus different types on nanocomposites. Major problem of conventional stir casting process for production of metal matrix composites is tendency of smaller particles specially nanoparticles to form clusters during pressing which overall contribute to increased material porosity and poor mechanical properties [1]. Due to the poor wettability between the metal matrix and ceramic particles, the particulates tend to agglomerate in the matrix [2].

The purpose of this paper is to study and predict the strength of particle reinforced metal matrix composites and understand the clustering of graphite particles in AA7020 alloy matrix from the scanning electron microscope (SEM) and two dimensional finite element analyses. The shape of graphite (Gr) nanoparticle considered in this work is spherical and it has isotropic behavior. A two-dimensional unit-cell model with periodic boundary conditions was developed using finite element method (FEM) to analyze the stress distribution in the clustering and non-clustering regions.

The manufacture of graphite was made possible by the development of high temperature electric furnaces near the end of the 19th century. The raw material for most manufactured graphites is calcined petroleum coke (amorphous carbon). The calcined coke is then milled to various particle sizes. Desired blends of coke particles are then mixed with coal tar pitch. This mixture is then pressed or extruded into billets. The billets are baked in an oxygen-free atmosphere to drive off the volatiles from the pitch. The result is an amorphous carbon product which is held together with carbonaceous pitch residue. This carbon is transformed to graphite (graphitized) by further heat treating at extremely high temperatures. In the present work isotropic graphite particles were used as shown in figure 2

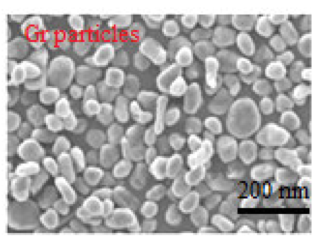


Figure 1: Isotropic graphite particles.

2. MATERIALS METHODS

The matrix material was AA7020 alloy. The reinforcement material was Gr nanoparticles of average size 100nm. Gr/AA7020 alloy composites were fabricated by the stir casting process and low pressure casting technique with argon gas at 3.0 bar. The composite samples were give solution treatment and cold rolled to the predefined size of tensile specimens. The heat-treated samples were machined to get flat-rectangular specimens (figure 1) 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. The test speed was 2 mm/min. A strain gauge was used to determine elongation. In the current work, a unit cell comprising of nine particles was implemented to analyze the tensile behavior Gr /AA7020 composites at three (10%, 20% and 30%) volume fractions of Gr. 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 with reference to application of finite element method for several metal matrix composites [4-17]. The finite element analysis was carried out on a unit cell without clustering of Gr particles is shown in figure 3a and that with clustering of Gr particles is shown in figure 3b.

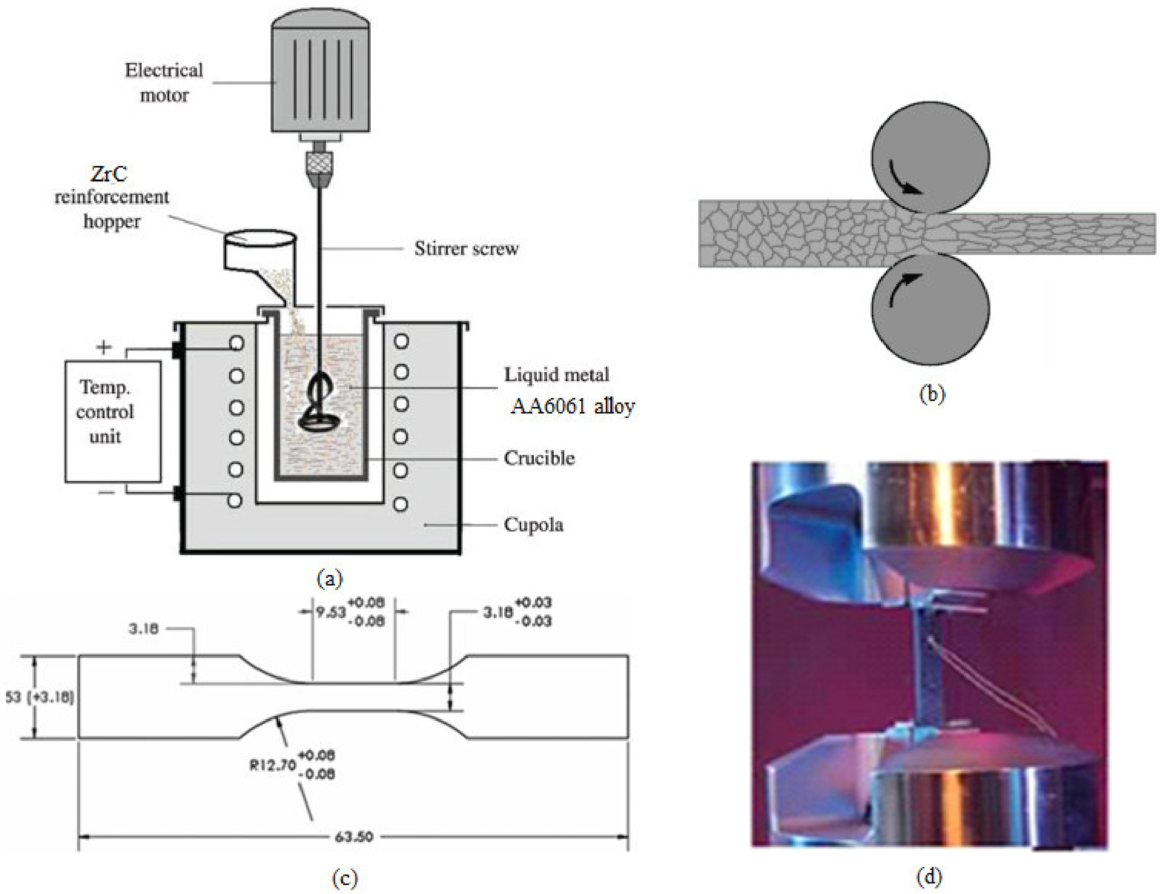


Figure 2: Stir casting process; cold rolling (b); shape and dimensions of tensile specimen (c); and tensile testing on UTM (d).

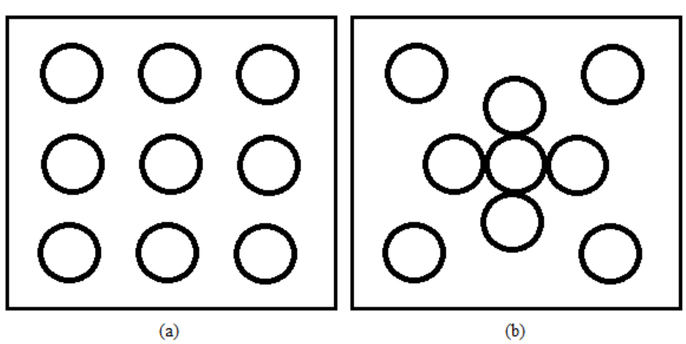


Figure 3: The interphase in a nanoparticle-reinforced composite: (a) without clustering and (b) with clustering.

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 [18, 19] is stated below:

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

$$k = E_m m_m / E_p m_p$$

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, $\delta = E_p / E_m$.

The transverse modulus is given by

$$E_t = \frac{E_m E_p}{E_m + E_p(1-{v_p}^{2/3})/{v_p}^{2/3}} + E_m\left(1 - {v_p}^{2/3} - {v_v}^{2/3}\right) \quad (4)$$

3. RESULTS AND DISCUSSION

Figure 4a shows the variation of normalized tensile strengths of the composites with the volume fractions of Gr particles. Adding the reinforcement to the matrix alloy led to the increased tensile strength without clustering Gr particles. However, due to the effect of the reinforcement clusters the tensile strength decreases with increase of Gr content in AA7020 alloy matrix. The tensile stresses obtained from the finite element analysis (FEA) are higher than those obtained from the mathematical expression mentioned in Eq.(1) and the experimental procedure as shown in figure 4a.

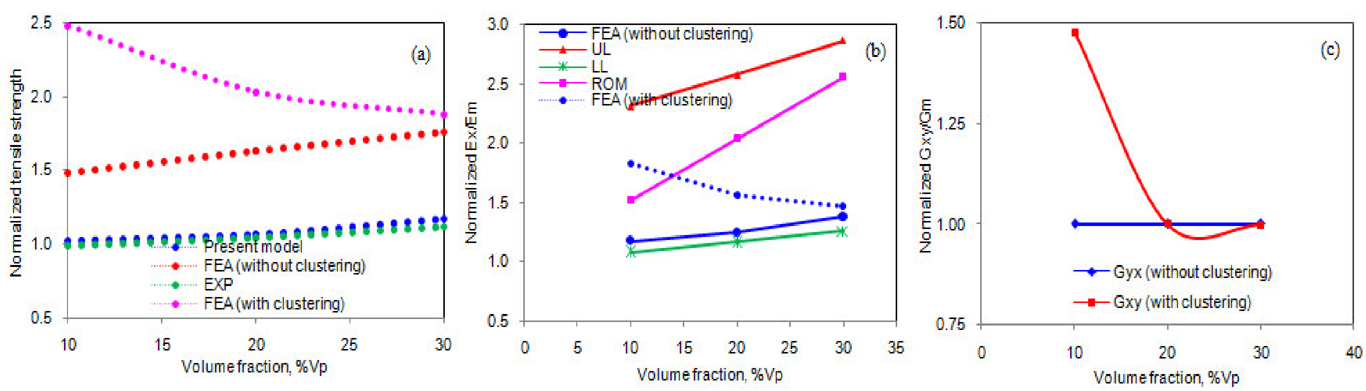
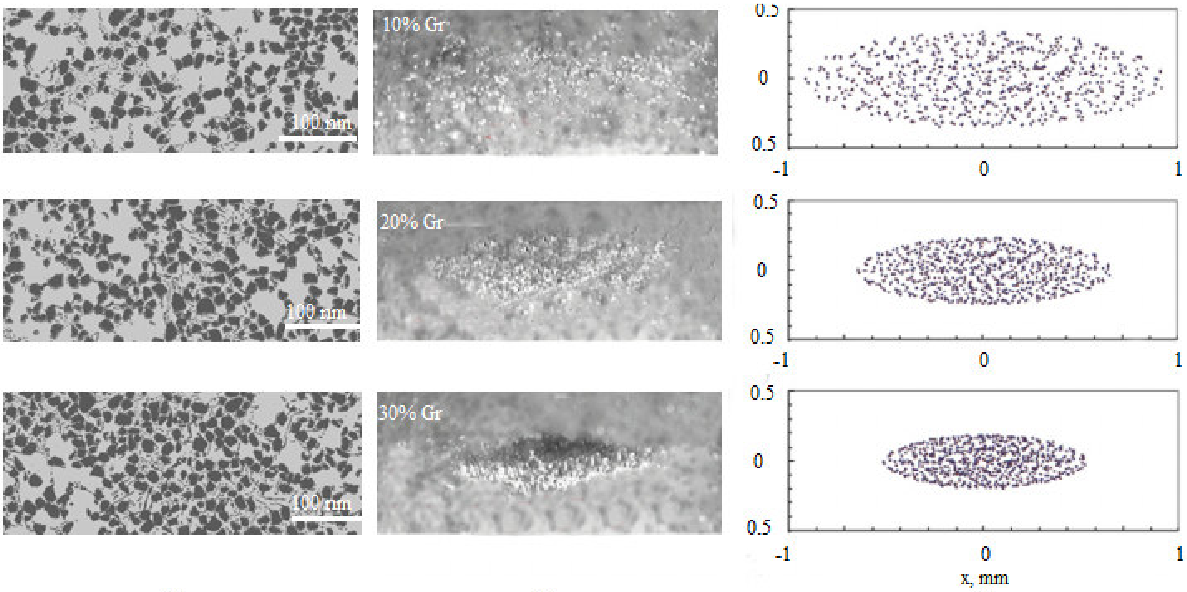


Figure 4: Effect of volume fraction on (a) normalized strength, (b) normalized tensile elastic modulus and (c) normalized shear modulus of Gr/AA7020 composites.

The Gr particles distributions in various composites are shown in figure 5. For the composite with a volume fraction of 10 vol.%, the Gr particles were randomly distributed with less number of clusters (figure 5a). For the composites with higher reinforcement contents (≥ 20 vol.%), although the distributions of the Gr particles were still relatively homogeneous, number of clusters began to increase. The number of Gr particles per a cluster in 30%Gr/AA7020 alloy composites is higher than that in 20%GR/AA7020 alloy composites. The cluster density (i.e., the number of Gr particles per cluster) increases with increase in volume fraction of Gr particles (figure 5c). The normalized elastic modulus increases with increase of volume fraction of non-clustered Gr particles in AA7020 alloy matrix; while it decreases with increase of volume fraction of clustered Gr particles in AA7020 alloy matrix (figure 4b). The normalized shear modulus is constant with increase of volume fraction of Gr without clustering of particles (figure 4c); whereas it decreases with increase of volume fraction of Gr with clustering of particles.

There is no much variation in the shear modulus for the volume fractions of 20% and 30% with clustered Gr particles. This result seems to indicate that small variations in the degree of clustering (figure 4c).



(a) (b) (c)

Figure 5: Microstructure showing distribution of 10%, 20% and 30% Gr nanoparticles in AA7020 alloy matrix.

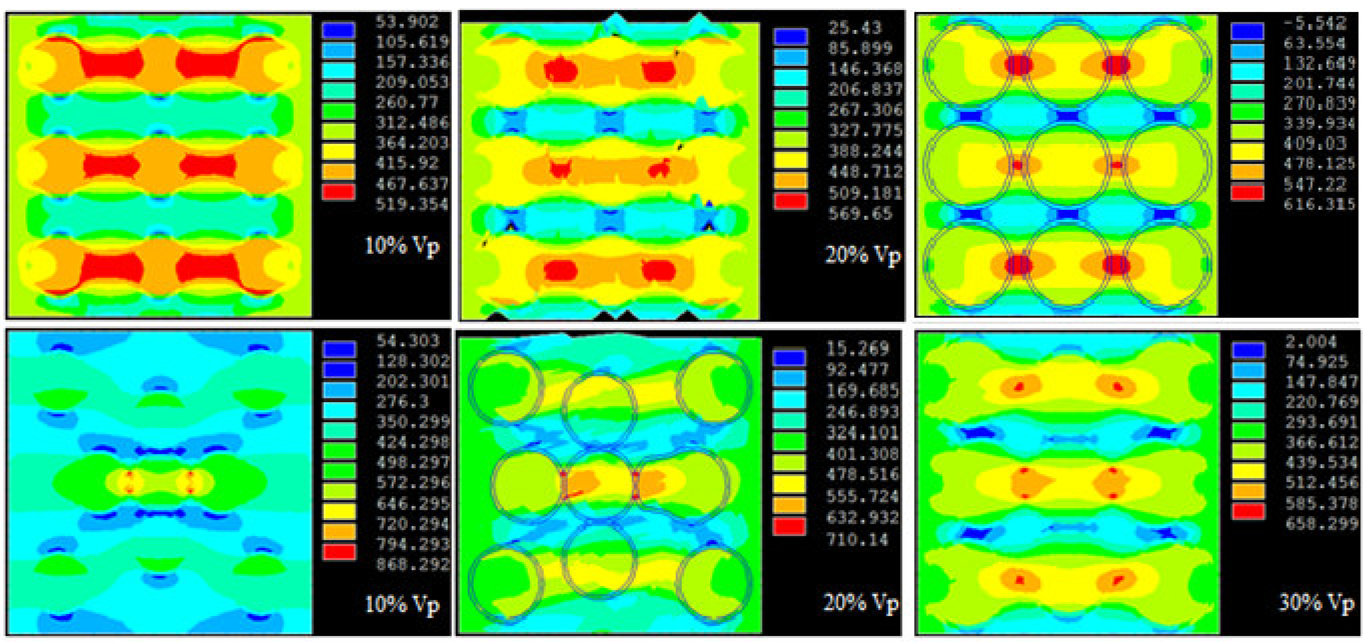


Figure 6: Images of tensile stresses obtained from FEA: (a) without clustering and (b) with clustering.

In all the models (figure 6), Gr particles-AA7020 alloy interface edges experience higher stresses. This is attributed to the fact of the stress concentration in the vicinity of the reinforcement. It indicates clearly that the tensile stress increases with increase of volume fraction of Gr particles without clustering; whereas it decreases with volume fractions with clustering of Gr particles in AA7020 alloy matrix.

4. CONCLUSION

Gr/AA7020 alloy composites were analyzed following two different schemes: (i) uniform distribution of Gr particles without clustering and (ii) clustering of Gr particles. The stresses developed in the clustering regions are higher than those developed in other sides of the clustering regions. The tensile stress, shear stress and elastic modulus decrease with the clustering of particles in Gr/AA7020 composites.

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