Role of Porosity and Clustering on Performance of AA1100/Boron Carbide Particle-Reinforced Metal Matrix Composites

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Abstract: *AA1100/B_4C metal matrix composites manufactured by stir casting practice and high pressure die casting process to investigate the effect of clustering and porosity on their mechanical properties. Tension tests were conducted on specimens reinforced with different volume fractions of B_4C. Two types of finite element models were proposed to suggest that the strength of the MMCs could be estimated from the load transfer model approach that takes into consideration the extent of clustering and porosity. The model has been successful in predicting the experimentally observed strength the AA1100/B_4C metal matrix composites. The microstructures of AA1100/B4C composites have revealed the occurrence of particle clustering and porosity. The normalized tensile strength and elastic modulus decrease with porosity and clustering of B_4C nanoparticles.*

Keywords: *AA1100 alloy, boron carbide, unit cell, finite element analysis, clustering, porosity.*

1. INTRODUCTION

Aluminum alloys reinforced with particulates are more attractive than traditional aluminum alloys for applications requiring higher stiffness and strength [1, 8]. Stir casting route is the most promising one for synthesizing discontinuous reinforcement dispersed aluminum alloy matrix composites because of its relative simplicity and easy adaptability with all shape casting processes [9-15]. The composites produced by stir casting have many defects such as particles clustering and high porosity content, which have a deleterious effect on the mechanical properties [16-23]. In cast metal-matrix composites, particle clustering (figure 1) is due to the combined effect of reinforcement settling and the rejection of the reinforcement particles by the matrix dendrites while these are growing into the remaining liquid during solidification [24-30].

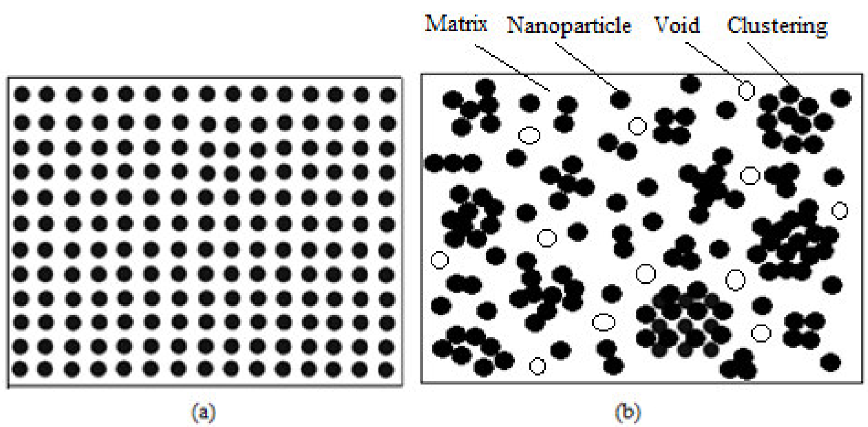

Figure 1: Distribution of particles: (a) without voids and clustering and (b) with voids and clustering.

The objective of this paper is to study the effect of particle clustering and porosity on micromechanical behavior 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 AA1100 alloy. The reinforcement material was boron carbide (B_4C) nanoparticles of average size 100nm. AA1100/ B_4C metal matrix composites were fabricated by the stir casting process (figure 2a) and high pressure die casting technique (figure 2b) with pressure at 25 MPa. The test samples were machined to get flat-rectangular specimens (figure 2d) 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 2c). The test speed was 2 mm/min. A strain gauge was used to determine elongation (figure 2c). In the current work, a unit cell comprising of nine particles was implemented to analyze the tensile behavior AA1100/ B_4C metal matrix composites at three (10%, 20% and 30%) volume fractions of B_4C 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 B_4C 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.

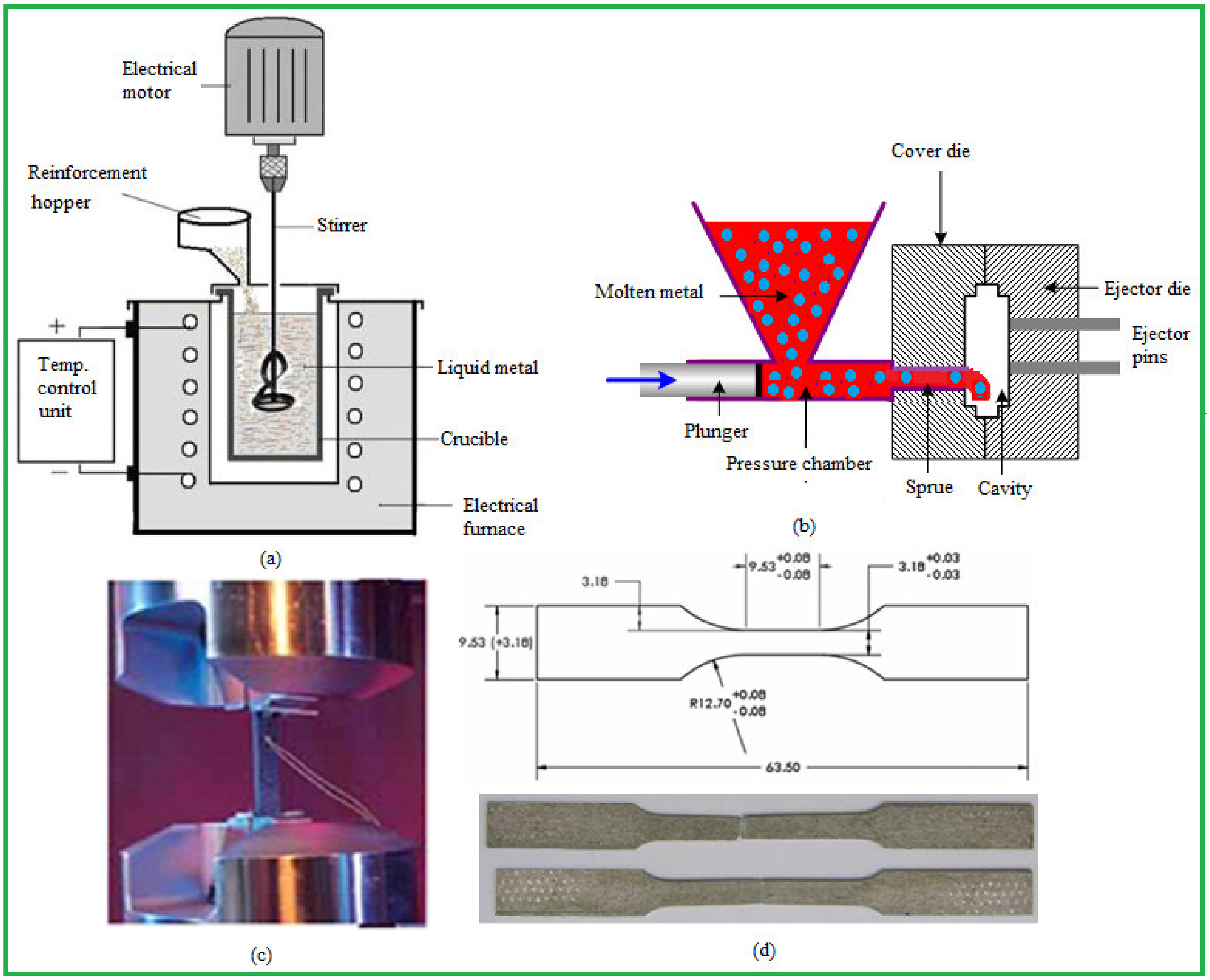

Figure 2: Fabrication and testing of composites: (a) stir casting process, (b) high pressure die casting, (c) tensile testing and (d) tensile specimens.

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:

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

$$k = E_m m_m / E_p m_p$$

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

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

where, $\delta = E_p / E_m$.

3. RESULTS AND DISCUSSION

The solidification microstructure of the samples as shown in figure 3 reveals random distribution of B_4C nanoparticles in AA1100 alloy matrix. The clustering of particles and porosity are also seen in the microstructure. The dark spots are particle clusters or some pores produced in the etching process. The clustering of nanoparticles increased with increase of volume fraction. The clustering of particles is more serious in the center of the tensile sample than that in the edge due to high pressure die casting process. Only a few of small particles can be engulfed at the interdendritic boundaries in the later stage of the solidification.

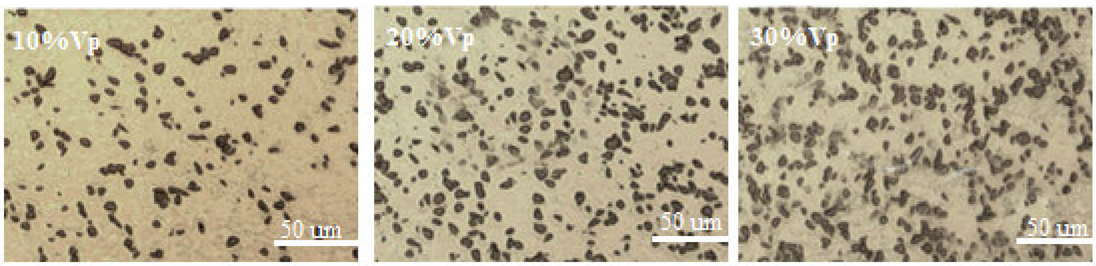

Figure 3: Microstructure showing distribution of B_4C nanoparticles, clustering and porosity in AA1100 alloy matrix.

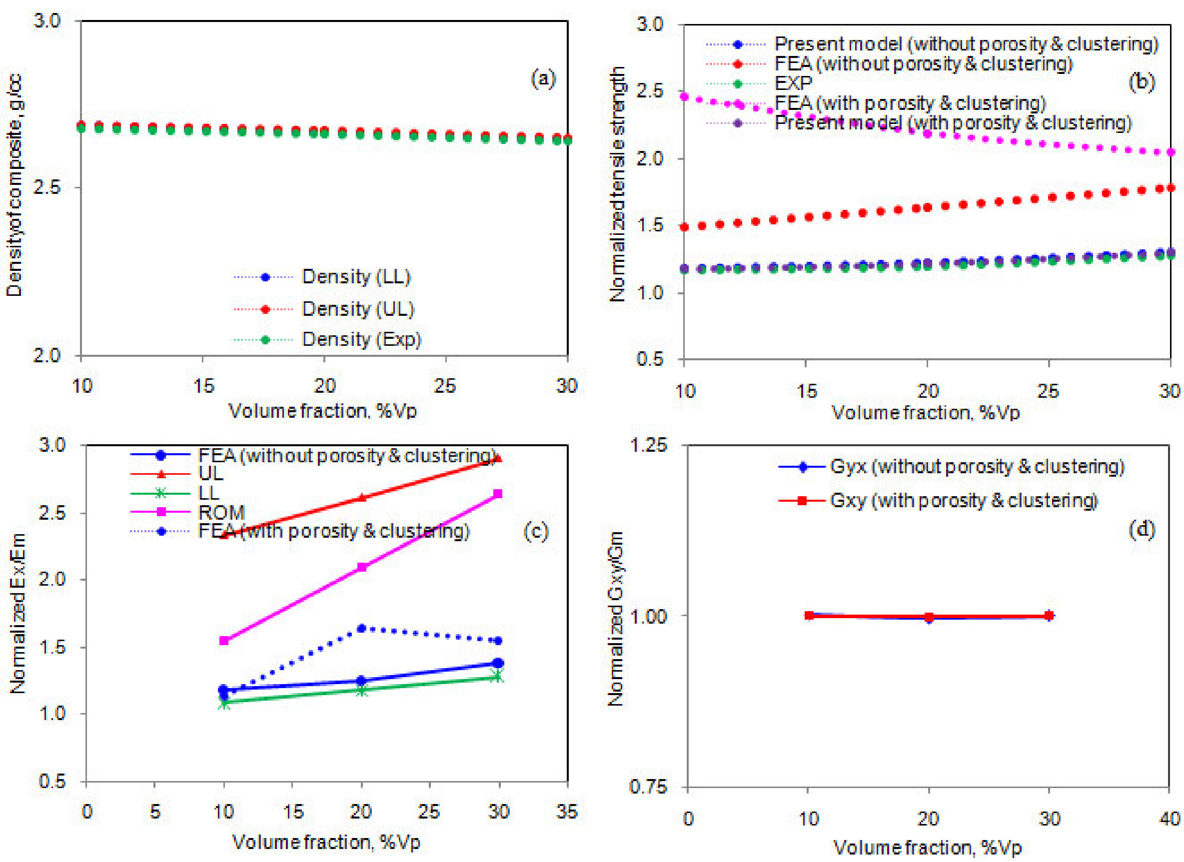

Figure 4: Effect of volume fraction on (a) density (b) normalized tensile stress, (c) normalized tensile elastic modulus and (d) normalized shear modulus of AA1100/B_4C composites.

The density of AA1100/B_4C metal matrix composites decreased as shown in figure 4a with increase of volume fraction of B_4C nanoparticles in AA1100 alloy matrix. The densities of AA1100 alloy matrix and B_4C nanoparticles are, respectively, 2.71 g/cc and 2.51 g/cc. Figure 4b represents the tensile stresses induced in the composites along the load direction. Adding B_4C nanoparticles to AA1100 alloy matrix increased tensile strength without porosity and clustering in AA1100/ B_4C metal matrix composites. Due to the effect of porosity and clustering in AA1100/ B_4C metal matrix composites, the tensile strength decreased. 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. It should be noted that the vol.% of the clusters has not increased regularly with increasing B_4C content. It is also important to note that the B_4C particulate clusters also have a significant effect on the tensile properties of the composites. As shown in figure 4b, the normalized tensile strength was very low at higher B_4C contents, mostly due to the increased amount of clustering and voids. This seems to be especially true for the composite containing 30 vol.% of B_4C when the strength is expected to be much higher than at lower B_4C levels. But, it was lower due to the increased amount of clustering and porosity. The normalized elastic modulus increased with increase of volume fraction of B_4C nanoparticles in AA1000 alloy matrix without porosity and clustering in the composites; while it decreased with increase of volume fraction of B_4C particles above 20 vol.% in AA1100 alloy matrix with porosity and clustering (figure4c). The normalized shear modulus is constant with increase of volume fraction of B_4C 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. Without porosity in the composites, the induced stress increased with increase of volume fraction of B_4C in AA1100 alloy matrix. With porosity and clustering in the composites, the induced stress was high. This indicates that the stress exceeds the allowable stress in the composites with porosity and clustering for the same load as that applied on the composites without porosity. This is attributed to the fact of the stress concentration in the vicinity of the porosity and clustering. However, the stress decreased with increase of volume fraction B_4C nanoparticles. This trend is in agreement with the results obtained from experimental procedure and mathematical computation.

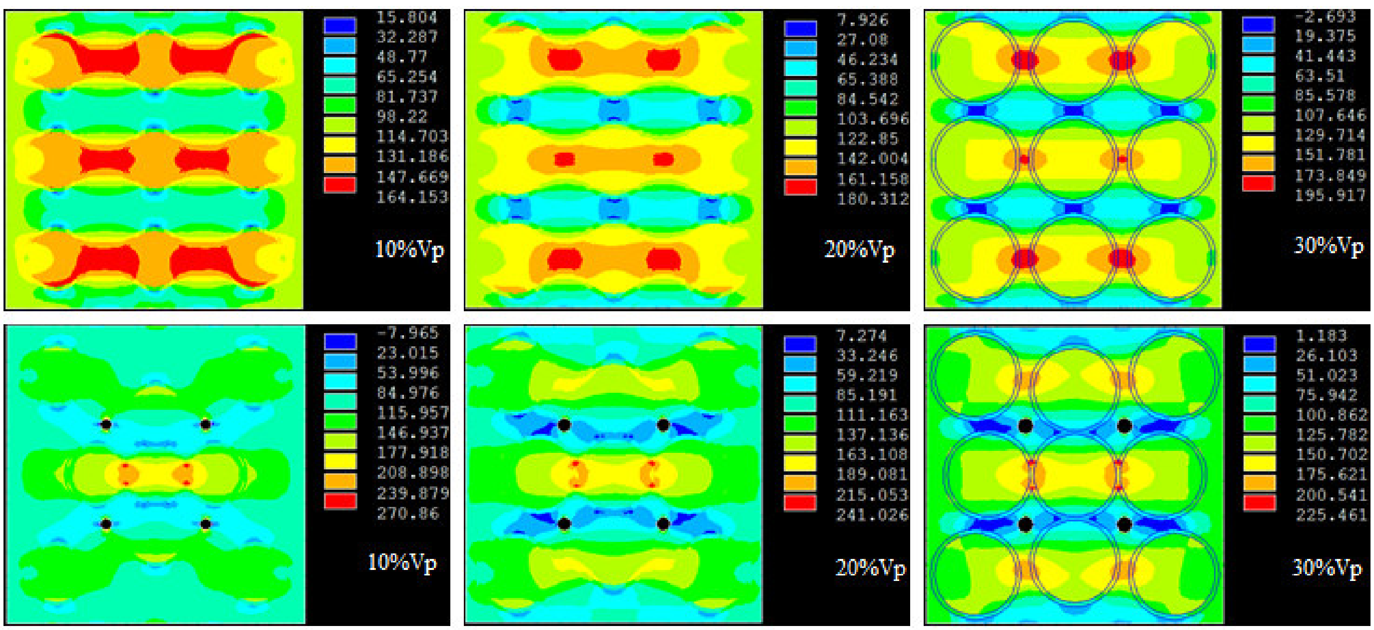

Figure 5: Images of von Mises stresses obtained from FEA: (a) without clustering and porosity and (b) with clustering and porosity.

During experimentation, the formation of necking was not observed in the tensile samples before failure and that the fracture strain of the composites was much lower than that of the AA1100 alloy matrix. Even though the composites did not exhibit much ductility on a macroscopic scale, SEM fractographs indicated that the fracture occurred by a locally ductile mechanism (figure 6). Typical fracture surfaces (figure 5) consisted of a bimodal distribution of dimples larger dimples associated with the B_4C particulates and smaller dimples associated with the ductile failure of the AA1100 alloy matrix. Decohesion from the matrix initiates at the matrix/B_4C interface. As can be seen figure 6, the clustered particles and voids are the sites for damage accumulation ahead of the crack. Cluster fracture is the dominant mode of fracture, with the clusters perpendicular to the loading direction. Cluster fracture occurs at an early stage of the tensile loading process, and cracks in the fractured clusters grow to final fracture. Thus, clustering of the reinforcement in the composite makes a negative contribution to the strength of the particulate-reinforced metal matrix composites. Also, the voids of porosity make a negative contribution to the strength of the composites. The influence of voids on the mechanical behavior of composites is a complex problem due to the large number of variables involved. Among those factors are: shape, size and location of the voids; mechanical properties of particles, matrix and interface; mechanical loads present and their nature (static or cyclic). The interface of the clustered particles is the preferred location of the voids. Cracks emanating from the voids are also seen in fractographs. On the fracture surface, ductile dimples and particles in the voids are commonly observed. As indicated earlier, the predominant fracture mode of particulate-reinforced metal matrix composites is cluster cracking, which occurs at an early stage of loading. Since the ductility of the composites is low, it is reasonable to assume that the cracks through the fractured clusters and particles obey the fracture mechanics approach, and have a plane strain plastic zone. The plastic zone size increases with increasing load, and failure of the composite occurs when the plastic zones of adjacent cracks coalesce. The tested specimens failed in shear with cracks emanating either from voids or from the clustered regions as observed in figure 6.

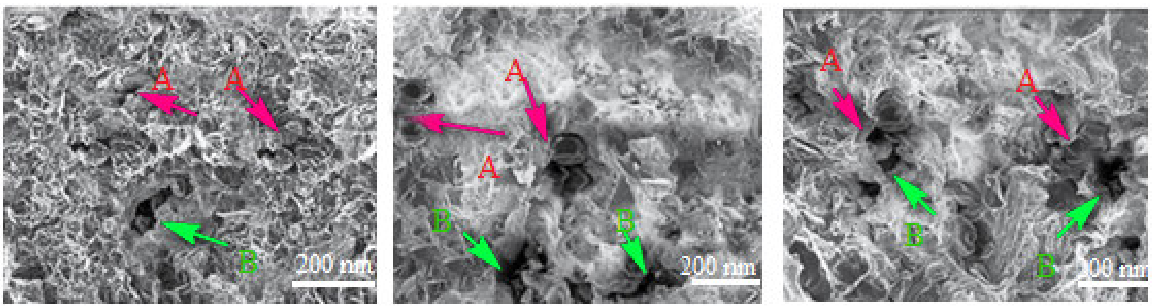

Figure 6: SEM images of tested specimens showing porosity and clustering of particles.

4. CONCLUSION

AA1100/B_4C metal matrix composite produced presented a larger amount of clusters and a few voids due to high pressure die casting process. The voids are typically located at the interface of clustered particles. The cracks clearly emanate from the voids and clustered regions. The rate of strength decrease with porosity and clustering of nanoparticles was analyzed for tensile strength for three volume fractions of boron carbide nanoparticles in AA1100 alloy matrix. The strength degradations were generally within the range of data reported in the literature.

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