Microstructure-Property Relationship of AA3003/Boron Nitride Particle-Reinforced Metal Matrix Composites Cast by Bottom-Up Pouring

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Abstract: *AA3003/BN 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 properties. Tension tests were conducted on specimens reinforced with different volume fractions of BN. Two types of finite element models were used to estimate the strength of the MMCs. The microstructures of AA3003/BN composites were observed particle clustering and porosity. The stress intensity decreases with or without particle clustering and porosity; however the stress intensity was found to high in the composites having porosity and particle clustering.*

Keywords: *AA3003 alloy, boron nitride, unit cell, finite element analysis, clustering, porosity.*

1. INTRODUCTION

Aluminum metal matrix composites have considerable applications in aerospace, automotive and military industries due to their high strength to wear ratio, stiffness, light weight, good wear resistance and improved thermal and electrical properties. Boron nitride (BN) is an interesting material owing to its unique combination of properties, such as low density, high melting point, high thermal conductivity and high electrical resistivity [1]. Literature studies reveal the positive influence of boron nitride particles on the mechanical properties improvement in aluminum matrix composites. Ex-situ methods wherein externally manufactured nanoparticles are introduced into the metallic alloy tend to yield materials that are plagued by particle clustering, interface de-bonding, contamination, and porosity. Homogeneous distribution of the nanoparticles is more readily attained by in-situ processing methods wherein the reinforcing particles are created directly in the aluminum alloy. Excessive particle clustering that increased when smaller nanoparticles were used [2-18]. Composite materials demonstrate varying strength due to the presence of dislocation, vacancy defects, porosity and chemical impurities. Only a limited number of studies have been conducted to study the effect of porosity on the elastic modulus, tensile strength and the fracture strength of the BN –Al composite [19-29].

The objective of this paper is to study the effect of structure-property relationship on mechanical behavior of AA3003/BN nanocomposites. Finite element method (FEM) was used particle clustering and porosity on micromechanical behavior using experimental procedure. 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 AA3003 alloy. The reinforcement material was BN nanoparticles of average size 100nm. AA3003/BN 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 BN 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). In the current work, a unit cell comprising of nine particles was implemented to analyze the tensile behavior AA1100/BN metal matrix composites at three (10%, 20% and 30%) volume fractions of BN 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 BN 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.

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.

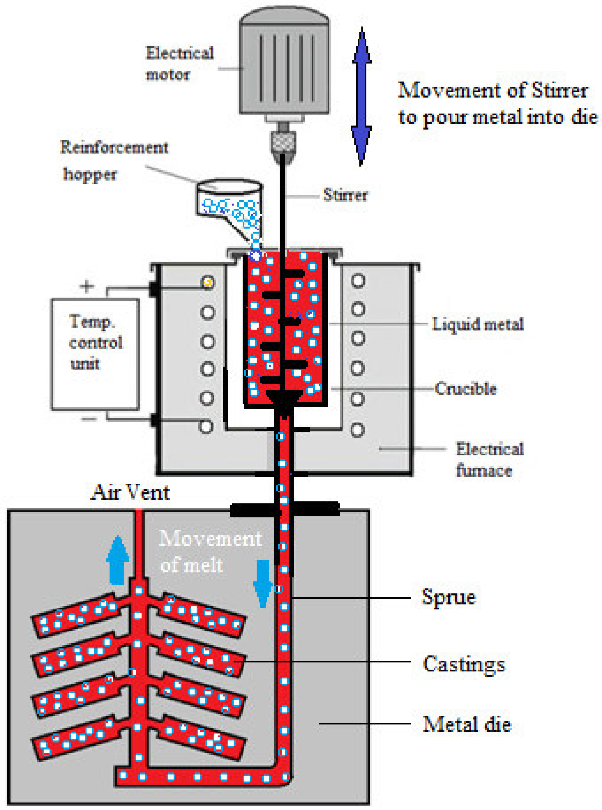

Figure 1: Concept of bottom-up pouring of composite metal.

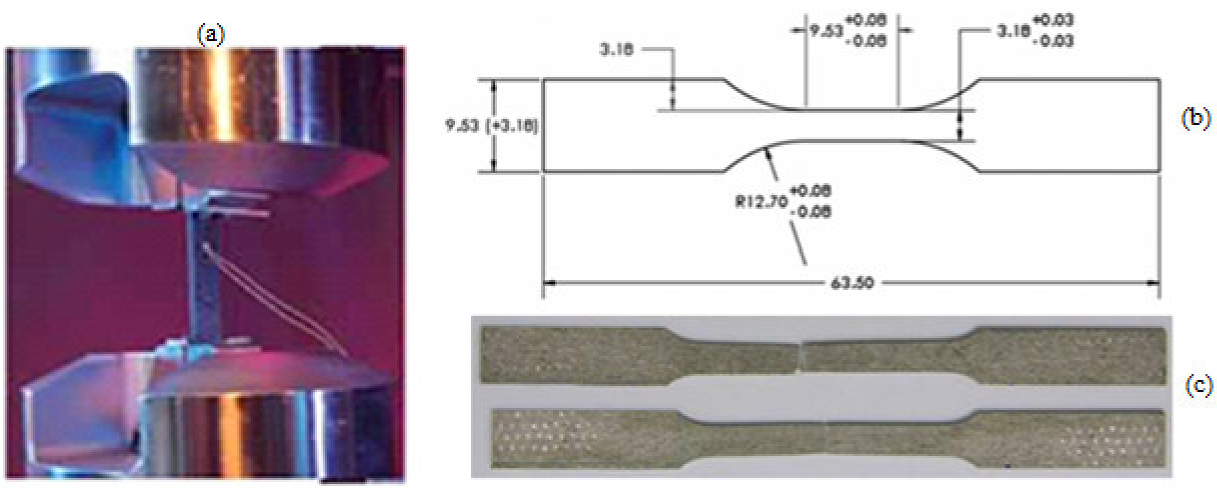

Figure 2: Testing of composites: (a) tensile testing, (b) dimensions (mm) of tensile specimen and (c) tensile specimens.

The upper-bound equation is given by

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

The lower-bound equation is given by

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

where, $\delta = E_p/E_m$.

3. RESULTS AND DISCUSSION

The clustering of particles and porosity are seen in the microstructures shown in figure 3. The dark spots are particle clusters. The clustering of nanoparticles increased with increase of volume fraction. Some porosity voids are observed in the inter-nanoparticle regions.

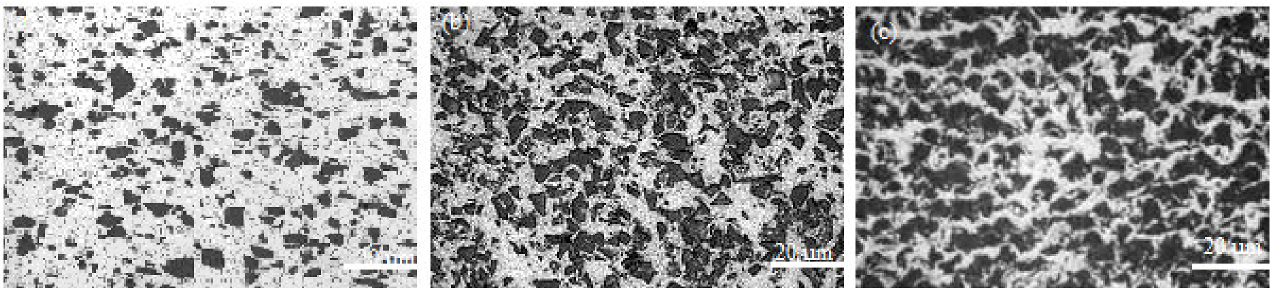

Figure 3: Microstructure showing distribution of BN nanoparticles, clustering and porosity in AA3003 alloy matrix.

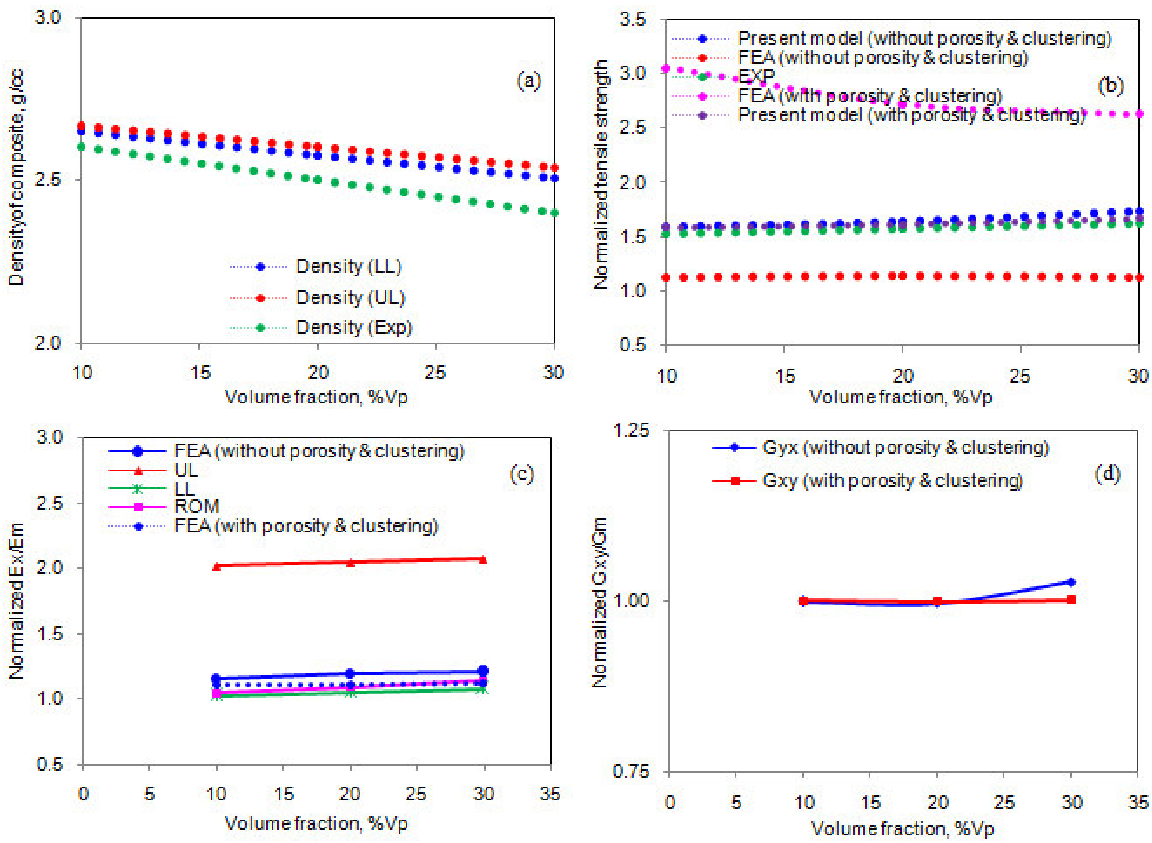

Figure 4: Effect of volume fraction on (a) density (b) normalized tensile stress, (c) normalized tensile elastic modulus and (d) normalized shear modulus of AA3003/BN composites.

The density of AA3003/ BN metal matrix composites decreased as shown in figure 4a with increase of volume fraction of BN nanoparticles in AA1100 alloy matrix. The densities of AA3003 alloy matrix and BN nanoparticles are, respectively, 2.73 g/cc and 2.1 g/cc. 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. The tensile strength was increased without porosity and clustering in AA3003/BN metal matrix composites. As shown in figure 4b, the normalized tensile strength was very low at higher BN contents, mostly due to the increased amount of clustering and voids. The normalized elastic modulus was unaffected with increase of volume fraction of BN nanoparticles in AA3003 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 SBN without porosity and clustering, but it increased slightly with 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 and clustering in the composites, the stress intensity decreased with increase of volume fraction of BN in AA3003 alloy matrix. However, the stress intensity 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 due to domination of the stress concentration in the vicinity of the porosity and clustering.

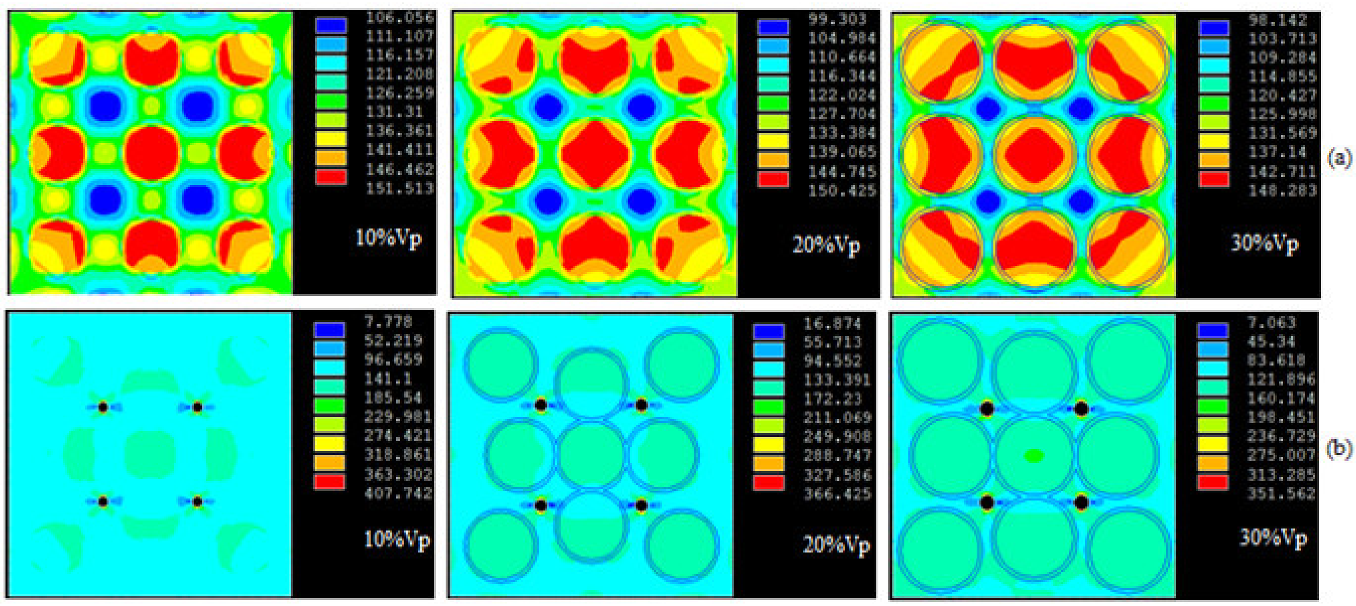

Figure 5: Images of von Mises stresses obtained from FEA: (a) without clustering and porosity and (b) with clustering and porosity.

1. CONCLUSION

AA3003/BN metal matrix composites had clusters and porosity voids. The stress intensity decreases with or without porosity and clustering of nanoparticles in the composites. The stress intensity was very high in AA3003/BN composites with porosity and clustering because of stress concentration effects.

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