Effect of Particle Clustering on Micromechanical Properties of Boron Nitride/AA3003 Alloy Particle-Reinforced Metal Matrix Composites

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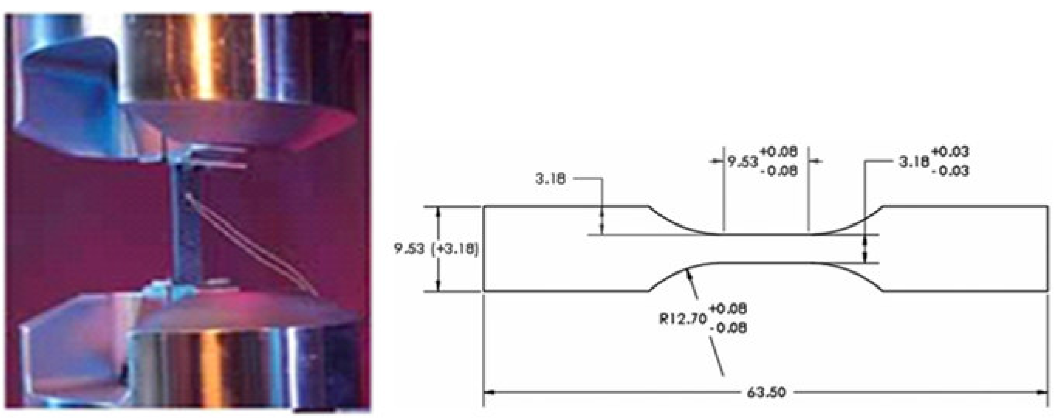
Abstract: *In the present work, the BN/ AA3003 metal matrix composites were fabricated at 10%, 20% and 30% volume fractions of BN. These composites were analyzed with finite element analysis code with and without clustering of BN particles. The microstructure of BN /AA3003 alloy composites reveals the clustering of BN particles. The FEA results confirm the experimental results. The tensile strength and elastic modulus decrease with clustering of BN particles in AA3003 alloy matrix.*

Keywords: *AA3003, boron nitride, spherical nanoparticle, RVE model, finite element analysis, clustering.*

1. INTRODUCTION

Fabrication of metal matrix nanocomposites is much more complicated than that of micro-metal matrix composites. When the particles scale down from the micro- to the nano-level, many additional difficulties have to be solved and new issues have to be faced. The reaction between ceramic nanoparticles with the matrix is still unclear. The inappropriate bonding interface may lead to the failure of the composites. Clustering of particles is another issue of paramount importance, to be solved especially in large parts. Good dispersion of fillers and pigments is a prerequisite for good mechanical properties. For instance, multiple studies have shown that filler agglomerates act as stress concentrators, reducing tensile and impact strength. The ubiquitous van der Waals forces ensure that particles attract each other, thus favoring agglomeration. It can be determined that the strength increases with an increase of aspect ratio and a decrease of clustering degree. For the composite directly reinforced with as-coated whiskers, clustering of whiskers is so extensive that tensile fracture will easily occur at clustered regions. It can be determined that the strength increases with an increase of aspect ratio and a decrease of clustering degree [1, 2].

The objective of this paper is to study the effect of particle clustering on interface debonding and particle fracture using the finite element method (FEM). The shape of boron nitride nanoparticle considered in this work is spherical. The periodic particle distribution was a square array [3-6]. Two models were used in the computational framework. The first one is uniform distribution of nanoparticles without clustering. The second one is uniform distribution of nanoparticles with clustering.



(a) (b)

Figure 1: Tensile testing: UTM with temperature controlled chamber and (b) shape and dimensions of tensile specimen.

2. MATERIALS METHODS

The matrix material was AA3003 alloy. The reinforcement material was boron nitride (BN) nanoparticles of average size 100nm. AA3003 alloy/BN 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 BN/AA3003 composites at three (10%, 20% and 30%) volume fractions of BN and at different temperatures. 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 discretization a unit cell without clustering of BN particles is shown in figure 2a and that with clustering of BN particles is shown in figure 2b.

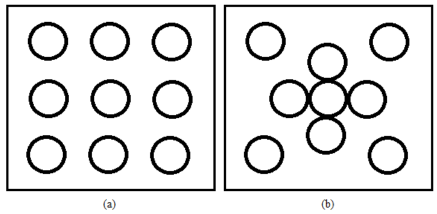


Figure 2: The interphase in a nanoparticle-reinforced composite: (a) without clustering and (b) with clustering.

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 [7, 9] is stated below:

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

$$k = E_m m_m / E_p m_p$$

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

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

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, $\delta = E_p / E_m$.

The transverse modulus is given by

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

3. RESULTS AND DISCUSSION

The optical micrograph as shown in figure 3 reveals random distribution of 20%BN and 30% BN (30% Vp) particles in AA3003 alloy matrix. The clustering of particles is also seen in the microstructure.

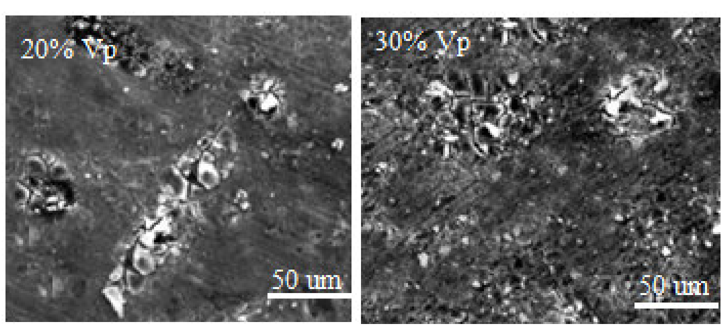


Figure 4: Microstructure showing distribution of 20% and 30% BN nanoparticles in AA3003 alloy matrix.

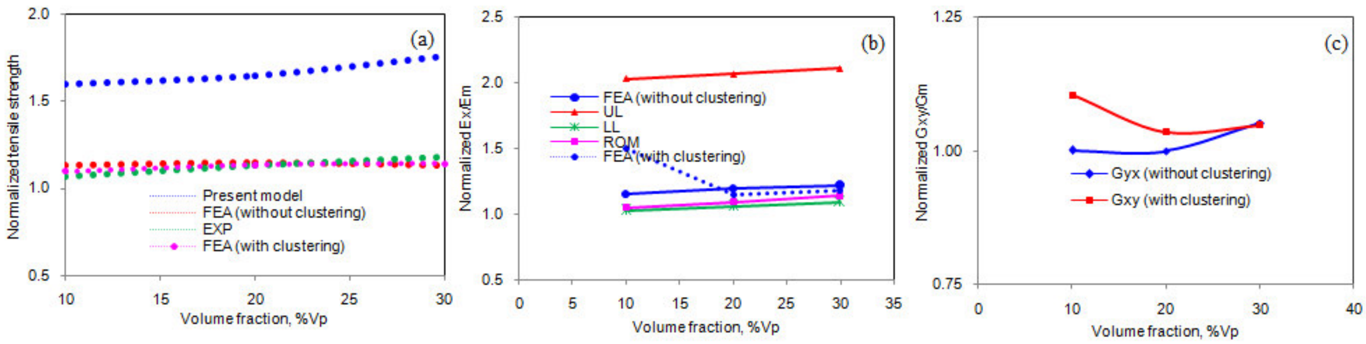


Figure 5: Effect of volume fraction on (a) normalized strength, (b) normalized tensile elastic modulus and (c) normalized shear modulus of BN/AA3003 composites.

Figure 5a represents the normalized tensile stresses induced in the composites along the load direction. The tensile stresses induced in the composites were normalized with tensile strength of AA3003 alloy matrix. The results obtained from the finite element analysis (FEA) are lower than those obtained from the mathematical expression mentioned in Eq.(1) and the experimental procedure. For the case without clustering of BN particles, the tensile stress increases with increase of volume fraction of BN in AA3003 alloy matrix. But, the tensile stress decreases with increase of volume fraction of BN in AA3003 alloy matrix in the case of clustering of BN particles. The normalized elastic modulus increases with increase of volume fraction of non-clustered BN particles in AA3003 alloy matrix; while it decreases with increase of volume fraction of clustered BN particles in AA3003 alloy matrix (figure 5b). The normalized shear modulus is increases with increase of volume fraction of BN without clustering of particles and it decreases with clustering of BN particles as seen from figure 5c.

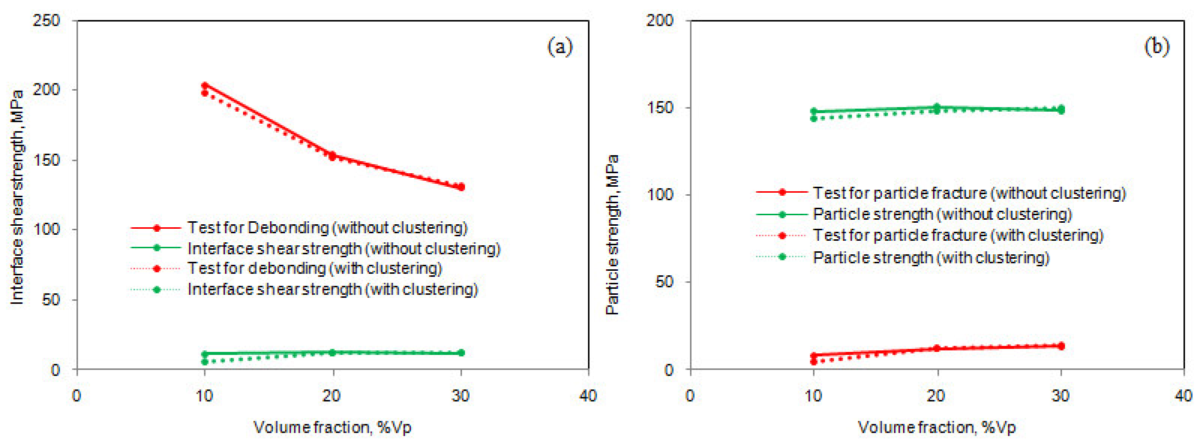


Figure 6: Criterion for interfacial debonding (a) and for particle fracture (b).

If the particle deforms in an elastic manner (according to Hooke's law) then,

$$\tau = \frac{n}{2}\sigma_p \quad (5)$$

where, n is a dimensionless constant given by:

$$n = \left[\frac{2E_m}{E_p(1+v_m)ln(1+v_p)}\right]^{1/2}$$

σ_p is the particle stress.
For the interfacial debonding/yielding to occur, the interfacial shear stress reaches its shear strength:

$$\tau = \tau_{max} \quad (6)$$

For particle/matrix interfacial debonding [10-18] can occur if the following condition is satisfied:

$$\tau_{max} < \frac{n\sigma_p}{2} \quad (7)$$

It is observed from figure 6a that the interfacial debonding occurs between BN nanoparticle and AA3003 alloy matrix as the condition in Eq.(7) is satisfied.

If particle fracture occurs when the stress in the particle reaches its ultimate tensile strength, $\sigma_{p,uts}$, then setting the boundary condition at

$$\sigma_p = \sigma_{p,\,uts} \tag{8}$$

The relationship between the strength of the particle and the interfacial shear stress [10-18] is such that if

$$\sigma_{P,uts} < \frac{2\tau}{n} \tag{9}$$

Then the particle will fracture. From the figure 6b, it is observed that the BN nanoparticle was not fractured as the condition in Eq. (9) is not satisfied.

As seen from figure 7 the von Mises stress induced at the interface are sufficient to break interface between the particles. Hence, the interfacial debonding was occurred between the particle and the matrix.

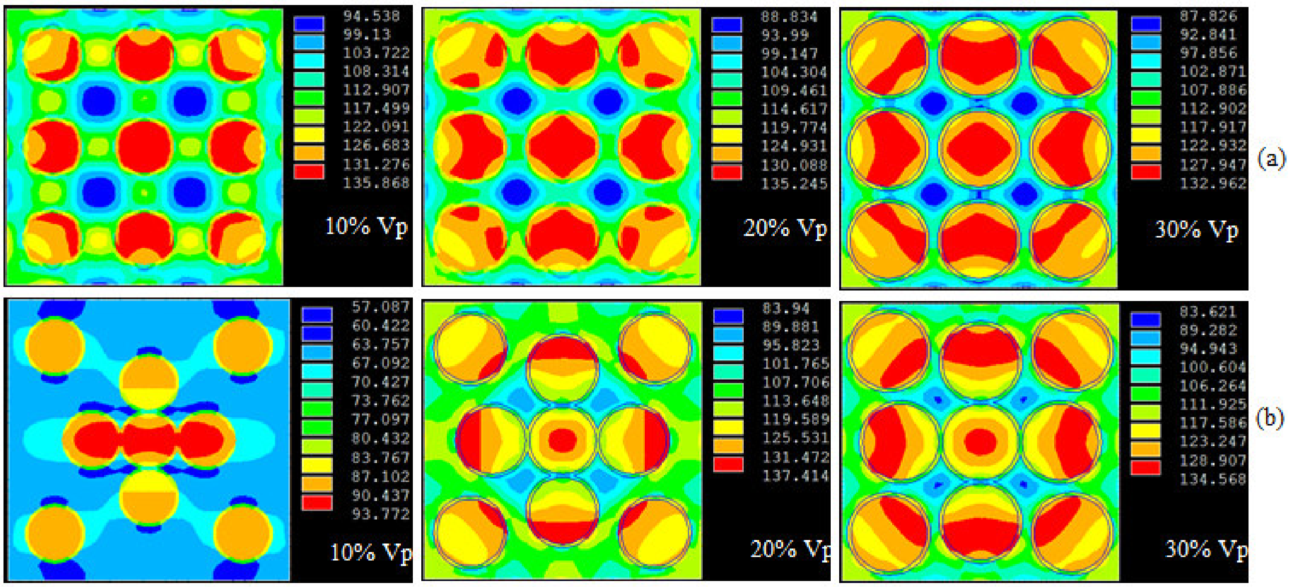


Figure 7: Images of von Mises stresses obtained from FEA: (a) without clustering and (b) with clustering.

4. CONCLUSION

The microstructure of BN/ AA3003 alloy composites reveals the clustering of particles. The results obtained from FEA match with those of experimental procedure. The tensile stress, shear stress and elastic modulus decrease with the clustering of particles BN/AA3003 composites.

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