Investigation of the Clustering Behavior of Titanium Diboride Particles in TiB_2/AA2024 Alloy Metal Matrix Composites

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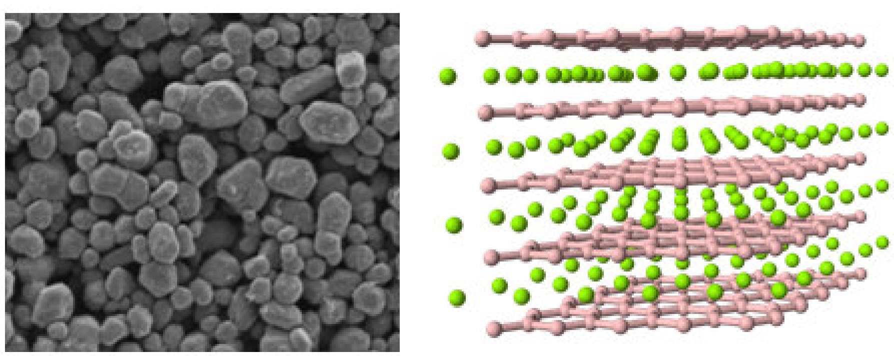
Abstract: *In the present work, TiB_2/AA2024alloy metal matrix composites were fabricated at 10%, 20% and 30% volume fractions of TiB_2. These composites were also analyzed with finite element analysis software with and without clustering of TiB_2 particles. The stress induced was found to be high in the clustering regions. The tensile strength and elastic modulus decreased with clustering of TiB_2 particles in AA2024 alloy matrix.*

Keywords: *AA2024, titanium diboride, spherical nanoparticle, unit-cell, finite element analysis, clustering.*

1. INTRODUCTION

In preparing the metal matrix composites based on Al, the addition of the reinforcement is generally made to the matrix through stir casting. Some of the major problems associated with the stir casting techniques are non-uniform distribution of particles within the matrix and poor wettability of the particles by the matrix. Clustering of TiB_2 particles by casting route is quite common. Titanium boride clusters arise as a result of too long holding times during stir casting process [1, 2]. In cast metal-matrix composites, particle clustering 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 [3]. Titanium diboride (TiB_2) is an extremely hard ceramic which has excellent heat conductivity, oxidation stability and resistance to mechanical erosion. TiB_2 is resistant to oxidation in air at temperatures up to 1100 °C, and to hydrochloric and hydrofluoric acid, but reacts with alkalis, nitric acid and sulfuric acid [4].

The objective of this work is to systematically elucidate the effects associated with nanoparticle additions and clustering of TiB_2 particles formed during stir casting process. 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 shape of TiB_2 nanoparticle considered in this work is spherical and it has isotropic behavior.



(a) (b)

Figure 1: TiB_2 particles and crystal structure.

2. MATERIALS METHODS

The matrix material was AA2024 alloy. The reinforcement material was TiB_2 nanoparticles (figure 1) of average size 100nm. TiB_2/AA2024 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 2) 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 TiB_2/AA2024 composites at three (10%, 20% and 30%) volume fractions of TiB_2. 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 [5-18]. The finite element analysis was carried out on a unit cell without clustering of TiB_2 particles is shown in figure 3a and that with clustering of TiB_2 particles is shown in figure 3b.

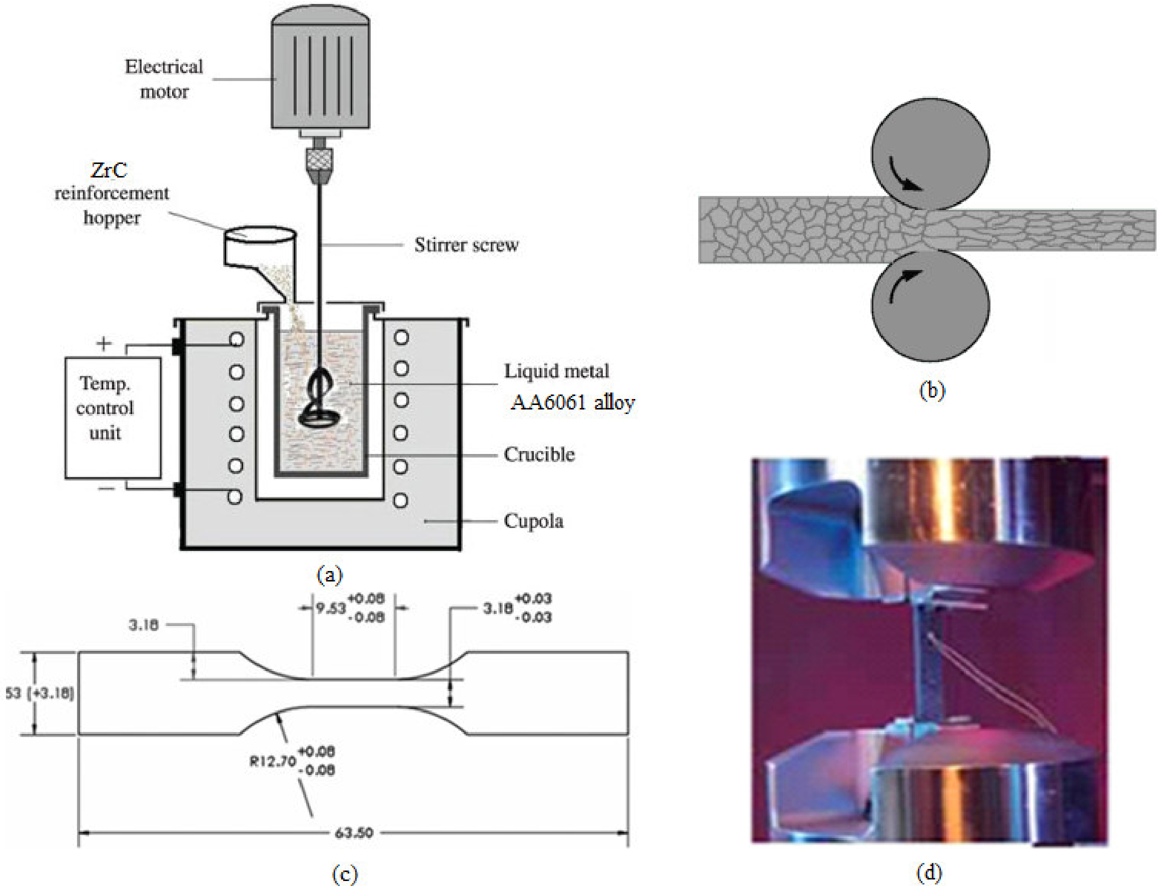


Figure 2: Stir casting process; cold rolling (b); shape and dimensions of tensile specimen (c); and tensile testing on UTM (d).

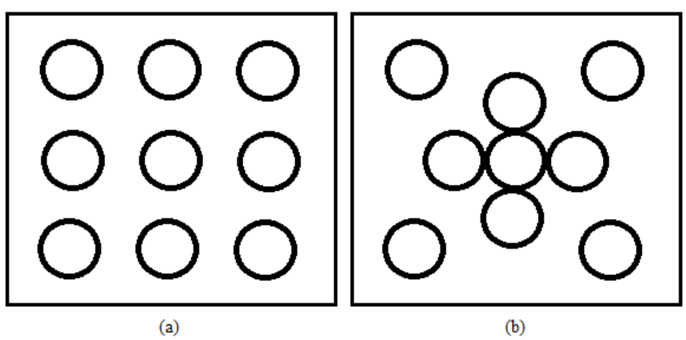


Figure 3: The interphase in a nanoparticle-reinforced composite: (a) without clustering and (b) with clustering.

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 [19, 20] 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

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

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, $\delta = E_p / E_m$.

The transverse modulus is given by

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

3. RESULTS AND DISCUSSION

Addition of TiB_2 nanoparticles to AA2024 alloy matrix increased tensile strength without clustering TiB_2 particles as shown in figure 4a. On account of agglomeration of TiB_2 nanoparticles, the tensile strength decreased with increase of TiB_2 content in AA2024 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.

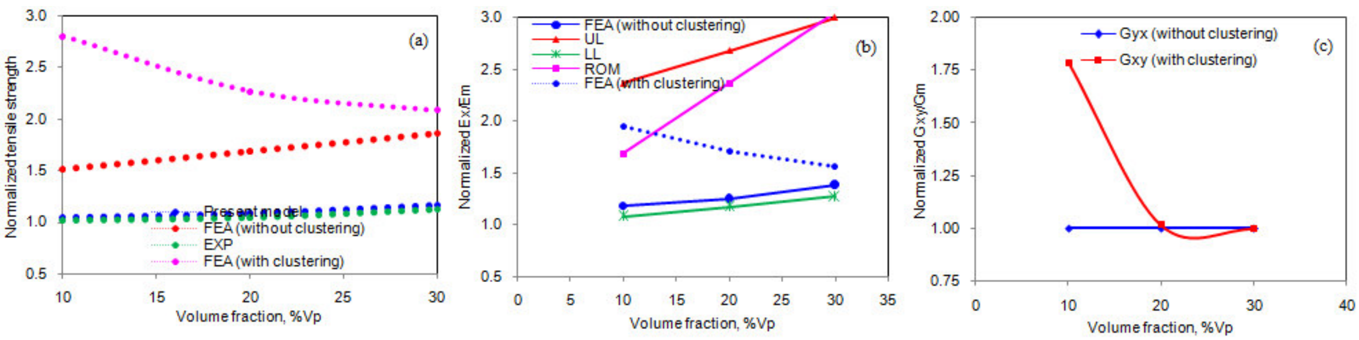


Figure 4: Effect of volume fraction on (a) normalized strength, (b) normalized tensile elastic modulus and (c) normalized shear modulus of TiB_2/AA2024 composites.

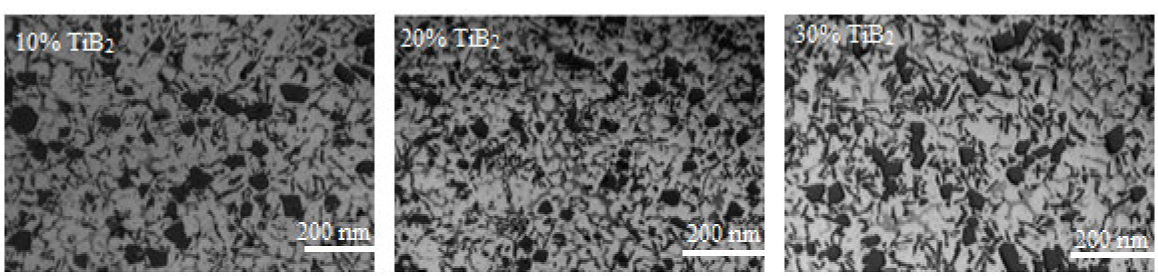


Figure 5: Microstructure showing distribution of 10%, 20% and 30% TiB_2 nanoparticles in AA2024 alloy matrix.

The distributions of TiB_2 nanoparticles in various composites are shown in figure 5. For the composite with a volume fraction of 10 vol.%, less number of clusters were formed (figure 5a). For the composites with higher reinforcement contents (≥ 20% TiB_2 nanoparticles) the number of clusters was high. The number of TiB_2 particles per a cluster in 30% TiB_2/AA2024 alloy composites is higher than that in 20% TiB_2/AA2024 alloy and 20% TiB_2/AA2024 alloy composites. The cluster density increased with increase in volume fraction of TiB_2 particles (figure 5c). The normalized elastic modulus increased with increase of volume fraction of non-clustered TiB_2 particles in AA2024 alloy matrix; while it decreased with increase of volume fraction of clustered TiB_2 particles in AA2024 alloy matrix (figure 4b). The normalized shear modulus is constant with increase of volume fraction of TiB_2 without clustering of particles but it decreased with clustering of TiB_2 nanoparticles(figure 4c).

In all the models (figure 6), TiB_2 particles-AA2024 alloy interface regions experience higher stresses. This is attributed to the fact of the stress concentration in the region of interface. It indicates clearly that the tensile stress increased with increase of volume fraction of TiB_2 particles without clustering; whereas it decreased with volume fractions with clustering of TiB_2 particles in AA2024 alloy matrix.

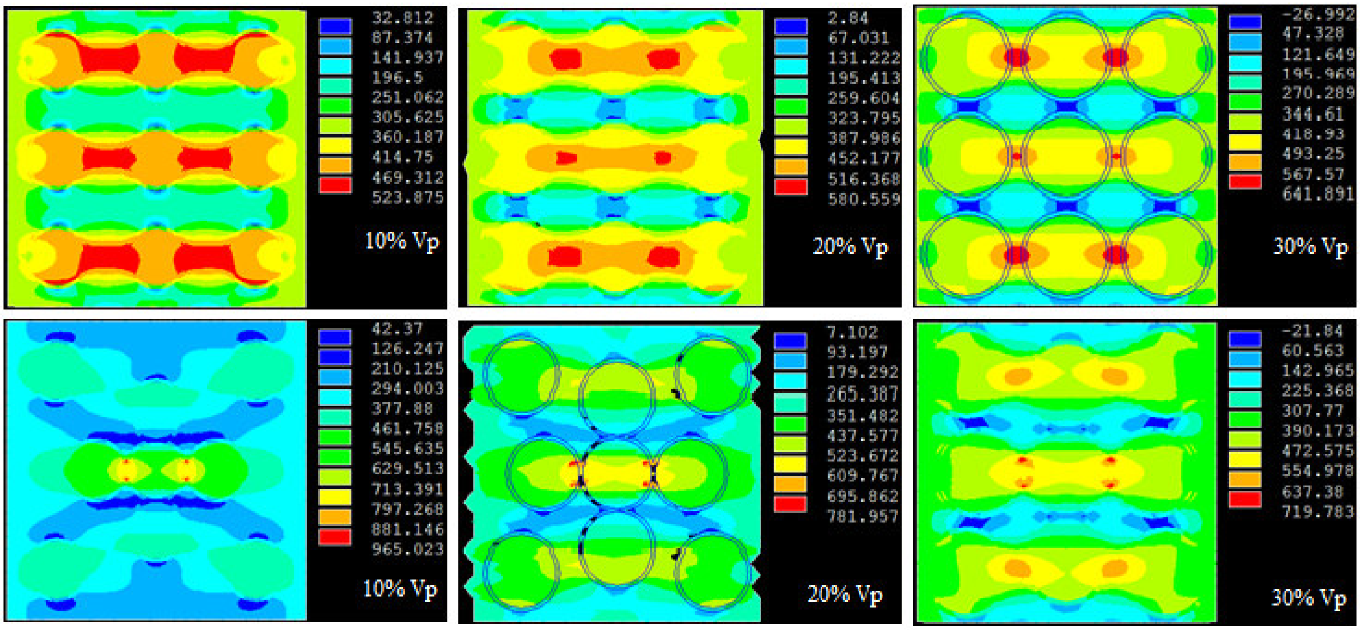


Figure 6: Images of tensile stresses obtained from FEA: (a) without clustering and (b) with clustering.

4. CONCLUSION

TiB_2/AA2024 alloy composites were analyzed following two different schemes: (i) uniform distribution of TiB_2 particles without clustering and (ii) clustering of TiB_2 particles. The stresses developed in the clustering regions are higher than those developed in other sides of the clustering regions. The tensile stress and elastic modulus have decreased with the clustering of particles in TiB_2/AA2024 composites.

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