Effect of Clustering Induced Porosity on Micromechanical Properties of AA6061/Titanium Oxide Particulate Metal matrix Composites

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Abstract: *Titanium oxide nanoparticle reinforced AA6061 metal matrix composite specimens were produced high pressure die casting technique in bottom pouring stir casting. The porosity and clustering content and their influence on micromechanical properties were evaluated in as-cast condition by finite element method and experimental procedure. Porosity and clustering were measured with different volume percents of titanium oxide nanoparticles reinforced to Aa6061 metal matrix composites. Porosity content was significantly linear with increasing percentage of titanium oxide nanoparticles in the clusters. The tensile strength and stiffness of have been decreased with increased porosity and clustering of* TiO_2 *nanoparticles.*

Keywords: *AA6061 alloy, titanium oxide, unit cell, finite element analysis, clustering, porosity.*

1. INTRODUCTION

Particulate MMCs have been shown to offer improvements in strength, wear resistance, structural efficiency, reliability and control of physical properties such as density and coefficient of thermal expansion, thereby providing improved engineering performance in comparison to the un-reinforced matrix [1, 2]. Agglomeration induces unwanted brittle nature to the MMC and is more severe when the particulate size is in sub-micron or nanoscale range. Such microstructural inhomogenity can create strain gradients locally and reduces the tensile strength significantly [3-5]. Severe agglomeration nature of nanoparticles, due to high cohesive energy, combined with lack of dispersive technology for mixing non-wettable nano-particles have hindered the progress in fabrication of high performance nanoparticulate MMCs with liquid processing routes. Porosity is among the difficulties occurring in cast MMC which has significantly affected the composite mechanical behavior. In the earlier research papers, there was a focus on the effect of porosity on the mechanical properties of various aluminum alloy matrix composites reinforced with nanoparticles of carbides [7-13], nitrides [14, 15], oxides [16-22], carbon/graphite [23-27] and others [28, 29]. For the fabrication of all these composites, stir casting process was used to mix the matrix material and the reinforcement nanoparticles. Porosity formation in stir-cast discontinuous reinforced MMC was originated from gas entrapment during vigorous stirring method, air bubbles entering either the slurry or as an air envelope to the particles, water vapor on the surface of the reinforcing particles, hydrogen evolution and solidification shrinkage[30]. The porosity presence has also affected the yield strength, ductility, Poisson's ratio and ultimate tensile strength of MMC [7-31]. The yield strength and ultimate tensile strength were decreased by increasing porosity content.

The stir casting process and high pressure die casting technique was employed for the fabrication of AA6061/titanium oxide metal matrix composites by varying the titanium oxide (TiO_2) volume fractions of 10%, 20% and 30%. Two unit cell models consisting of circular TiO_2 nanoparticles modeled to obtain composites with and without clustering and porosity using finite element methods. Several techniques have been used to quantify clustering of particles in a composite [32-34]. The micromechanical properties were estimated using finite element methods, experimental procedure and empirical formulation.

2. MATERIALS METHODS

The matrix material was AA6061 alloy. The reinforcement material was TiO_2 nanoparticles of average size 100nm. AA6061/TiO_2 metal matrix composites were fabricated by the stir casting process and high pressure die casting technique with pressure at 25 MPa. The test samples were machined to get flat-rectangular specimens 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 present work, a unit cell comprising of nine particles was implemented to analyze the micromechanical behavior AA6061/TiO_2 metal matrix composites at three (10%, 20% and 30%) volume fractions of TiO_2 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 TiO_2 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:

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

$$k = E_m m_m / E_p m_p$$

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, $\delta = E_p/E_m$.

3. RESULTS AND DISCUSSION

The density of AA6061/TiO_2 metal matrix composites increased as shown in figure 1a with increase of volume fraction of TiO_2 nanoparticles. This is due to fact that the density (4.05g/cc) of SiO_2 is higher than that (2.70 g/cc) of AA6061 alloy.

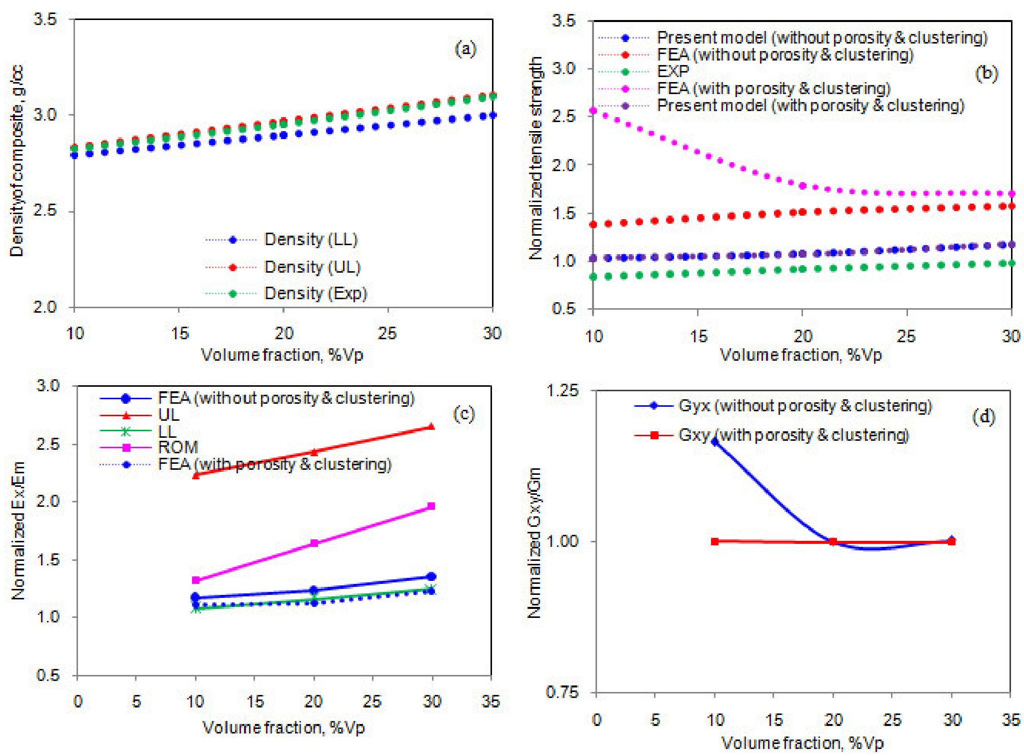

Figure 1: Effect of volume fraction on (a) density (b) normalized tensile stress, (c) normalized tensile elastic modulus and (d) normalized shear modulus of AA6061/TiO_2 composites.

Reinforcing of TiO_2 nanoparticles into AA6061 alloy matrix increased the tensile strength (figure 1b) and stiffness (figure 1c) without porosity and clustering. The shear modulus (figure 1d) was not affected by the quantity of TiO_2 loading in the AA6061 alloy matrix. The volume fraction of clusters and porosity voids increased with increase in volume fraction TiO_2 nanoparticles in AA6061 alloy matrix as shown in figure 2. Also the porosity increased with increase of nanoparticles in a cluster as shown in figure 3. This can be attributed to high pressure die casting technique. The nanoparticles were forced closure because of the applied pressure during die casting process. Consequently, the cluster density was increased. Due to increased number of nanoparticles in a cluster and the shape of the nanoparticles, the microporosity was induced across the cluster. This is further confirmed by the increased content of Ti in the clusters as shown in figure 4. The titanium content increased with increase of volume fraction of TiO_2 nanoparticles. The tensile strength decreased owing to porosity and clustering in AA6061/TiO_2 metal matrix composites. As a result of stress concentrations at voids and clustered regions, 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.

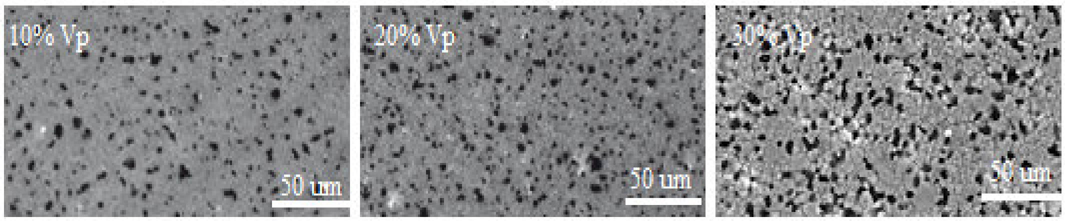

Figure 2: Distribution of nanoparticles and their clustering.

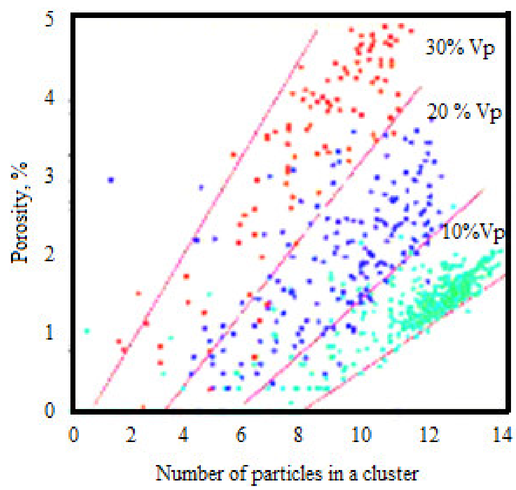

Figure 3: Influence of high pressure die casting process on clustering and porosity.

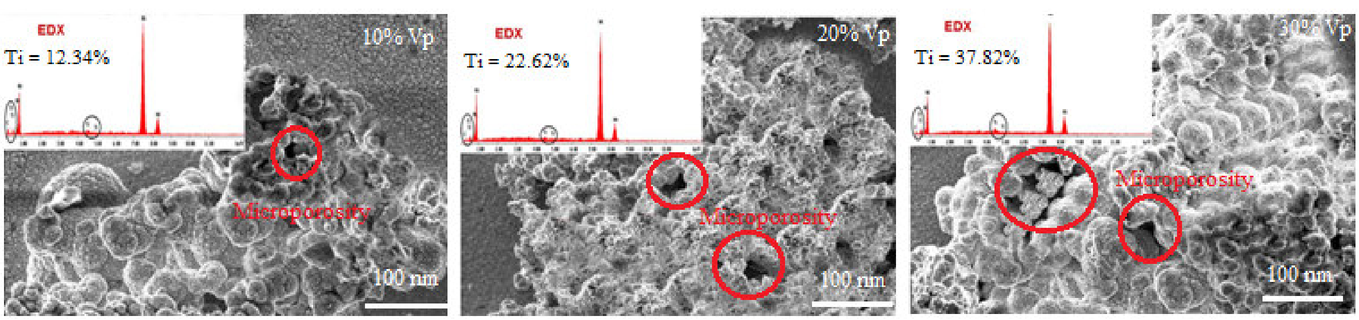

Figure 4: Ti content in the clusters.

Without porosity and clustering in the composites, the stress intensity remains constant with increase in the volume fraction of TiO_2 in AA6061 alloy matrix (figure 5a). With porosity and clustering in the composites, the stress intensities were high in the composites. However, the stress intensity decreased with increase of TiO_2 nanoparticles in AA6061 alloy matrix (figure 5b).

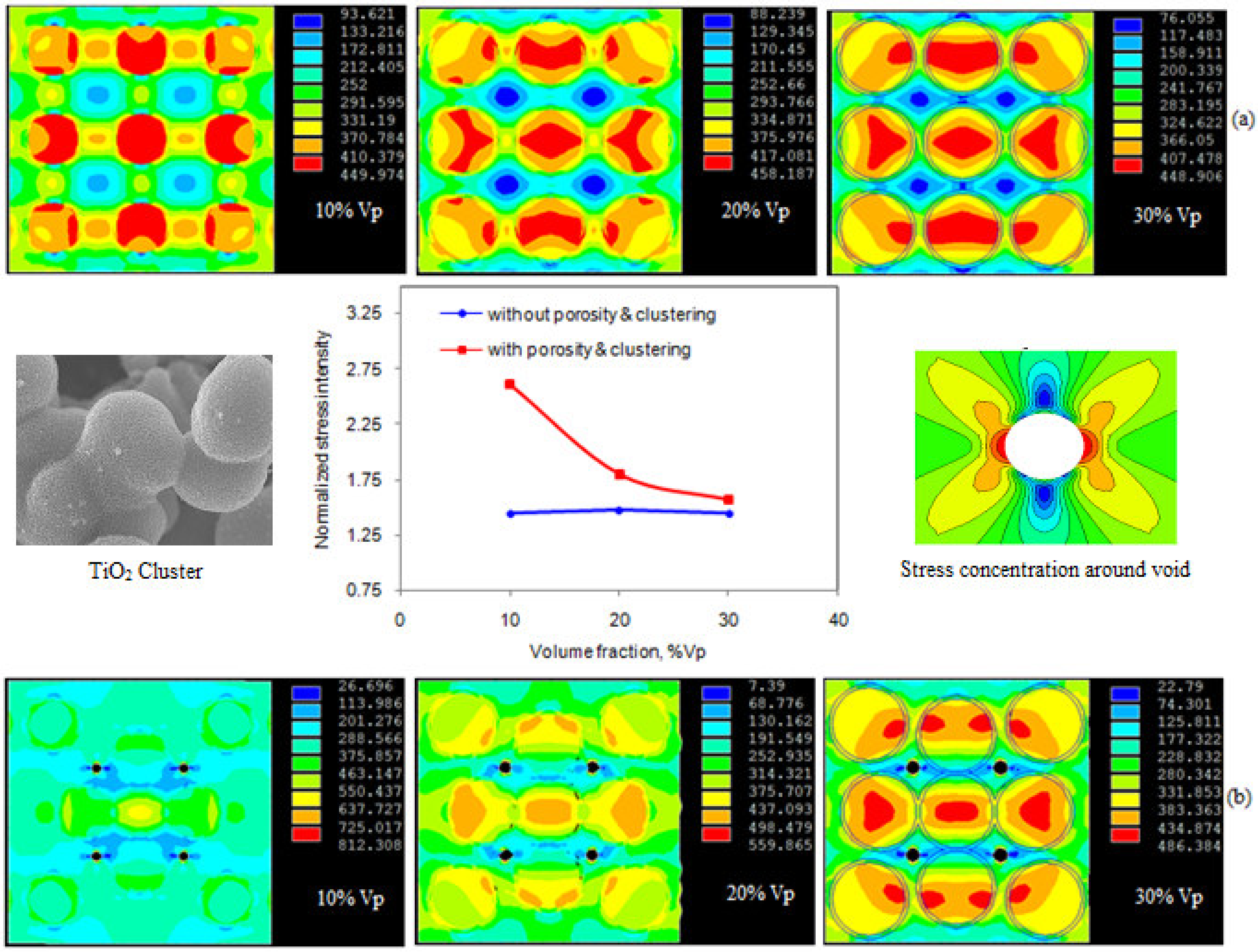

Figure 5: Images of stress intensities obtained from FEA: (a) without clustering and porosity and (b) with clustering and porosity.

4. CONCLUSION

In AA6061/TiO_2 metal matrix composites, the porosity has been increased with increase of TiO_2 nanoparticles in the clusters. Increase in volume fraction of TiO_2 nanoparticles has reduced the tensile strength and stiffness of AA6061/TiO_2 metal matrix composites. The stress intensity has been found decreased with the increase of volume fraction of SiO_2 in the AA4015 alloy matrix.

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