Structure and Properties of Liquid Metal Processed Zirconium Oxide Reinforced AA3003 Alloy

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Abstract: *AA3003/ZrO_2 metal matrix composites manufactured by stir casting practice and high pressure die casting process to investigate the effect of clustering and porosity on their micromechanical properties. Tension tests were conducted on specimens reinforced with different volume fractions of ZrO_2. Two types of finite element models were proposed with and without clustering and porosity. The microstructures of AA3003/ZrO_2 composites have revealed the increase of pore size, porosity content and number of clusters with increased volume fraction of ZrO_2 nanoparticles in AA3300 alloy matrix. The stress intensities have decreased with increase of volume fraction of ZrO_2 nanoparticles.*

Keywords: *AA3003 alloy, zirconium oxide, unit cell, finite element analysis, clustering, porosity.*

1. INTRODUCTION

The degree of clustering of particles has a significant influence on the mechanical behavior of particle reinforced metal matrix composites. The clustered particles act as crack initiation sites and generally have a negative effect on tensile strength, ductility, toughness, and fatigue strength of the composite [1–5]. Porosity formation in stir-cast particulate reinforced metal matrix composite 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 [6-18]. There was a linear correlation between the amount of alumina reinforced and the porosity volume fraction measured [19]. In the earlier studies [20-30] reported it was found that the porosity tends to occur at the matrix-reinforcement interfaces. Depending on the processing parameter, porosity presence was higher at the top of the casting and increased with particulate incorporation.

In this paper, the two-dimensional finite element analysis of the elasto-plastic deformation of composites reinforced with zirconium oxide spherical nanoparticles was carried out to deal with the effect of clustering and porosity on the micromechanical properties. The local stress and strain fields were computed for microstructures with clustering of particles and porosity, and compared with those of homogeneous composites with regular particle distributions. 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 zirconium oxide (ZrO_2) nanoparticles of average size 100nm. AA3003/ ZrO_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 AA3003/ZrO_2 metal matrix composites at three (10%, 20% and 30%) volume fractions of ZrO_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 ZrO_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:

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

$$k = E_m m_m / E_p m_p$$

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

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

where, $\delta = E_p / E_m$.

3. RESULTS AND DISCUSSION

The density of AA3003/ ZrO_2 metal matrix composites increased as shown in figure 1a with increase of volume fraction of ZrO_2 nanoparticles. This is due to fact that the density (5.5 g/cc) of ZrO_2 is higher than that (2.73 g/cc) of AA3003 alloy.

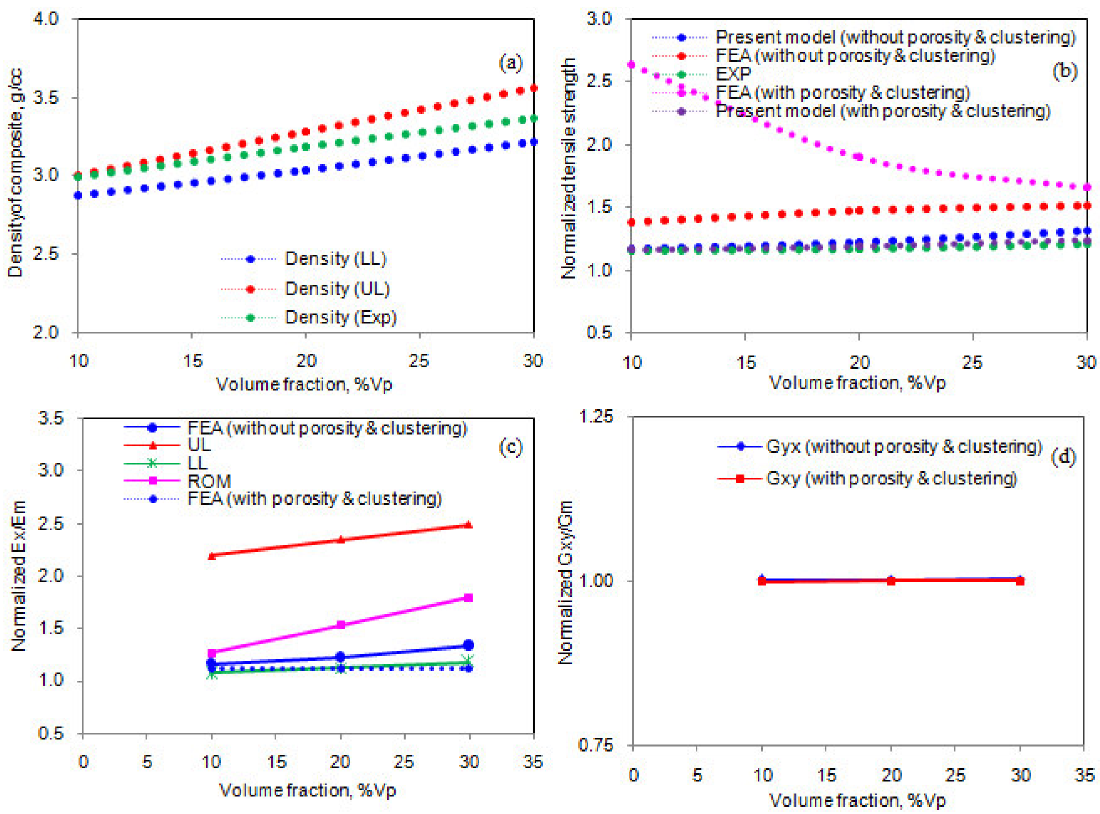

Figure 1: Effect of volume fraction on (a) density (b) normalized tensile stress, (c) normalized tensile elastic modulus and (d) normalized shear modulus of AA2024/TiB_2 composites.

Addition of ZrO_2 nanoparticles to AA3003 alloy matrix increased tensile strength without porosity and clustering as shown in figure 1b. The porosity was the result of stir casting process. The pore diameter and porosity content increase with increase of ZrO_2 nanoparticles in AA3003 alloy matrix as shown in figure 2. The clustering of particles is on account of high pressure die casting technique. In the high pressure die-casting technique the nanoparticles were forced closer. Subsequently, the nanoparticles form the clusters. The volume fraction of clusters increases with increase in volume fraction ZrO_2 nanoparticles in AA3003 alloy matrix as shown in figure 3. The tensile strength decreased owing to porosity and clustering in AA3003/ZrO_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. The normalized elastic modulus increased with increase of volume fraction of ZrO_2 nanoparticles in AA3003 alloy matrix without porosity and clustering in the composites; while it decreased with increase of volume fraction of ZrO_2 nanoparticles with porosity and clustering (figure 1c). The normalized shear modulus is constant with increase of volume fraction of ZrO_2 with and without porosity and clustering (figure 1d).

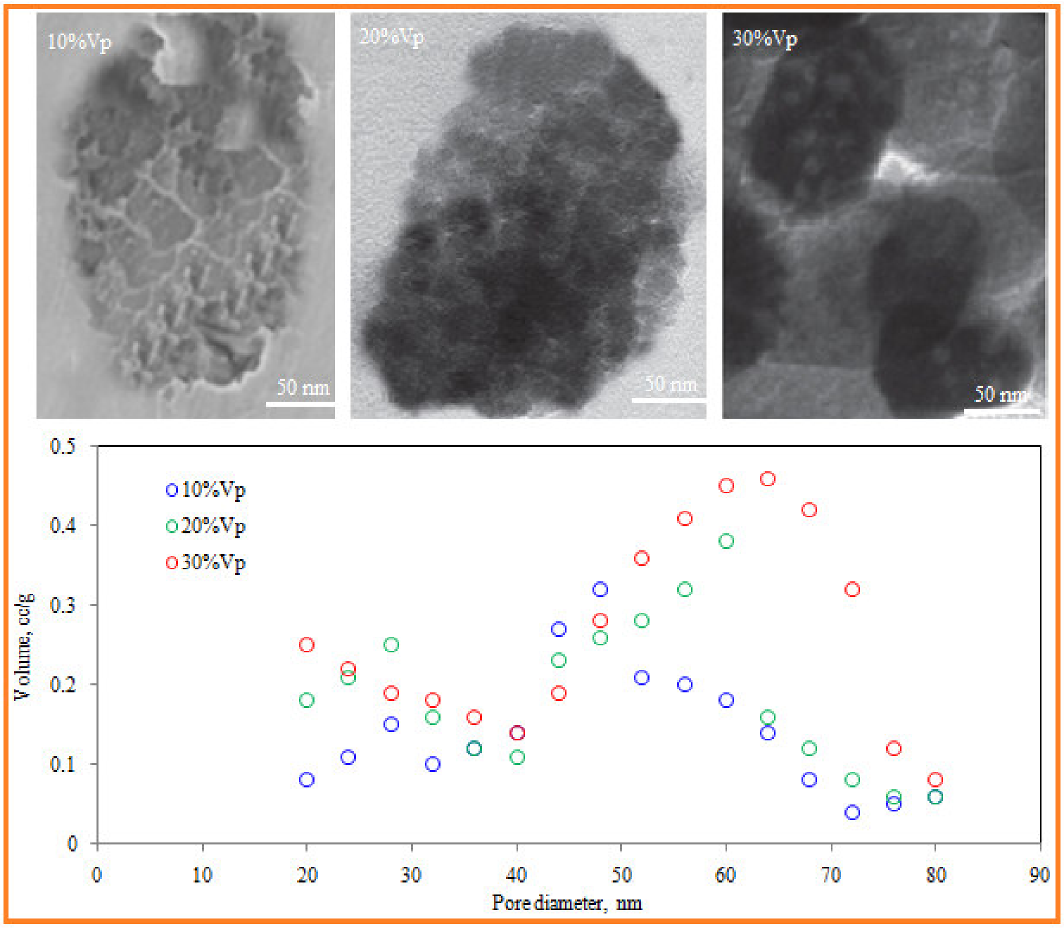

Figure 2: Porosity in AA3003/ZrO_2 metal matrix composites.

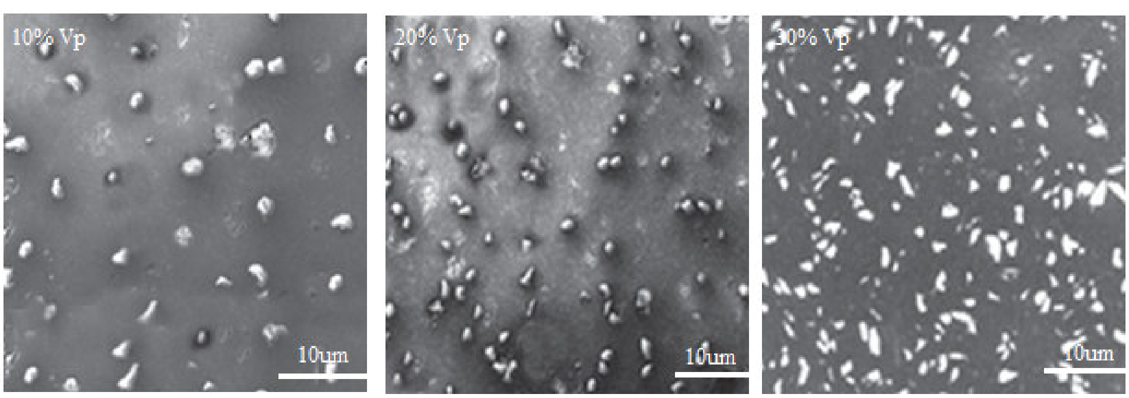

Figure 3: Clustering of ZrO_2 nanoparticles.

In all the finite element models (figure 4), the amount of porosity and volume of clustering were maintained constant. Without porosity and clustering in the composites, the stress intensity is gradually decreased with increase in the volume fraction of ZrO_2 in AA3003 alloy matrix (figure 4a). For vol.% of ZrO_2 less than 20%, the stress intensity is not affected by the content of

ZrO_2 in AA3003 alloy matrix. With porosity and clustering in the composites, the stress intensities were high in the composites. But, the stress intensity decreased with increase of volume fraction of ZrO_2 (figure 4b). In general, the tensile strength increases with increase of volume fraction of particle reinforcement in the metal matrix composites. At high volume fractions of ZrO_2, the stress intensities were suppressed by the increase in the tensile strength of AA3003/ZrO_2 composites.

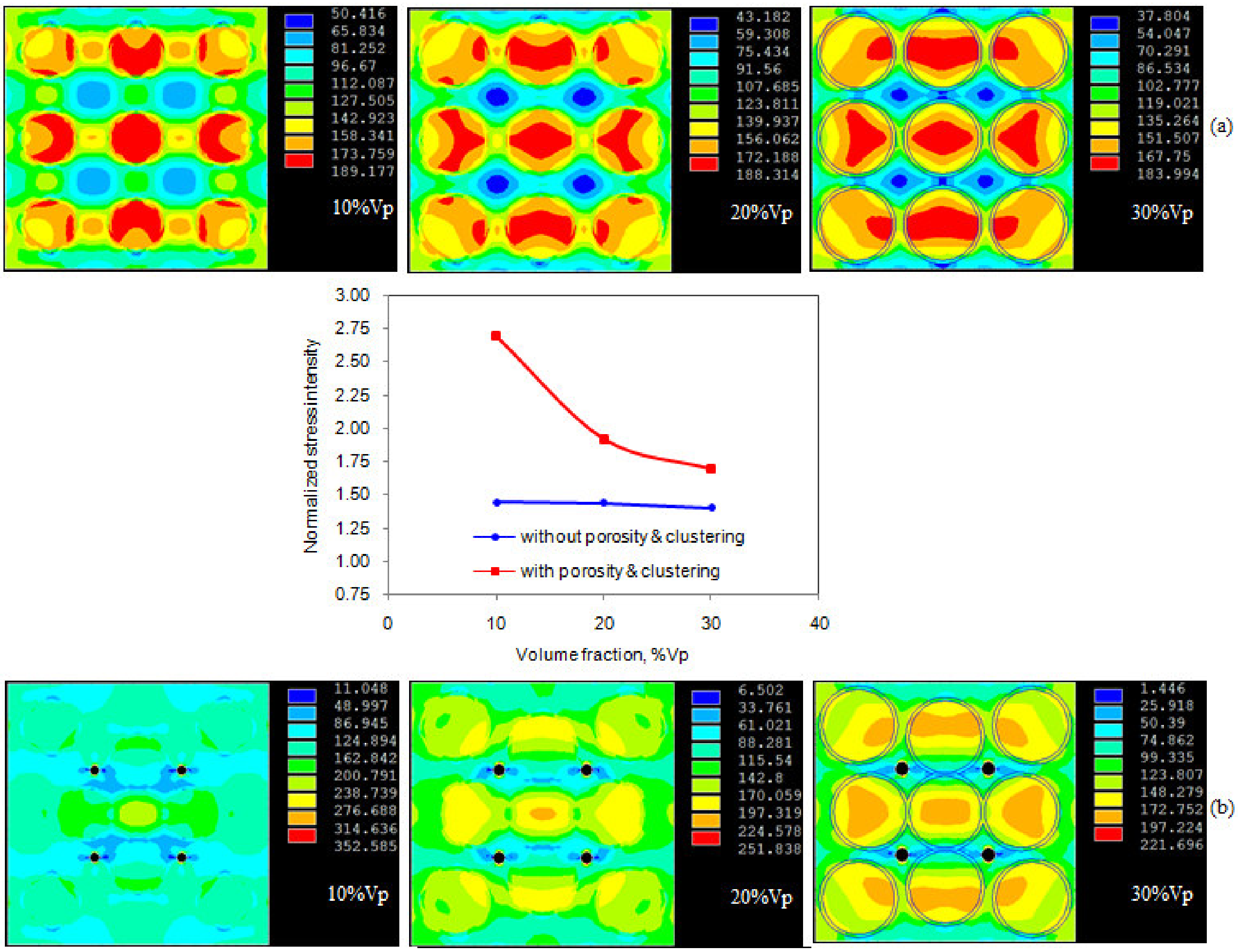

Figure 4: Images of stress intensities obtained from FEA: (a) without clustering and porosity and (b) with clustering and porosity.

4. CONCLUSION

In AA3003/ZrO_2 metal matrix composites, the pore size, porosity and clustering content have been increased with increase in volume fraction of ZrO_2 nanoparticles. The stress intensities decreased with the increase of volume fraction of ZrO_2 in the AA3003 alloy matrix.

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