Effects of Porosity on Mechanical Properties of Zirconium Oxide/AA1100 Alloy Metal Matrix Composites

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Abstract: In the present work, the ZrO_2/AA1100 alloy metal matrix composites were analyzed for micromechanical properties in the presence of porosity. The results obtained from the finite element analysis of ZrO_2/AA1100 alloy composites were in agreement with the experimental result. The tensile strength and elastic modulus have decreased with the presence of porosity in ZrO_2/AA1100 alloy composites.

Keywords: Zirconium oxide, AA1100 alloy, unit cell models, finite element analysis, porosity.

1. INTRODUCTION

Defects can inadvertently be produced in composite materials during the manufacturing process. The most common defect is porosity. The porosity may be in the form of small voids in the matrix. Porosity levels can be critical, as they affect mechanical properties of the metal matrix composites [1-6]. From previous reviews, among the causes of porosity formation are air bubbles entering the melt matrix material, water vapor on the particles surfaces, gas entrapment during mixing process, evolution of hydrogen, and shrinkage during solidification. Stir casting method is a relatively low cost liquid processing present to produce MMC and hence, this processing technique had been utilized in this study [7-20]. Moreover, this type of processing is now in commercial use for particulate Al-based composites [21-30] and the material produced is suitable for further operations, such as pressure die-casting [30-39].

The current work presents the effect of porosity, volume fraction of particles and distribution of particles on micromechanical behavior of zirconium oxide/AA1100 metal matrix composites. The shape of zirconium oxide (ZrO_2) nanoparticle considered in this work is spherical. Finite element analysis was used to analyze unit cells with and without porosity.

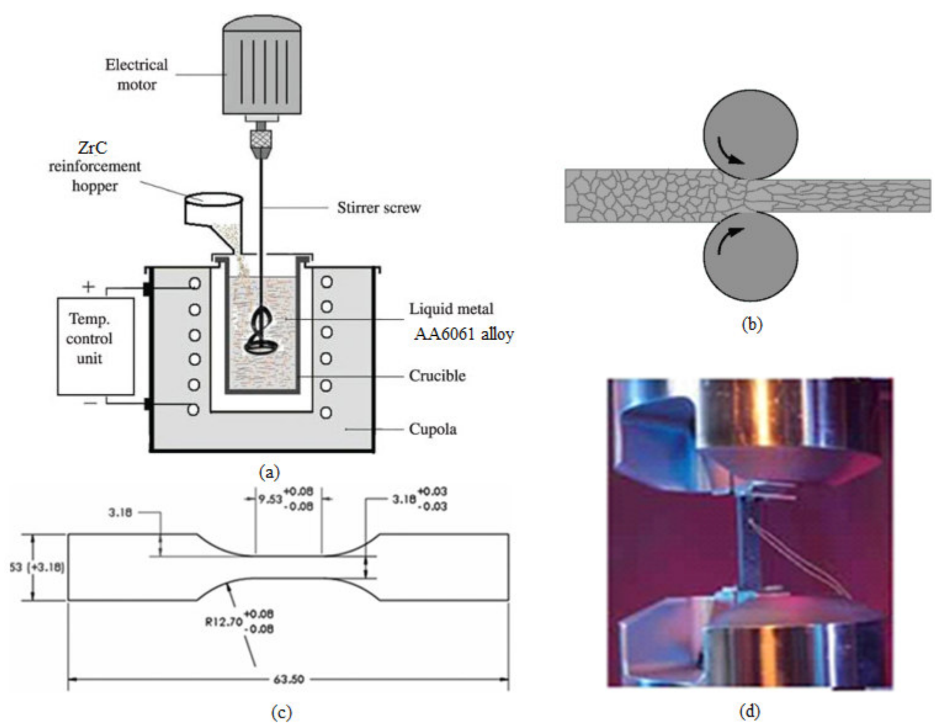

Figure 1: Stir casting process; cold rolling (b); shape and dimensions of tensile specimen (c); and tensile testing on UTM (d).

2. MATERIALS METHODS

The matrix material was AA1100 alloy. The reinforcement material was ZrO_2 nanoparticles of average size 100nm. ZrO_2/AA1100 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 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 ZrO_2/AA1100 composites at three (10%, 20% and 30%) volume fractions of ZrO_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. The finite element analysis was carried out on a unit cell without porosity as shown in figure 2a and with porosity as shown in figure 2b.

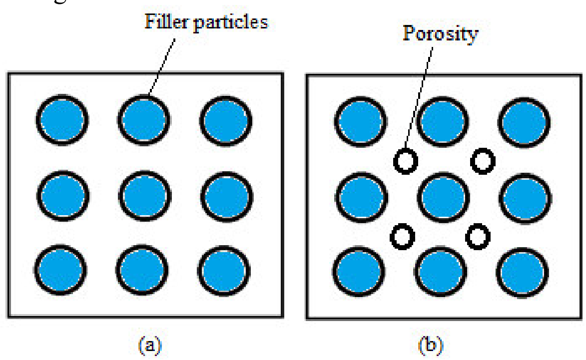

Figure 2: Unit cells: (a) without porosity and (b) with porosity.

Density of the composite is calculated from 'Rule of Mixture' as follows:

$$\left(\frac{v_p}{\rho_p}+\frac{1-v_p}{\rho_m}\right) \leq \rho_c \leq (1-v_p)\rho_m \qquad (1)$$

where v_p is the volume fraction of particles and ρ_c, ρ_p, and ρ_m are densities of composite, particles and matrix, respectively.

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:

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

$$k = E_m m_m / E_p m_p$$

where, vv and vp are the volume fractions of voids/porosity and nanoparticles in the composite respectively, mp and mm are the possion's ratios of the nanoparticles and matrix respectively, dp is the mean nanoparticle size (diameter) and Em and Ep 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

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

The lower-bound equation is given by

$$\frac{E_c}{E_m} = 1 + \frac{v_p-v_p}{\delta/(\delta-1)-(v_p+v_v)^{1/3}} \qquad (4)$$

where, $\delta = E_p/E_m$.

3. RESULTS AND DISCUSSION

Figure 3a shows the variation of normalized tensile strengths of the composites with volume fractions of ZrO_2 particles. Adding ZrO_2 particles to AA1100 alloy matrix increased tensile strength without porosity ZrO_2/AA1100 composites. Due to the effect of porosity in ZrO_2/AA1100 composites, the tensile strength decreased; but it increased with increase of ZrO_2 content in

AA1100 alloy matrix. The tensile stresses obtained from the finite element analysis (FEA) were higher than those obtained from the mathematical expression mentioned in Eq.(2) and the experimental procedure as shown in figure 3a. This is owing to the ignorance of clustering of ZrO_2 particles in AA1100 alloy matrix.

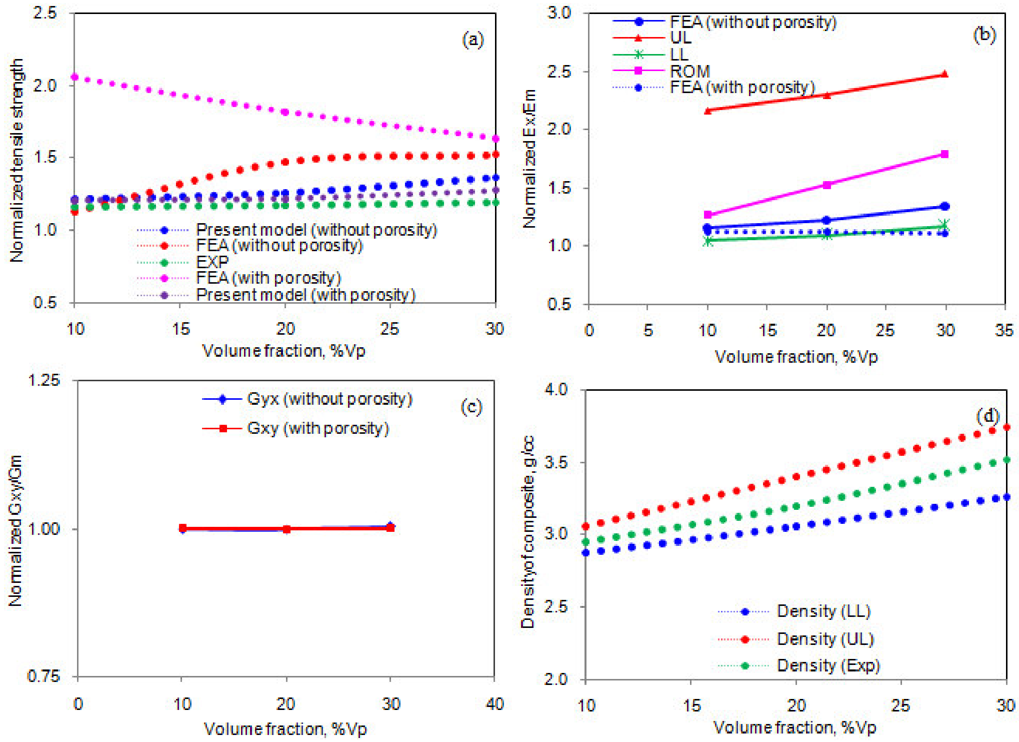

Figure 3: Effect of volume fraction on (a) normalized strength, (b) normalized tensile elastic modulus, (c) normalized shear modulus and (d) density of ZrO_2/AA1100 composites.

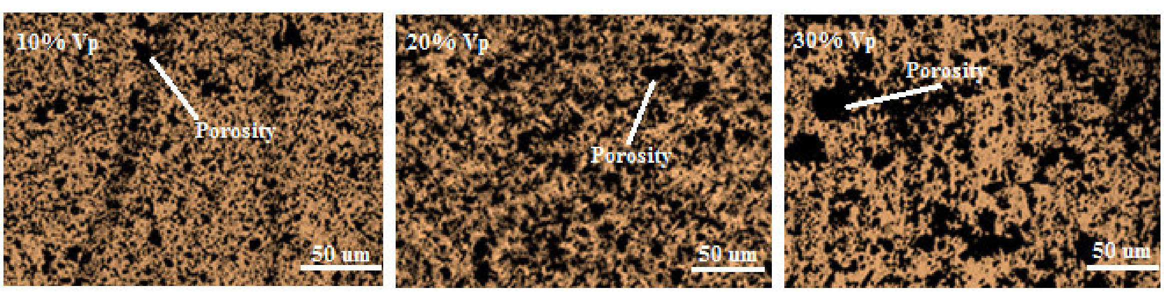

Figure 4: Microstructure showing distribution of 10%, 20% and 30% ZrO_2 nanoparticles in AA1100 alloy matrix.

The normalized elastic modulus increased with increase of volume fraction of ZrO_2 particles in AA1000 alloy matrix without porosity in the composites; while it decreased with increase of volume fraction of clustered ZrO_2 particles in AA1100 alloy matrix with porosity (figure 3b). The normalized shear modulus is constant with increase of volume fraction of ZrO_2 with and without porosity (figure 3c). The porosity in various composites is shown in figure 3d. The porosity level increased with increase of volume fraction of ZrO_2 in AA1100 alloy matrix as shown in figure 4d. This is confirmed with the microstructures of the composites shown in figure 4.

In all the models (figure 5), the amount of porosity was maintained constant. Without porosity in the composites, the induced stress increased with increase of volume fraction of ZrO_2 in AA1100 alloy matrix. With porosity in the composite, the induced stress was high. This indicates that the stress exceeds the allowable stress in the composites with porosity for the same load as that applied on the composites without porosity. This is attributed to the fact of the stress concentration in the vicinity of the porosity. However, the stress decreased with increase of volume fraction ZrO_2. This trend is in agreement with the results obtained from experimental procedure and mathematical computation.

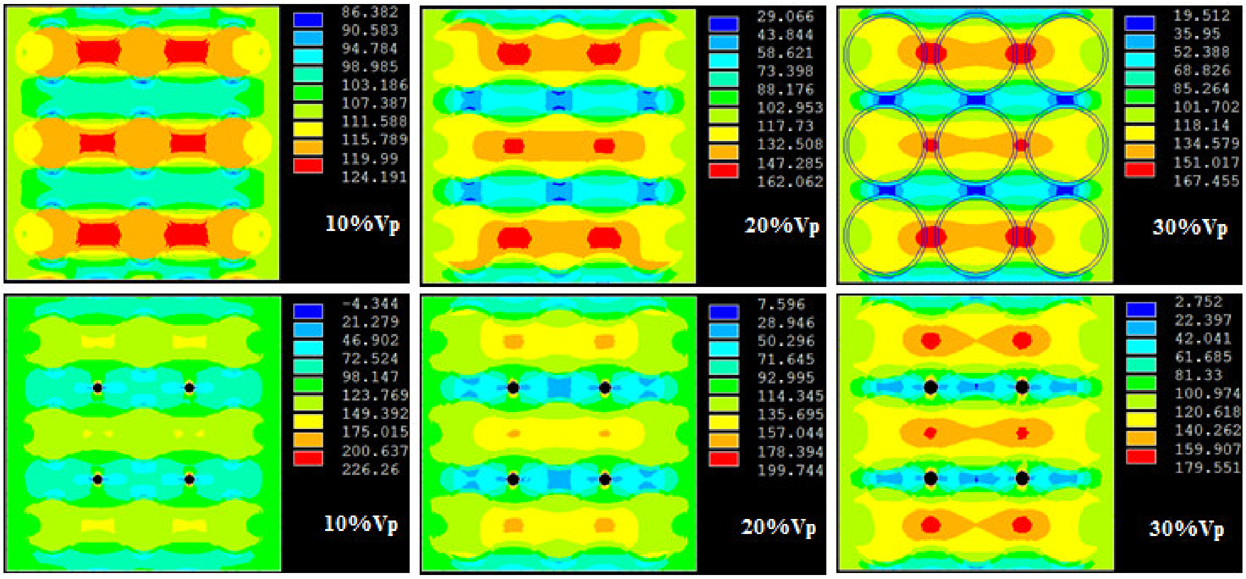

Figure 5: Images of tensile stresses obtained from FEA: (a) without porosity and (b) with porosity.

4. CONCLUSIONS

The porosity has been increased with increase of ZrO_2 particles in AA1100 alloy matrix. In the presence of porosity, the stresses developed in the composites have exceeded the allowable stress for the same load applied on all the composite specimens. The stress concentrations were observed in the regions of porosity in the composites. The elastic modulus decreased with porosity in the composites.

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