Effect of Porosity Formation during Synthesis of Cast AA4015/Titanium Nitride Particle-Metal Matrix Composites

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Abstract: In the current work, the AA4015/TiN metal matrix composites were analyzed for tensile properties in the presence of porosity. The density increased with increase of TiN in AA4015 alloy matrix. The tensile strength and elastic modulus of AA4015/TiN composites have decreased due to porosity in the composites.

Keywords: Titanium nitride, AA4015 alloy, unit cell models, finite element analysis, porosity.

1. INTRODUCTION

Combinations of metals with ceramics are the most common form of metal matrix composites [1-9]. In recent years, nano-sized materials have also drawn much interest as reinforcements in metal matrix composites because of their superior properties compared with those of micro-sized particles [10-21]. Liquid-state processes such as vortex method, squeeze casting and pressure infiltration process provide greater freedom in component design and manufacturing [22-28]. However, very large specific surface area and high interfacial energy of nano-size reinforcements result in their poor wetting, agglomeration tendency and poor distribution in the melt [29-36].

The objective of this paper was to investigate the effect of porosity, volume fraction of particles during synthesis of AA4015/titanium nitride metal matrix composites. The shape of titanium nitride (TiN) nanoparticle considered in this work is spherical. Finite element analysis was used to analyze unit cells with and without porosity.

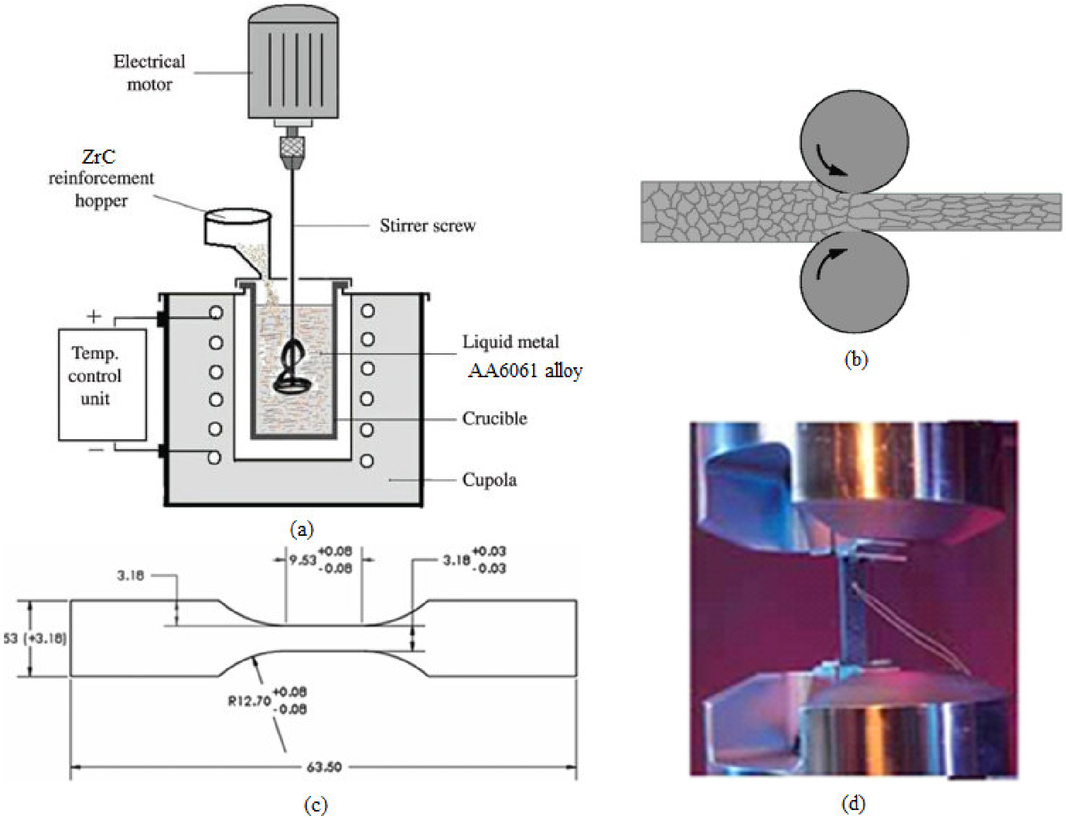

Figure 1: Stir casting process; cold rolling (b); shape and dimensions of tensile specimen (c); and tensile testing on UTM (d).

2. MATERIALS METHODS

The matrix material was AA4015 alloy. The reinforcement material was TiN nanoparticles of average size 100nm. AA4015/TiN 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 AA4015/TiN composites at three (10%, 20% and 30%) volume fractions of TiN. 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 that with porosity as shown in figure 2b.

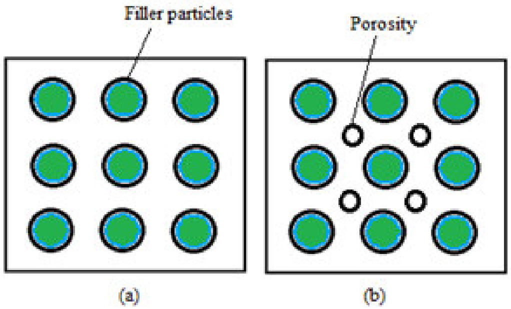

Figure 2: Unit cells: (a) without porosity and (b) with porosity.

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

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

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:

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

$$k = E_m m_m / E_p m_p$$

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

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

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

Without porosity, the tensile strength was increased due to addition of TiN particles to AA4015 alloy matrix; it decreased with porosity (figure 3a). 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 TiN particles in AA4015 alloy matrix. The density variation in various composites is shown in figure

3b. The density increased with increase of volume fraction of TiN in the AA4015 alloy matrix. This is the reason for the reduction of tensile stress with porosity. This is confirmed with the microstructures of the composites shown in figure 4.

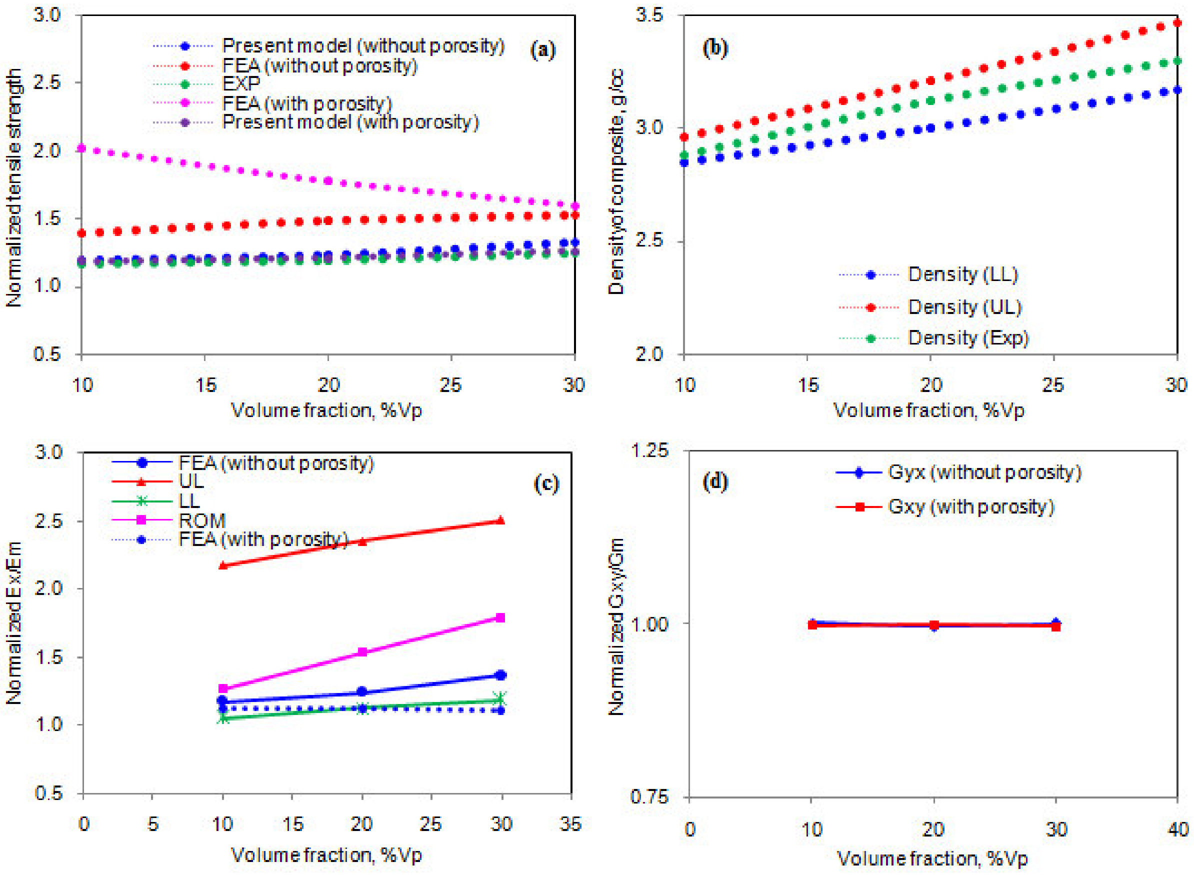

Figure 3: Effect of volume fraction on (a) normalized strength, (b) normalized tensile elastic modulus, (c) normalized shear modulus and (d) density of AA4015/TiN composites.

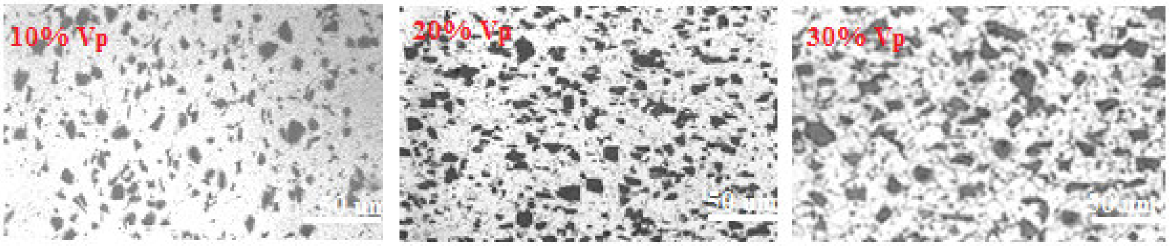

Figure 4: Microstructure showing porosity and distribution of 10%, 20% and 30% TiN nanoparticles in AA4015 alloy matrix.

The normalized elastic modulus increased with increase of volume fraction of TiN particles in AA4015 alloy matrix without porosity; whereas, it decreased with increase of volume fraction of clustered TiN particles in AA4015 alloy matrix with porosity (figure 3c). The normalized shear modulus was constant with increase of volume fraction of TiN in the AA4015 alloy matrix with or without porosity (figure 3d).

Without porosity in the composites, the tensile stress increased with increase of volume fraction of TiN in AA4015 alloy matrix. With an assumption of constant porosity in all the composites, the tensile stress was exceeded the allowable stress in the composites with porosity for the same load as that applied on the composites without porosity as shown in figure 5b. This is attributed to the development of the stress concentrations in the vicinity of the porosity. This trend is in agreement with the results obtained from experimental procedure and mathematical computation. The fracture of matrix material is seen in the composites having 30% TiN.

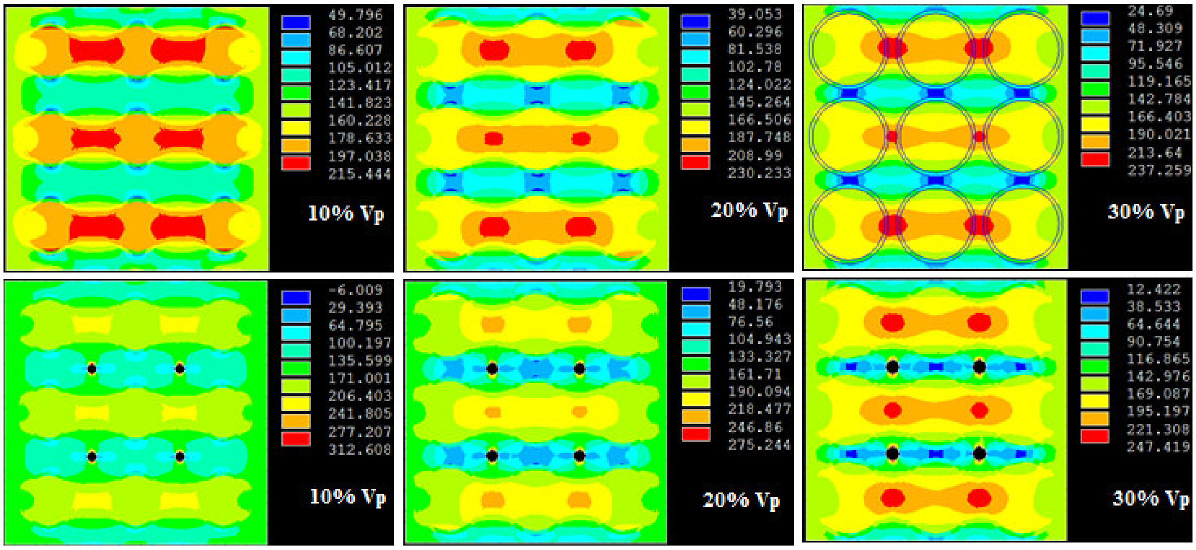

Figure 5: Images of tensile stresses obtained from FEA: (a) without porosity and (b) with porosity.

4. CONCLUSIONS

The density of AA4015/TiN has been increased with increase of TiN particles in AA4015 alloy matrix containing porosity in the matrix. In the presence of voids, the tensile stresses developed in the composites have exceeded the allowable stress for the same load applied on all the composite specimens. The elastic modulus and tensile stress decreased with porosity in the composites.

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