Sliding Wear and Micromechanical Behavior of AA1100/Titanium Oxide Metal Matrix Composites Cast by Bottom-Up Pouring

A. Chennakesava Reddy

Professor, Department of Mechanical Engineering, JNT University, Hyderabad, India
dr_acreddy@yahoo.com

Abstract: *AA1100/TiO_2 metal matrix composites were fabricated by stir casting practice and bottom-up pouring technique to investigate the effect of clustering and porosity on their mechanical and wear properties. Tension and wear tests were conducted on specimens reinforced with different volume fractions of TiO_2. Two types of finite element models were used to estimate the strength of the MMCs. The microstructures of AA1100/TiO_2 composites have revealed the occurrence of particle clustering and porosity. The normalized tensile strength and elastic modulus decrease with porosity and clustering of TiO_2 nanoparticles. The wear rate of AA1100/TiO_2 composites has decreased with increase of volume fraction of TiO_2 in AA2024 alloy matrix.*

Keywords: *AA1100 alloy, titanium oxide, unit cell, finite element analysis, clustering, porosity, wear.*

1. INTRODUCTION

In manufacturing industry there is continues demand to develop light weight, inexpensive and strong material. This demand has led to the development of aluminum alloy metal matrix composites. The reinforcements for MMCs can be broadly divided into four major categories, viz. Continuous fibers, discontinuous fibers, whiskers, and particulates [1]. The reinforcements are generally ceramic; which can be oxides, carbides and nitrides which are used because of their excellent combination of specific strengths and stiffness at both ambient and elevated temperatures. The different techniques employed for metal matrix composites are powder metallurgy, spray deposition, liquid metal infiltration, squeeze casting, stir casting, etc. All of them have their own advantages and disadvantages. Among the various processing techniques available for particulate or discontinuous reinforced metal matrix composites, stir casting is the technique which is in use for large quantity commercial production. In the particulate metal matrix composites, the particle size varies from micron to nano. Advantage of using nanoparticles as reinforcement is that their size is smaller than the critical crack length that typically initiates failure in composites. However, agglomeration of nanoparticles is the major problem. In fact, several investigations have shown that small levels of agglomeration can decrease the strain-to- failure by several tens of percent [2-14]. The major obstacle is the formation porosity during materials processing [15-26].

The present investigation has been focused on the micromechanical and wear behavior of AA1100/titanium oxide metal matrix composites with different composition (10%, 20% and 30% by volume of AA1100 alloy of titanium oxide (TiO_2). Bottom-up pouring was used to produce the composites. Tensile and sliding wear test were conducted on these MMCs. Also, the effects of particle clustering and porosity on micromechanical behavior were analyzed using experimental procedure and finite element method (FEM). 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 AA1100 alloy. The reinforcement material was TiO_2 nanoparticles of average size 100nm. AA1100/ TiO_2 metal matrix composites were fabricated by the stir casting process with bottom-up pouring technique (figure 1). The test samples were machined to get flat-rectangular specimens (figure 2b) 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 (figure 2a). The test speed was 2 mm/min. A strain gauge was used to determine elongation (figure 2a). The wear test was conducted on pin-on-disc machine. In the current work, a unit cell comprising of nine particles was implemented to analyze the tensile behavior AA1100/ 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.

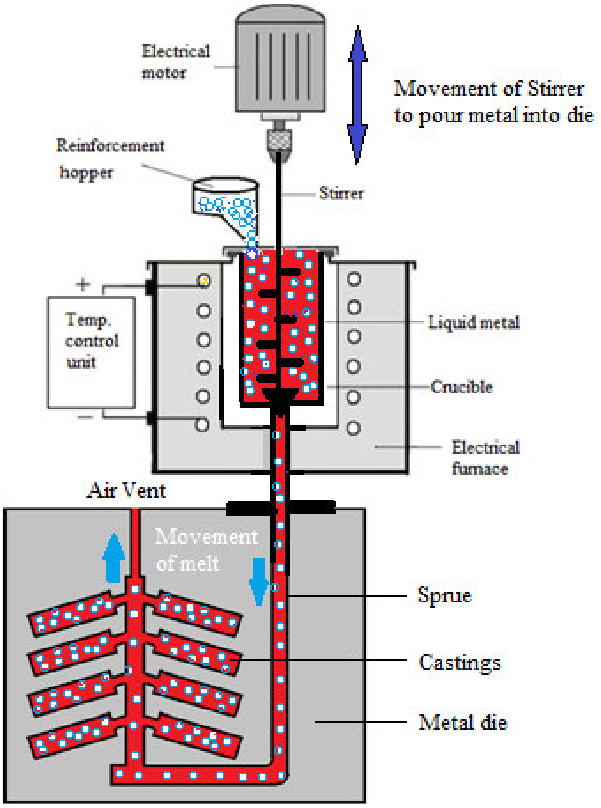
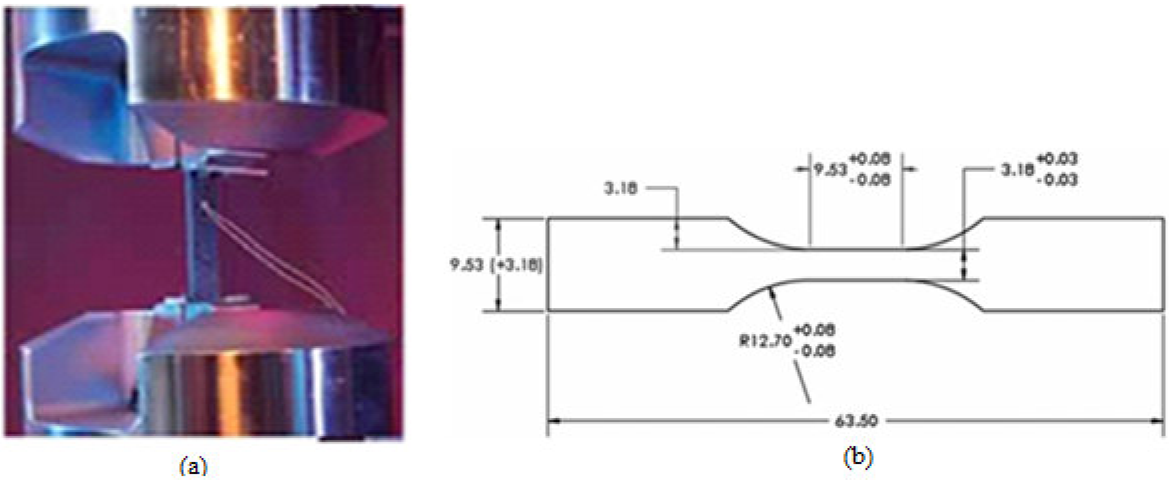


Figure 1: Concept of bottom-up pouring of composite metal.



(a)

(b)

Figure 2: Testing of composites: (a) tensile testing and (b) dimensions (mm) of tensile specimen.

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:

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

$$k = E_m m_m / E_p m_p$$

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

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

The lower-bound equation is given by

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

where, $\delta = E_p / E_m$.

Wear rate which relates to the mass loss to sliding distance (L) was calculated using the expression,

$$W_m = \frac{\Delta m}{L} \tag{4}$$

where, Δm is the moss loss in grams.

The volumetric wear rate W_v of the composite is relate to density (ρ) and the abrading time (t), was calculated using the expression,

$$W_m = \frac{\Delta m}{\rho \times t} \tag{5}$$

3. RESULTS AND DISCUSSION

The clustering of TiO_2 particles (red circles) and porosity (red arrows) are seen in the microstructures. The clustering of nanoparticles increased with increase of volume fraction.

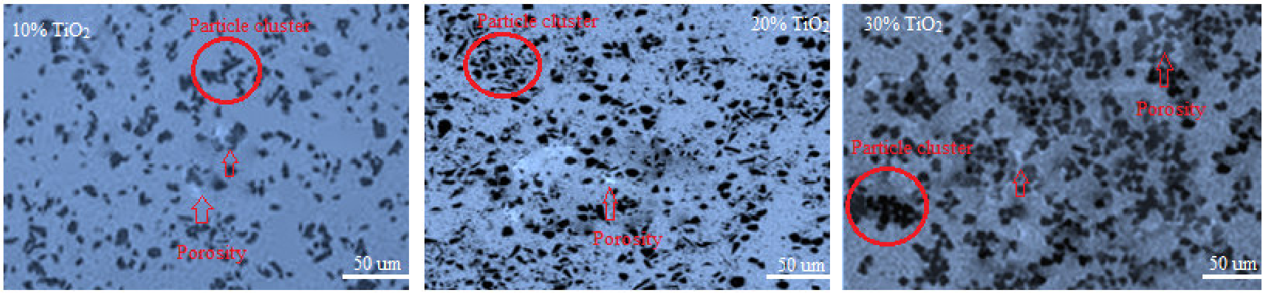


Figure 3: Microstructure showing distribution of TiO_2 nanoparticles, clustering and porosity in AA1100 alloy matrix.

The density of AA1100/ TiO_2 metal matrix composites increased as shown in figure 4a with increase of volume fraction of TiO_2 nanoparticles in AA1100 alloy matrix. The densities of AA1100 alloy matrix and TiO_2 nanoparticles are, respectively, 2.71 g/cc and 4.05 g/cc. In order to characterize the mechanical properties of AA1100 alloy/ TiO_2 composites, the strengths have been normalized with respect to 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.(1) and the experimental procedure as shown in figure 4b. This is owing to the occurrence of stress concentrations at voids and clustered regions. The tensile strength was increased without porosity and clustering in AA1100/ TiO_2 metal matrix composites. As shown in figure 4b, the normalized tensile strength was very low at higher TiO_2 contents, mostly due to the increased amount of clustering and voids. The normalized elastic modulus increased with increase of volume fraction of TiO_2 nanoparticles in AA1100 alloy matrix without porosity and clustering in the composites; while it was low with porosity and clustering (figure4c). The normalized shear modulus is constant with increase of volume fraction of TiO_2 with and without porosity and clustering (figure 4d).

In all the finite element models (figure 5), the amount of porosity and volume of clustering were maintained constant. With or Without porosity in the composites, the stress intensity decreased with increase of volume fraction of TiO_2 in AA1100 alloy matrix. However, the stress intensity levels were higher in the composites having porosity and clustering than those in the composites without porosity and clustering. This is attributed to the fact of the stress concentration in the vicinity of the porosity and clustering. This trend is in agreement with the results obtained from experimental procedure and mathematical computation.

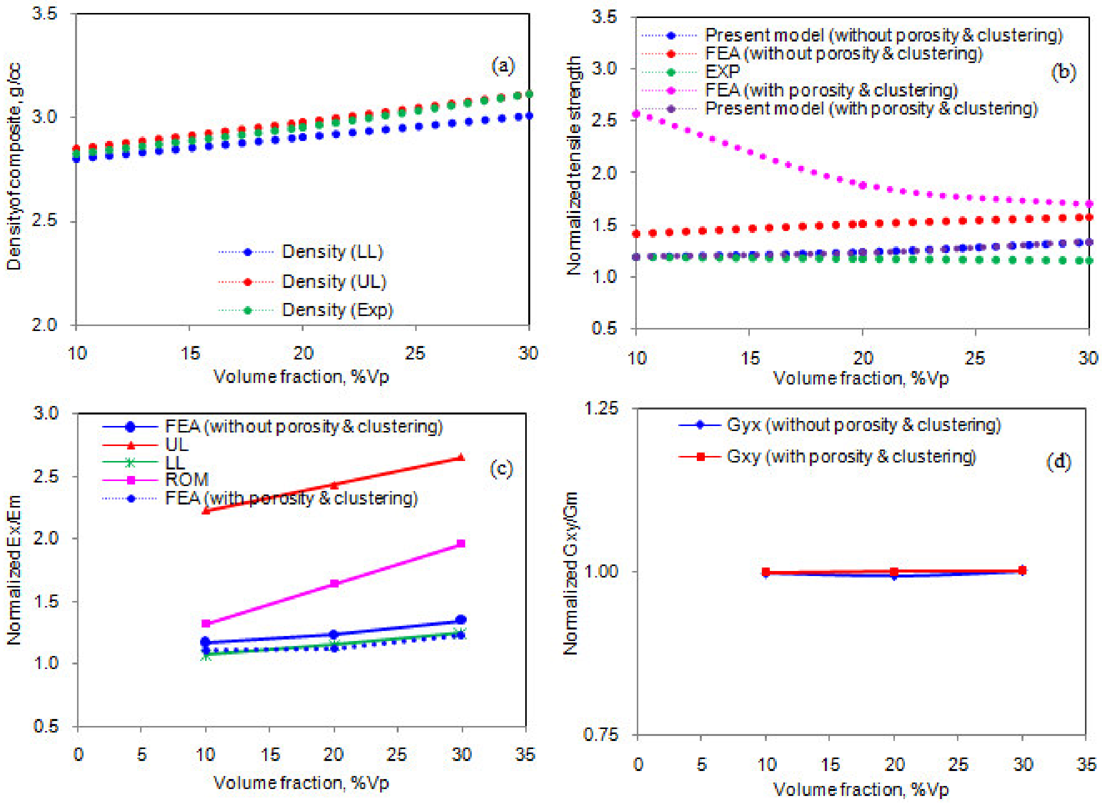


Figure 4: Effect of volume fraction on (a) density (b) normalized tensile stress, (c) normalized tensile elastic modulus and (d) normalized shear modulus of AA1100/ TiO_2 composites.

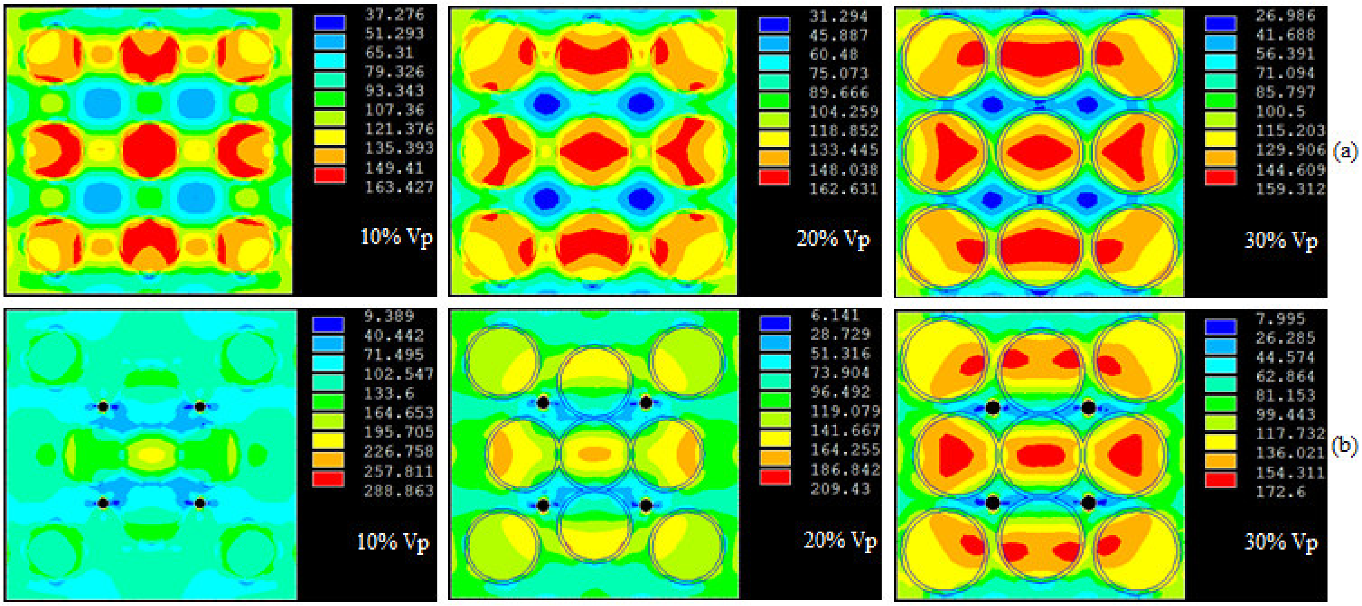


Figure 5: Images of von Mises stresses obtained from FEA: (a) without clustering and porosity and (b) with clustering and porosity.

The dry sliding wear tests were carried out for the specimens of AA1100 alloy, metal matrix composites having reinforcement with different volume fraction of 10%, 20% and 35% TiO_2. Wear rate was estimated by measuring the mass loss in the specimen after each test. The mass loss increases as the load value increases at constant sliding velocity (figure 6a). Also seen that the mass loss of the composites decrease with increase in the percentage of TiO_2. The rate of wear in case of AA1100 sample was extremely high in comparison to metal matrix composites. The volumetric wear has low value for the specimen having higher volume fraction of TiO_2 (figure 6b).

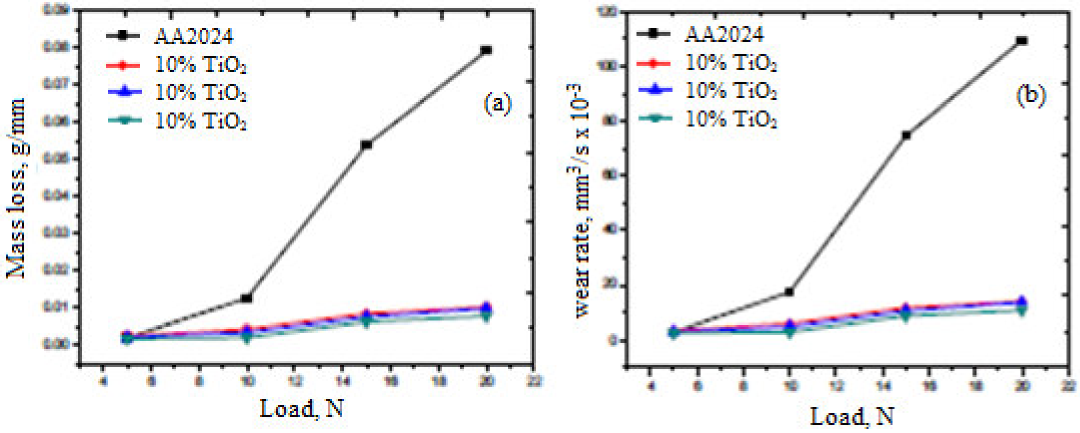


Figure 6: Wear analysis of AA1100/TiO_2 composites: mass loss and (b) volumetric wear rate.

4. CONCLUSION

AA1100/ TiO_2 metal matrix composites had clusters and porosity voids. The stress intensity was increased with porosity and clustering of graphite nanoparticles. The wear loss has decreased with increase of volume fraction of TiO_2 in AA1100 alloy matrix.

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