Bottom-Up Pouring and its Effect on Porosity and Clustering in Casting of AA1100/Silicon Nitride Particle-Reinforced Metal Matrix Composites

B. Kotiveera Chari and A. Chennakesava Reddy

1Professor, Department of Mechanical Engineering, NIT, Warangal, India
2Professor, Department of Mechanical Engineering, JNT University, Hyderabad, India
dr_acreddy@yahoo.com

Abstract: AA1100/Si$_3$N$_4$ metal matrix composites were fabricated by stir casting practice and bottom-up pouring technique to explore the effect of clustering and porosity on their mechanical properties. Tension tests were conducted on specimens reinforced with different volume fractions of Si$_3$N$_4$. Two types of finite element models were used to estimate the strength of the MMCs. The models have been successful in predicting the experimentally observed strength the AA1100/Si$_3$N$_4$ metal matrix composites. The microstructures of AA1100/Si$_3$N$_4$ composites have revealed the occurrence of particle clustering and porosity. The normalized tensile strength and elastic modulus decrease with porosity and clustering of Si$_3$N$_4$ nanoparticles.

Keywords: AA1100 alloy, silicon nitride, unit cell, finite element analysis, clustering, porosity.

1. INTRODUCTION

Metal matrix composites consist of lightweight metal alloys of aluminum, magnesium, or titanium, reinforced with ceramic particulate, whiskers, or fibers. The reinforcement is very important because it determines the mechanical properties, cost, and performance of a given composite. Particulate-reinforced composites are isotropic, having the same mechanical properties in all directions. Silicon nitride has a good thermal and chemical stability, high mechanical strength and hardness, and good wear, creep, and corrosion resistance [1]. Silicon nitride has poor wettability to aluminum. Therefore, discontinuity in the form of debonding exists due to non-adherence of reinforcement and matrix. Particle clusters act as crack or decohesion nucleation sites at stresses lower than the matrix yield strength, causing the metal matrix composites to fail at unpredictable low stress levels 2-14]. Porosity formation has always been associated to casting [15-26].

The objective of this paper is to study the effect of particle clustering and porosity on micromechanical behavior 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 silicon nitride (Si$_3$N$_4$) nanoparticles of average size 100nm. AA1100/Si$_3$N$_4$ metal matrix composites were fabricated by the stir casting process with bottom-up pouring technique (figure 1). Magnesium was added at 1%wt to the liquid melt to improve wettability of Si$_3$N$_4$ nanoparticles. 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 2c). In the current work, a unit cell comprising of nine particles was implemented to analyze the tensile behavior AA1100/ Si$_3$N$_4$ metal matrix composites at three (10%, 20% and 30%) volume fractions of Si$_3$N$_4$ 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 Si$_3$N$_4$ 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:

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

(1)
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.

\[ k = E_m m_m / E_p m_p \]

\[ \frac{E_C}{E_m} = \left( \frac{1 - v_v^{2/3}}{1 - v_v^{2/3} + v_p^{2/3}} \right) + \frac{1 + (\delta - 1) v_p^{2/3}}{1 + (\delta - 1) (v_p^{2/3} - v_p)} \]
The lower-bound equation is given by
\[
\frac{E_c}{E_m} = 1 + \frac{\nu_{p} - \nu_v}{\delta (\delta - 1) - (\nu_p + \nu_v)^{1/2}}
\]
where, \(\delta = \frac{E_p}{E_m}\).

3. RESULTS AND DISCUSSION

The microstructures of the samples are shown in figure 3. The clustering of particles and porosity are seen in the microstructures. The dark spots are particle clusters. The clustering of nanoparticles increased with increase of volume fraction. Some porosity voids can be seen in the inter-grain regions and inter-nanoparticle regions.

![Figure 3: Microstructure showing distribution of Si₃N₄ nanoparticles, clustering and porosity in AA1100 alloy matrix.](image)

![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/ Si₃N₄ composites.](image)

The density of AA1100/ Si₃N₄ metal matrix composites increased as shown in figure 4a with increase of volume fraction of Si₃N₄ nanoparticles in AA1100 alloy matrix. The densities of AA1100 alloy matrix and Si₃N₄ nanoparticles are, respectively, 2.71 g/cc and 3.31 g/cc. 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/Si₃N₄ metal matrix composites. It is significant to note that the Si₃N₄ particulate clusters have a major
effect on the tensile properties of the composites. As shown in figure 4b, the normalized tensile strength was very low at higher $\text{Si}_3\text{N}_4$ contents, mostly due to the increased amount of clustering and voids. This seems to be especially true for the composite containing 30 vol.% of $\text{Si}_3\text{N}_4$ when the strength is expected to be much higher than at lower $\text{Si}_3\text{N}_4$ levels. But, it was lower due to the increased amount of clustering and porosity. The normalized elastic modulus increased with increase of volume fraction of $\text{Si}_3\text{N}_4$ nanoparticles in AA1100 alloy matrix without porosity and clustering in the composites; while it was low with porosity and clustering (figure 4c). The normalized shear modulus is constant with increase of volume fraction of $\text{Si}_3\text{N}_4$ 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. Without porosity in the composites, the stress intensity increased with increase of volume fraction of $\text{Si}_3\text{N}_4$ in AA1100 alloy matrix. With porosity and clustering in the composites, the stress intensity was decreased with increase of volume fraction of $\text{Si}_3\text{N}_4$. This indicates that the stress intensity exceeds the allowable stress in the composites with porosity and clustering 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 and clustering. This trend is in agreement with the results obtained from experimental procedure and mathematical computation.

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

**CONCLUSION**

AA1100/ $\text{Si}_3\text{N}_4$ metal matrix composites had clusters and porosity voids. The voids are typically located at the interface of clustered particles. The stress intensity decrease with porosity and clustering of nanoparticles was analyzed for tensile strength for three volume fractions of silicon nitride nanoparticles in AA1100 alloy matrix. The strength degradations were generally within the range of experimental results.

**REFERENCES**


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