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

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Abstract: *AA1100/Si_3N_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_3N_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_3N_4 metal matrix composites. The microstructures of AA1100/Si_3N_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_3N_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_3N_4) nanoparticles of average size 100nm. AA1100/Si_3N_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_3N_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_3N_4 metal matrix composites at three (10%, 20% and 30%) volume fractions of Si_3N_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_3N_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:

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

$$k = E_m m_m / E_p m_p$$

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.

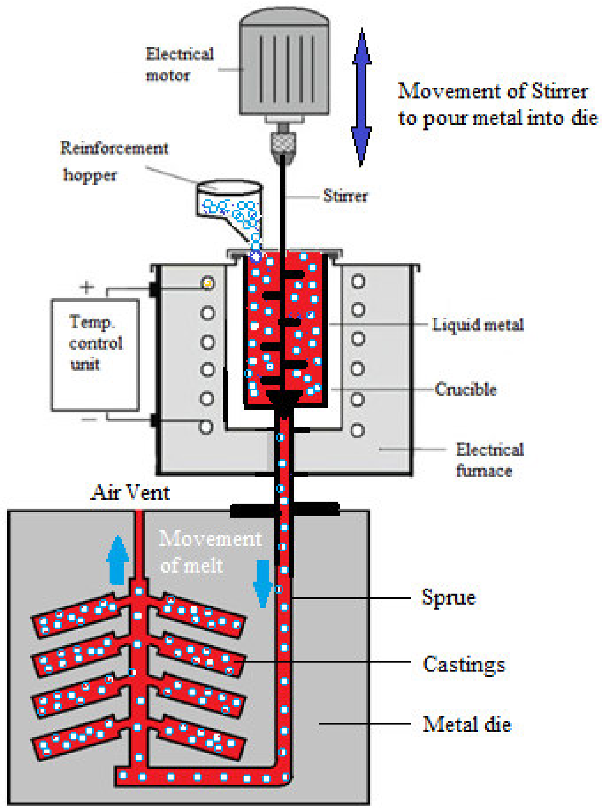

Figure 1: Concept of bottom-up pouring of composite metal.

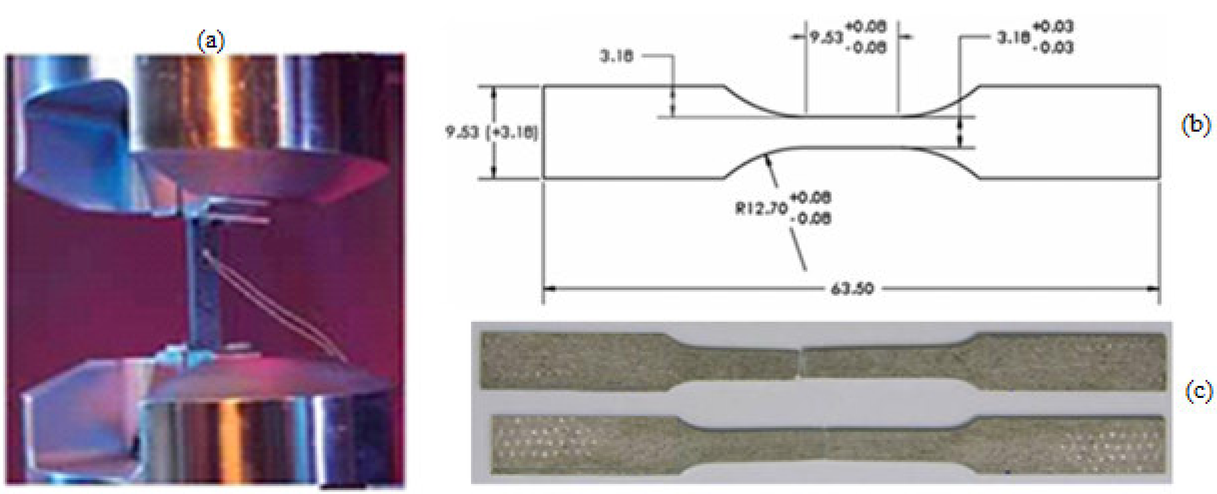

Figure 2: Testing of composites: (a) tensile testing, (b) dimensions (mm) of tensile specimen and (c) tensile specimens.

The upper-bound equation is given by

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

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 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.

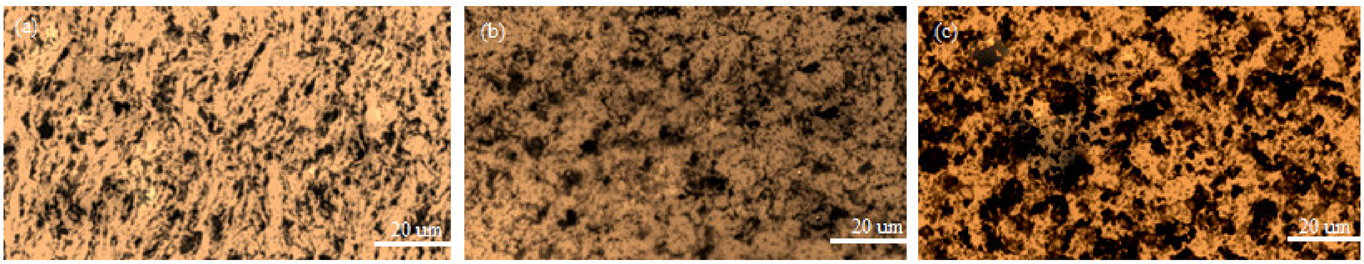

Figure 3: Microstructure showing distribution of Si_3N_4 nanoparticles, clustering and porosity in AA1100 alloy matrix.

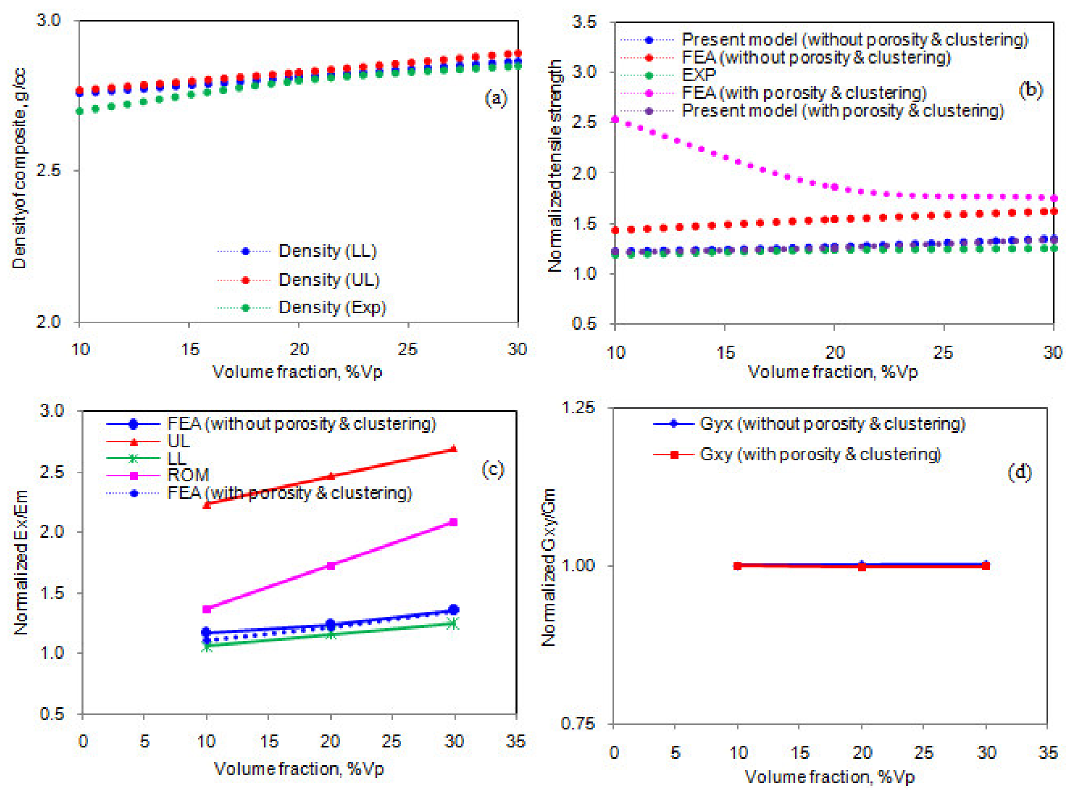

Figure 4: Effect of volume fraction on (a) density (b) normalized tensile stress, (c) normalized tensile elastic modulus and (d) normalized shear modulus of AA1100/ Si_3N_4 composites.

The density of AA1100/ Si_3N_4 metal matrix composites increased as shown in figure 4a with increase of volume fraction of Si_3N_4 nanoparticles in AA1100 alloy matrix. The densities of AA1100 alloy matrix and Si_3N_4 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/Si_3N_4 metal matrix composites. It is significant to note that the Si_3N_4 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 Si_3N_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 Si_3N_4 when the strength is expected to be much higher than at lower Si_3N_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 Si_3N_4 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 Si_3N_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 Si_3N_4 in AA1100 alloy matrix. With porosity and clustering in the composites, the stress intensity was decreased with increase of volume fraction of Si_3N_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.

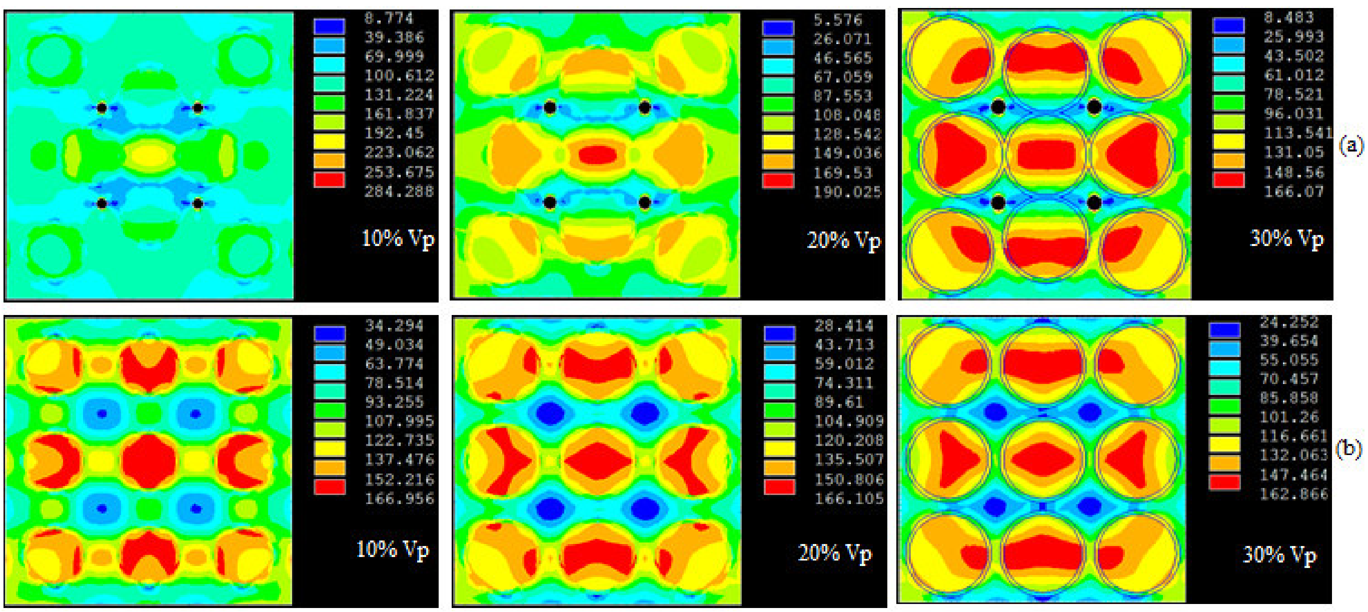

Figure 5: Images of von Mises stresses obtained from FEA: (a) without clustering and porosity and (b) with clustering and porosity.

CONCLUSION

AA1100/ Si_3N_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

1. I. S. Han, D. W. Seo, S. Y. Kim, K. S. Hong, K. H. Guahk, K. S. Lee, Properties of silicon nitride for aluminum melts prepared by nitride pressureless sintering [J]. Journal of the European Ceramic Society, 28, 2008, pp. 1057−1063.
2. M. Chamundeswari and A. C. Reddy, Evaluation of strength improvement in tempered AA5050/SiC metal matrix composites using finite element analysis: experimental validation, National Conference on Advances in Design Approaches and Production Technologies (ADAPT-2005), Hyderabad, 22-23rd August 2005, pp. 338-340.
3. S. Sujatha and A. C. Reddy, Assessment of strength improvement in heat treated AA2024/SiC metal matrix composites using finite element analysis: experimental validation, National Conference on Advances in Design Approaches and Production Technologies (ADAPT-2005), Hyderabad, 22-23rd August 2005, pp. 341-343.
4. B. Ramana, A. C. Reddy, and S. Somi Reddy, Fracture analysis of mg-alloy metal matrix composites, National Conference on Computer Applications in mechanical Engineering, Anantapur, 21st December 2005, pp.57-61.

5. A. Chennakesava Reddy and B. Kotiveerachari, Effect of Matrix Microstucture and Reinforcement Fracture on the Properties of Tempered SiC/Al-Alloy Composites, National conference on advances in materials and their processing, Bagalkot, 28-29th November, 2003, pp.78-81.
6. A. Chennakesava Reddy, Analysis of the Relationship Between the Interface Structure and the Strength of Carbon-Aluminum Composites, NATCON-ME, Bangalore, 13-14th March2004, pp.61-62.
7. A. Chennakesava Reddy, Studies on fracture behavior of brittle matrix and alumina trihydrate particulate composites, Indian Journal of Engineering & Materials Sciences, 9, 2003, pp.365-368.
8. A. Chennakesava Reddy, Experimental Evaluation of Elastic Lattice Strains in the Discontinuously SiC Reinforced Al-alloy Composites, National Conference on Emerging Trends in Mechanical Engineering, Nagapur, 05-06th February, 2004, pp.81, Paper No. e-TIME/110/E-07.
9. V. K. Prasad and A. C. Reddy, Tensile behavior of tempered AA5050/$Al2O_3$ metal matrix composites using RVE models: experimental validation, National Conference on Advances in Design Approaches and Production Technologies (ADAPT-2005), Hyderabad, 22-23rd August 2005, pp. 335-337.
10. K. Swapna Sudha and A. C. Reddy, Tensile performance of heat treated AA2024/$Al2O_3$ metal matrix composites using RVE models: experimental validation, National Conference on Advances in Design Approaches and Production Technologies (ADAPT-2005), Hyderabad, 22-23rd August 2005, pp. 332-334.
11. A. Chennakesava Reddy, Effect of CTE and Stiffness Mismatches on Interphase and Particle Fractures of Zirconium Carbide /AA5050 Alloy Particle-Reinforced Composites, 3rd International Conference on Composite Materials and Characterization, Chennai, India, 11-12 May 2001, pp. 257-262.
12. A. Chennakesava Reddy, Behavioral Characteristics of Graphite /AA6061 Alloy Particle-Reinforced Metal Matrix Composites, 3rd International Conference on Composite Materials and Characterization, Chennai, India, 11-12 May 2001, pp. 263-269.
13. A. Chennakesava Reddy, Simulation of MgO/AA6061 Particulate-Reinforced Composites Taking Account of CTE Mismatch Effects and Interphase Separation, 3rd National Conference on Materials and Manufacturing Processes, Hyderabad, India, 22-25 February 2002, pp. 184-187.
14. A. Chennakesava Reddy, Two dimensional (2D) RVE-Based Modeling of Interphase Separation and Particle Fracture in Graphite/5050 Particle Reinforced Composites, 3rd National Conference on Materials and Manufacturing Processes, Hyderabad, India, 22-25 February 2002, pp. 179-183.
15. A. Chennakesava Reddy, Investigation of the Clustering Behavior of Titanium Diboride Particles in TiB2/AA2024 Alloy Metal Matrix Composites, 4th International Conference on Composite Materials and Characterization, Hyderabad, India, 7-8 March 2003, pp.216-220.
16. A. Chennakesava Reddy, Finite Element Analysis Study of Micromechanical Clustering Characteristics of Graphite/AA7020 Alloy Particle Reinforced Composites, 4th International Conference on Composite Materials and Characterization, Hyderabad, India, 7-8 March 2003, pp. 206-210.
17. A. Chennakesava Reddy, Stir Casting Process on Porosity Development and Micromechanical Properties of AA5050/Titanium Oxide Metal Matrix Composites, 5th National Conference on Materials and Manufacturing Processes, Hyderabad, 9-10 June 2006, pp. 144-148.
18. A. Chennakesava Reddy, Effect of Porosity Formation during Synthesis of Cast AA4015/Titanium Nitride Particle-Metal Matrix Composites, 5th National Conference on Materials and Manufacturing Processes, Hyderabad, 9-10 June 2006, pp. 139-143.
19. A. Chennakesava Reddy, Role of Porosity and Clustering on Performance of AA1100/Boron Carbide Particle-Reinforced Metal Matrix Composites, 6th International Conference on Composite Materials and Characterization, Hyderabad, 8-9 June 2007, pp. 122-127.
20. P. Rami Reddy, A. Chennakesava Reddy, Formation of Gas Porosity and Clustering in Stir Cast AA2024/Titanium Diboride Particle-Reinforced Metal Matrix Composites and Influence on Micromechanical Properties, 6th International Conference on Composite Materials and Characterization, Hyderabad, 8-9 June 2007, pp. 128-132.
21. P. Rami Reddy, A. Chennakesava Reddy, Structure and Properties of Liquid Metal Processed Zirconium Oxide Reinforced AA3003 Alloy, 6th International Conference on Composite Materials and Characterization, Hyderabad, 8-9 June 2007, pp. 133-138.
22. A. C. S. Kumar, A. Chennakesava Reddy, Processing of AA4015-Silicon Oxide Particulate Metal Matrix Composites by Stir Casting Technology, 6th International Conference on Composite Materials and Characterization, Hyderabad, 8-9 June 2007, pp. 139-143.
23. A. C. S. Kumar, A. Chennakesava Reddy, Microstructural and Numerical Evaluation of Porosity and Clustering Control over Micromechanical Properties of Cast Titanium Nitride Reinforced AA5050 Alloy, 6th International Conference on Composite Materials and Characterization, Hyderabad, 8-9 June 2007, pp. 144-148.
24. A. Chennakesava Reddy, Effect of Clustering Induced Porosity on Micromechanical Properties of AA6061/Titanium Oxide Particulate Metal matrix Composites, 6th International Conference on Composite Materials and Characterization, Hyderabad, 8-9 June 2007, pp. 149-154.
25. S. Satyanarayana, A. Chennakesava Reddy, High pressure Die Casting of AA7020/Zirconium Carbide Particulate Metal matrix Composites, 6th International Conference on Composite Materials and Characterization, Hyderabad, 8-9 June 2007, pp. 155-159.
26. S. Satyanarayana, A. Chennakesava Reddy, Occurrence of Agglomeration and Porosity during High pressure Die Casting of AA8090/Graphite Particulate Metal matrix Composites, 6th International Conference on Composite Materials and Characterization, Hyderabad, 8-9 June 2007, pp. 160-164.