Synthesis and Characterization of Zirconium Carbide Nanoparticles Reinforced AA2024 Alloy Matrix Composites Cast by Bottom-Up Pouring

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Abstract: *AA2024/ZrC 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 ZrC. Two types of finite element models were used to estimate the strength of the MMCs. The microstructures of AA2024/ZrC composites have revealed the occurrence of particle clustering and porosity. The normalized tensile strength and elastic modulus decrease with porosity and clustering of ZrC nanoparticles.*

Keywords: *AA2024 alloy, zirconium carbide, unit cell, finite element analysis, clustering, porosity, wear.*

1. INTRODUCTION

Current aluminum casting alloys are not useful at temperatures exceeding 200ºC and pressures around 200 MPa, which are conditions that prevail in many applications such as the crown area of automotive pistons [1]. Nano-structured composite materials provide high strength, wear resistance, hardness, and exceptional microstructure stability when used in these severe conditions, and therefore they are suitable for such applications. Nanocomposite materials ensure performances far superior than alloys strengthened by micro-size particles [2]. Particles aggregations or clusters and poor wettability are the main processing problems in as cast composites. 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 [3-15. Porosity formation has always been coupled to casting process [16-27]. Zirconium carbide possesses high temperature oxidation resistance, high strength, high hardness, good thermal conductivity and toughness. Also, it is an important reinforcement in the preparation of composites for the structural materials.

Since zirconium carbide is having density of 6.73 g/cc, bottom-up pouring technique was developed for synthesizing AA2024/ zirconium carbide nanocomposite materials wherein the reinforcing nano-sized zirconium carbide particles were mixed using stir casting process in a molten aluminum alloy. The micromechanical behavior of AA2024/zirconium carbide metal matrix composites was studied. 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 AA2024 alloy. The reinforcement material was ZrC nanoparticles of average size 100nm. AA2024/ ZrC 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 AA2024/ ZrC metal matrix composites at three (10%, 20% and 30%) volume fractions of ZrC 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 ZrC 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:

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

$$k = E_m m_m / E_p m_p$$

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.

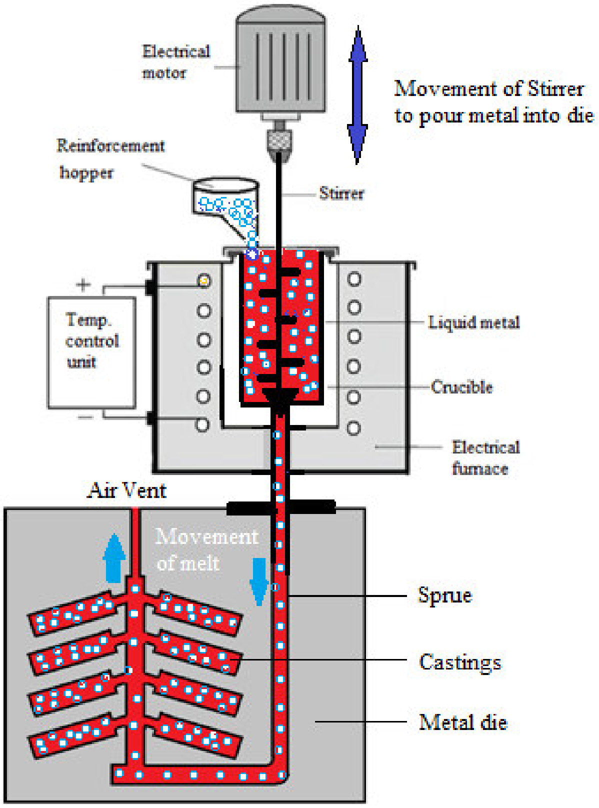

Figure 1: Concept of bottom-up pouring of composite metal.

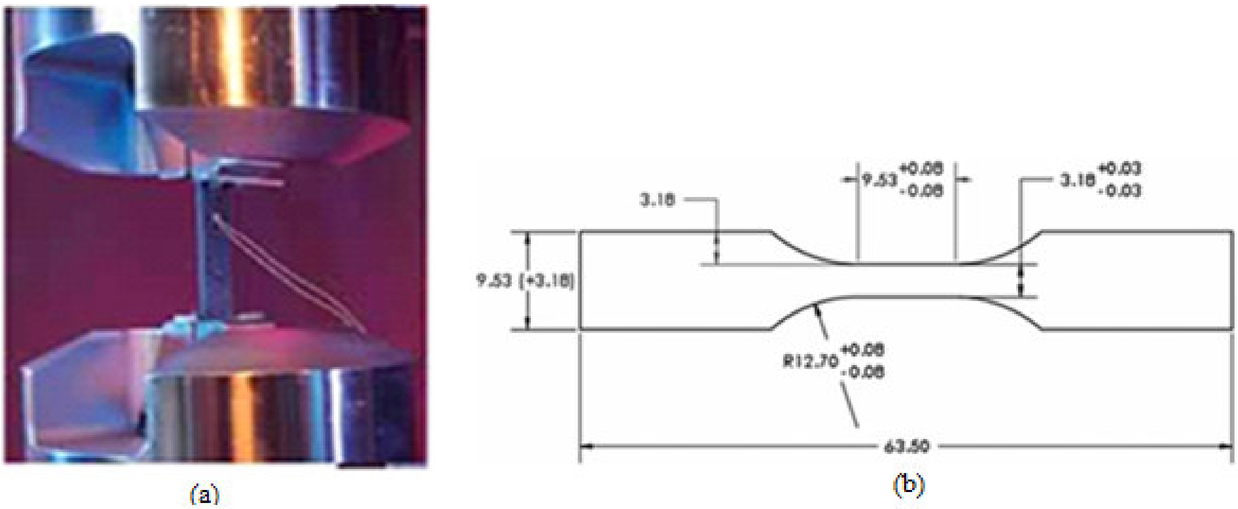

Figure 2: Testing of composites: (a) tensile testing and (b) dimensions (mm) of tensile specimen.

The upper-bound equation is given by

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

The lower-bound equation is given by

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

where, $\delta = E_p/E_m$.

3. RESULTS AND DISCUSSION

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

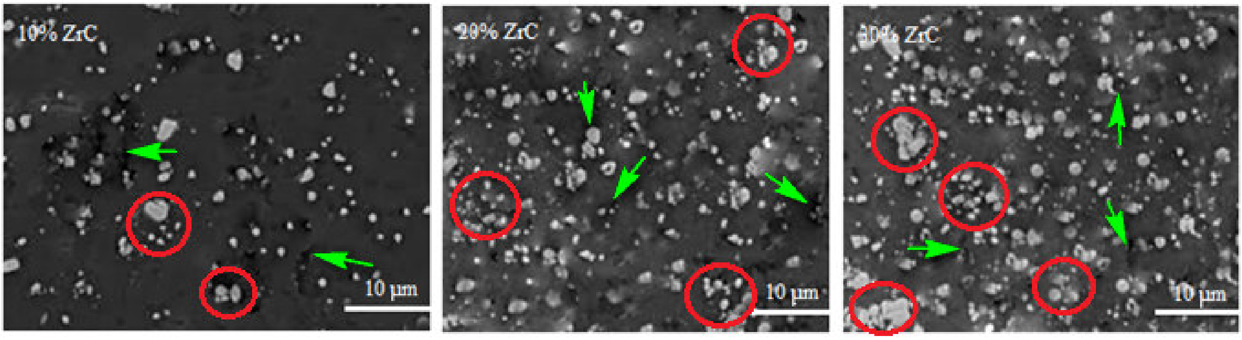

Figure 3: Microstructure showing distribution of ZrC nanoparticles, clustering and porosity in AA2024 alloy matrix.

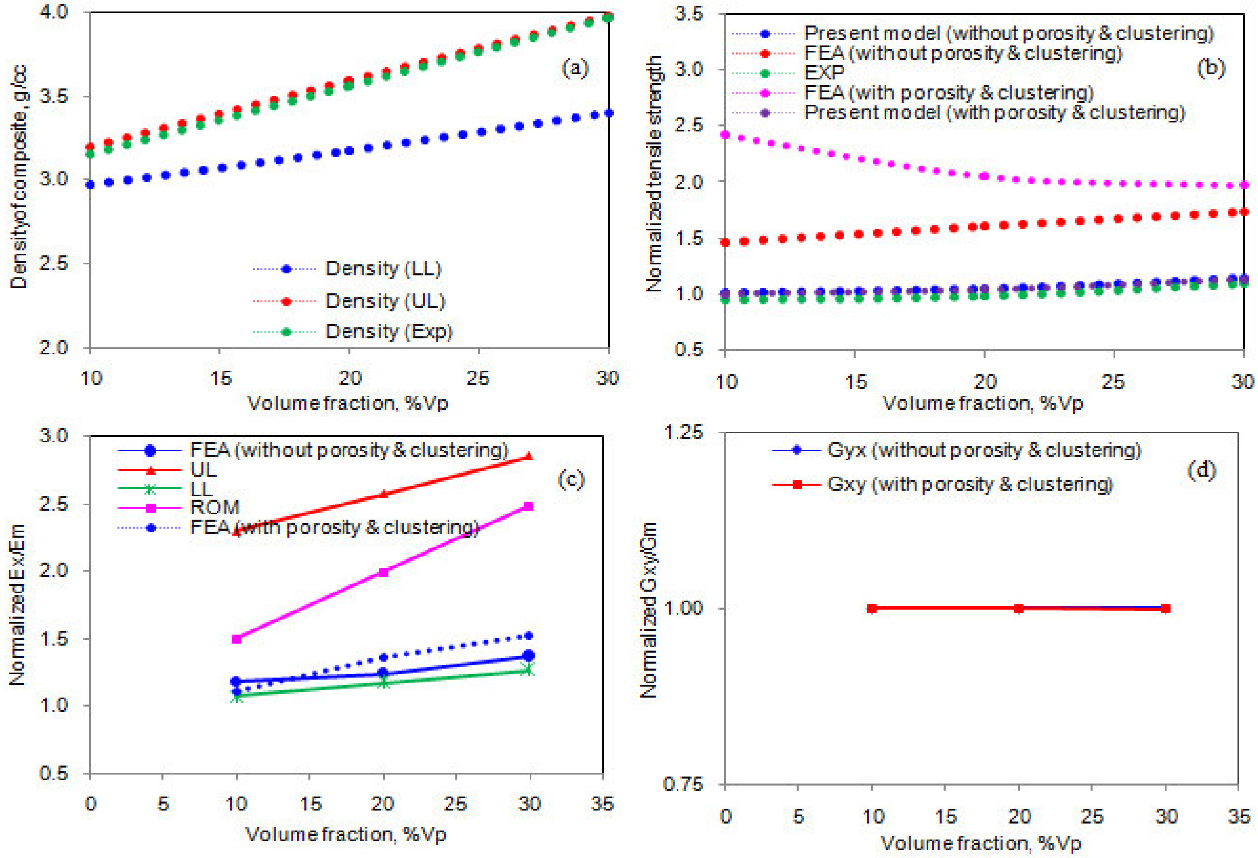

Figure 4: Effect of volume fraction on (a) density (b) normalized tensile stress, (c) normalized tensile elastic modulus and (d) normalized shear modulus of AA2024/ZrC composites.

The density of AA2024/ ZrC metal matrix composites increased as shown in figure 4a with increase of volume fraction of ZrC nanoparticles in AA2024 alloy matrix. The densities of AA2024 alloy matrix and ZrC nanoparticles are, respectively, 2.80 g/cc and 6.73 g/cc. In order to characterize the mechanical properties of AA2024 alloy/ZrC composites, the tensile strengths have been normalized with respect to AA2024 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 AA2024/ZrC metal matrix composites. As shown in figure 4b, the normalized tensile strength was very low at higher ZrC contents, mostly due to the increased amount of clustering and voids. The normalized elastic modulus increased with increase of volume fraction of ZrC nanoparticles in AA2024 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 ZrC 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 ZrC in AA2024 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.

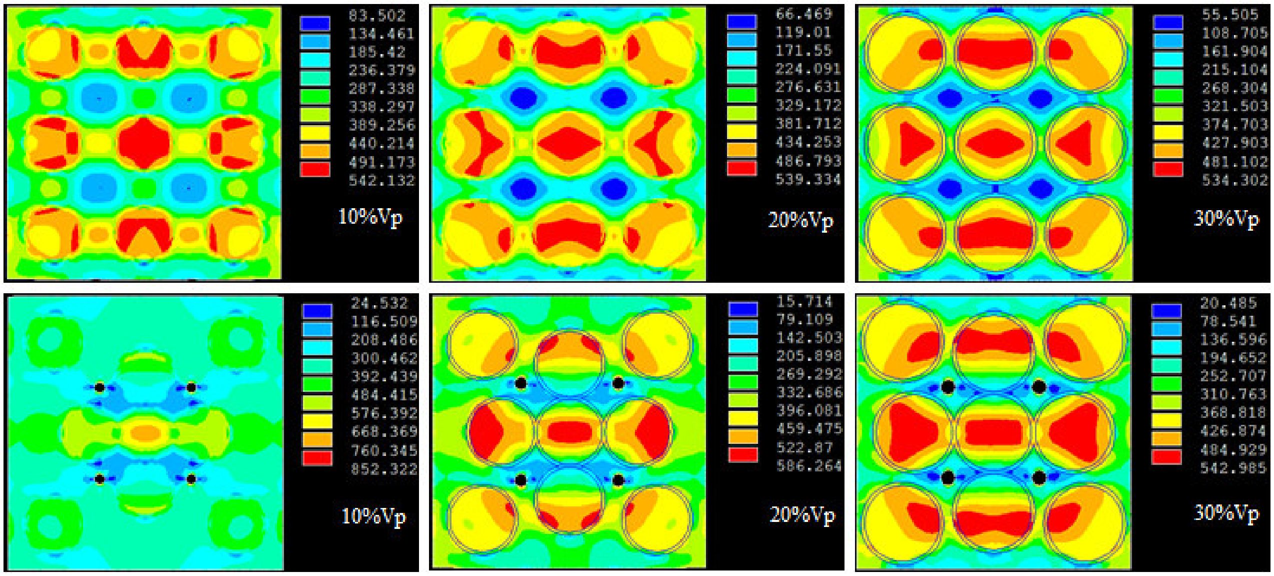

Figure 5: Images of von Mises stresses obtained from FEA: (a) without clustering and porosity and (b) with clustering and porosity.

4. CONCLUSION

AA2024/ ZrC metal matrix composites had clusters and porosity voids. The density of the composites increased with increase volume fraction of ZrC nanoparticles. The stress intensity was increased with porosity and clustering of ZrC nanoparticles.

REFERENCES

1. S.C. Tjong, Z.Y. Ma, Microstructural and mechanical characteristics of in-situ metal matrix composites, Materials Science and Engineering, 29, 2000, pp. 49-113.
2. M.J. Koczak and K.S. Kumar, U.S. Patent 4, 808, 372.370, 1989.
3. A. Chennakesava Reddy, Constitutive Behavior of AA5050/MgO Metal Matrix Composites with Interface Debonding: the Finite Element Method for Uniaxial Tension, 2nd National Conference on Materials and Manufacturing Processes, Hyderabad, India, 10-11 March 2000, pp. 121-127.
4. A. Chennakesava Reddy, Micromechanical and fracture behaviors of Ellipsoidal Graphite Reinforced AA2024 Alloy Matrix Composites, 2nd National Conference on Materials and Manufacturing Processes, Hyderabad, India, 10-11 March 2000, pp. 96-103.
5. 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.

6. 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.
7. 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.
8. 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.
9. 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.
10. A. Chennakesava Reddy and B. Kotiveerachari, Effect of Matrix Microstructure and Reinforcement Fracture on the Properties of Tempered SiC/Al-Alloy Composites, National conference on advances in materials and their processing, Bagalkot, 28-29 November, 2003, pp.78-81.
11. 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.
12. 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.
13. A. Chennakesava Reddy, Analysis of the Relationship Between the Interface Structure and the Strength of Carbon-Aluminum Composites, NATCON-ME, Bangalore, 13-14 March 2004, pp.61-62.
14. 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, 5-6 February, 2004, pp.81, Paper No. e-TIME/110/E-07.
15. A. Chennakesava Reddy, S. Sundararajan, Influences of ageing, inclusions and voids on the ductile fracture mechanism of commercial Al-alloys, Journal of Bulletin of Material Sciences Springer India, 28, 2005, pp. 75-79.
16. A. Chennakesava Reddy, Microstructure and Mechanical Properties of AA2219 Alloy Turbine Impeller Manufactured by Investment Casting, National Conference on Computer Applications in mechanical Engineering, Anantapur, 21 December 2005, pp. 321-323.
17. A. Chennakesava Reddy, Impact of Boron Coated Investment Shell Moulds on Surface Modification of Hypoeutectic Al-Si Alloys, National Conference on Computer Applications in mechanical Engineering, Anantapur, 21 December 2005, pp.324-326.
18. 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.
19. 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.
20. 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.
21. 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.
22. B. Kotiveera Chari, A. Chennakesava Reddy, Bottom-Up Pouring and its Effect on Porosity and Clustering in Casting of AA1100/Silicon Nitride Particle-Reinforced Metal Matrix Composites, 6th National Conference on Materials and Manufacturing Processes, Hyderabad, 8-9 August 2008, pp. 110-114.
23. Essa Zitoun, A. Chennakesava Reddy, Microstructure-Property Relationship of AA3003/Boron Nitride Particle-Reinforced Metal Matrix Composites Cast by Bottom-Up Pouring, 6th National Conference on Materials and Manufacturing Processes, Hyderabad, 8-9 August 2008, pp. 115-119.
24. A. Chennakesava Reddy, Wear and Mechanical Behavior of Bottom-Up Poured AA4015/Graphite Particle-Reinforced Metal Matrix Composites, 6th National Conference on Materials and Manufacturing Processes, Hyderabad, 8-9 August 2008, pp. 120-126.
25. S. Pitchi Reddy, A. Chennakesava Reddy, Effect of Needle-like Brittle Intermetallic Phases on Fracture Behavior of Bottom-up Poured AA5050/Titanium Carbide Particle-Reinforced Metal Matrix Composites, 6th National Conference on Materials and Manufacturing Processes, Hyderabad, 8-9 August 2008, pp. 127-132.
26. A. Chennakesava Reddy and Essa Zitoun, Matrix al-alloys for alumina particle reinforced metal matrix composites, Indian Foundry Journal, 55, 2009, pp.12-16.
27. A. Chennakesava Reddy, Mechanical properties and fracture behavior of 6061/SiCp Metal Matrix Composites Fabricated by Low Pressure Die Casting Process, Journal of Manufacturing Technology Research, 1, 2009, pp.273-286.