Effect of Cold Rolling on Porosity and Micromechanical Properties of AA6061/Zirconium Carbide Metal Matrix Composites

[1]A. C. S. Kumar and A. Chennakesava Reddy[2]

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

Abstract: The AA6061/ZrC alloy metal matrix composites were fabricated using stir casting process and analyzed for tensile properties in the presence of porosity. Porosity was measured with different volume percents of zirconium carbide particle reinforced to AA6061 alloy. The density increased with increase of ZrC particles in AA6061 alloy matrix. Development of porosity and increased content of reinforcement particles reduced the plastic deformation of matrix.

Keywords: Titanium oxide, AA6061 alloy, unit cell models, finite element analysis, porosity.

1. INTRODUCTION

Metal matrix composites have gained a considerable interest in the recent years because of the fact that addition of ceramic reinforcement in the metal matrix can improve specific strength, stiffness, wear, fatigue and creep properties compared to conventional engineering materials. Stir casting is one of the methods accepted for the production of large quantity commercially practiced [1-19]. It is attractive because of simplicity, flexibility and most economical for large sized components to be fabricated. It is a liquid state method of composite materials fabrication, in which a dispersed phase (ceramic particles, short fibers) is mixed with a molten matrix metal by means of mechanical stirring. The main factors that control the properties of metal matrix composites fabricated using casting techniques include: reinforcement distribution, wetting of reinforcement by matrix alloy porosity in the cast metal matrix and chemical reaction between reinforcement material and the matrix alloy [20-38].

The objective of this research work was to fabricate AA6061 alloy/zirconium carbide metal matrix composites using stir casting technique. The effects of porosity on micromechanical properties were investigated using experimental practice and finite element analysis. For the finite element analysis, the spherical shaped zirconium carbide particles were assumed to analyze unit cells with and without porosity.

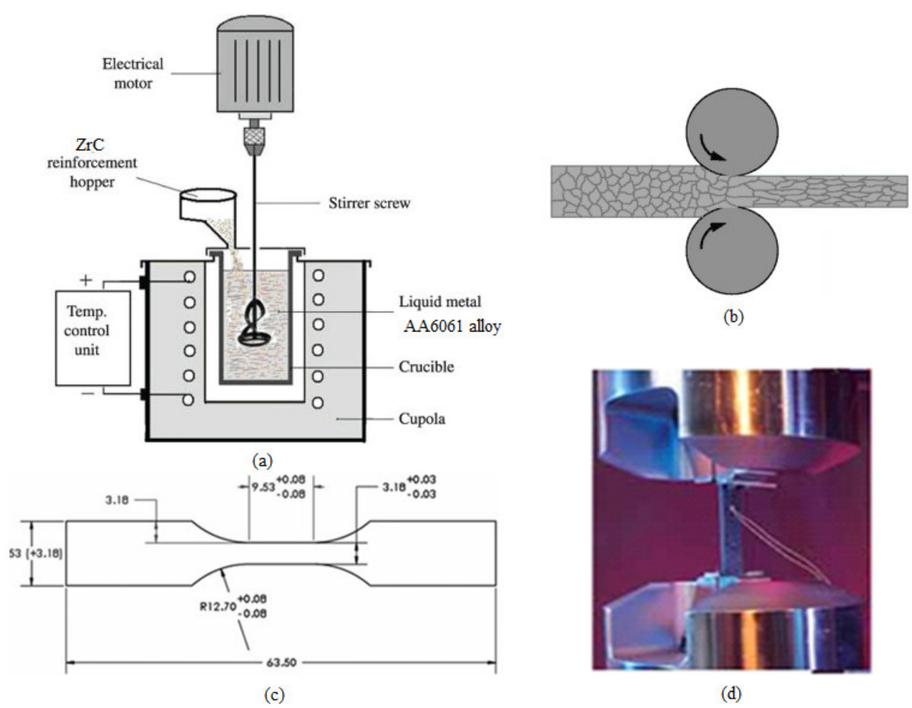

Figure 1: Stir casting process; cold rolling (b); shape and dimensions of tensile specimen (c); and tensile testing on UTM (d).

2. MATERIALS METHODS

The matrix material was AA6061 alloy. The reinforcement material was ZrC nanoparticles of average size 100nm. AA6061/ZrC alloy 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 AA6061/ZrC composites at three (10%, 20% and 30%) volume fractions of ZrC. 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.

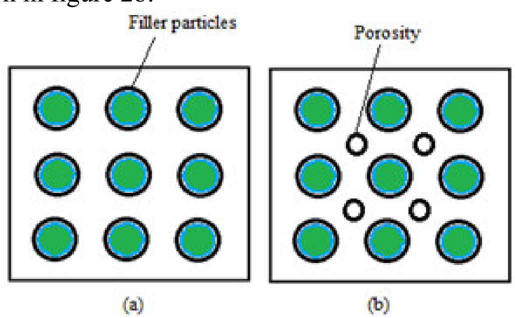

Figure 2: Unit cells: (a) without porosity and (b) with porosity.

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

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

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:

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

$$k = E_m m_m / E_p m_p$$

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

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

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

The tensile strength was increased due to addition of ZrC particles without porosity AA6061/ ZrC metal matrix composites; 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. The density increased with increase of volume fraction of ZrC in the AA6061 alloy matrix (figure 3b). The reason could be attributed increasing volume percentages of reinforced particles were added to the base matrix. The densities of ZrC and AA6061 alloy are, respectively, 6.73 g/cc and 2.70 g/cc. The porosity presence has affected the yield strength, ductility, Poisson's ratio and ultimate tensile strength of metal matrix composites [38, 39]. This is confirmed with the microstructures of the composites shown in figure 4.

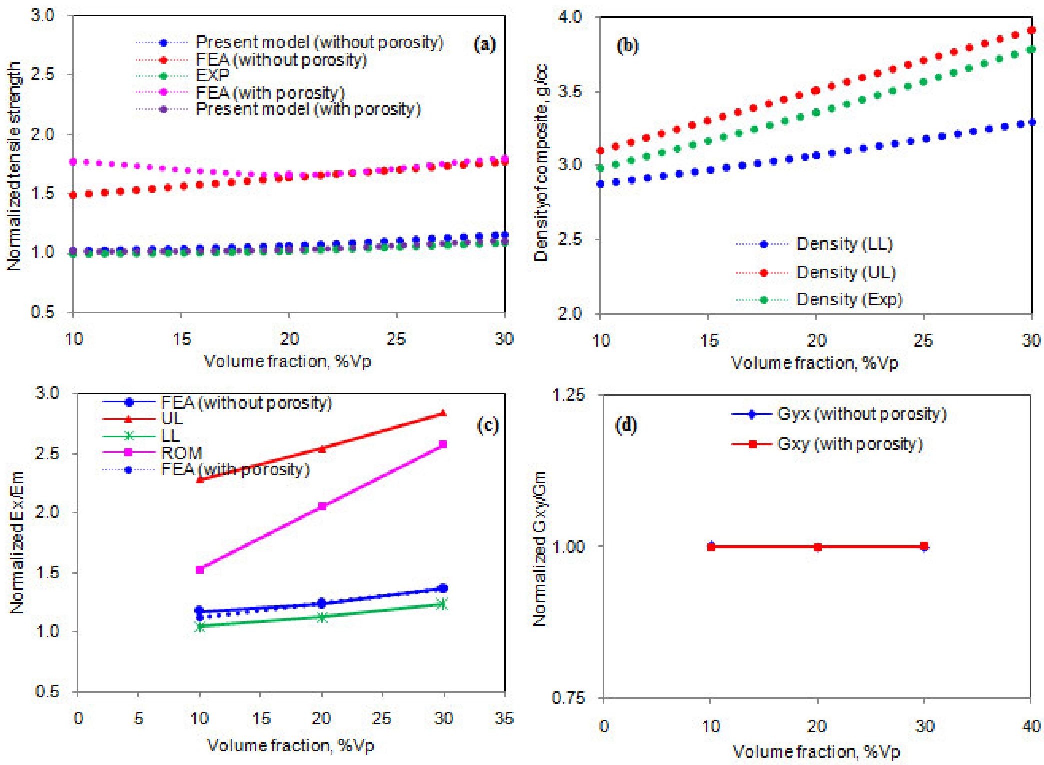

Figure 3: Effect of volume fraction on (a) normalized strength, (b) normalized tensile elastic modulus, (c) normalized shear modulus and (d) density of AA6061/ ZrC composites.

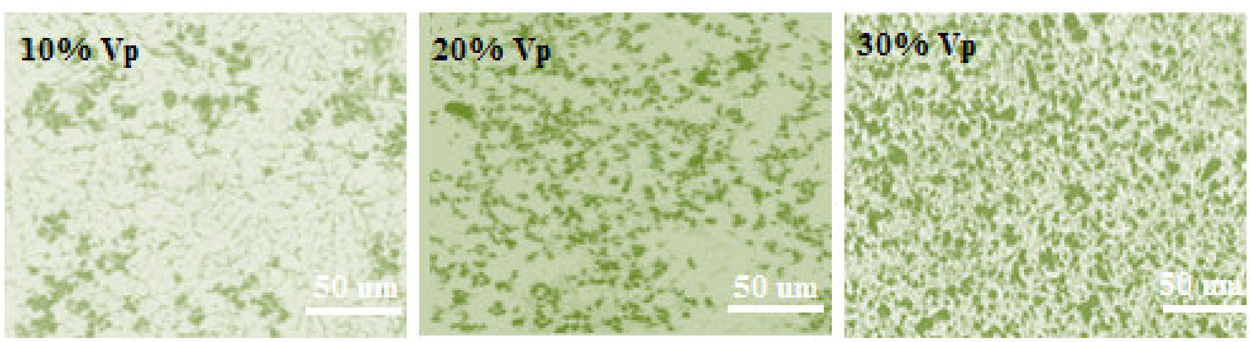

Figure 4: Microstructure showing porosity and distribution of 10%, 20% and 30% ZrC nanoparticles in AA6061 alloy matrix.

The normalized elastic modulus increased with increase of volume fraction of ZrC particles in AA6061 alloy matrix with or without porosity. This is due to the increase of tensile beyond allowable tensile stress and decrease of ductility simultaneously. The normalized shear modulus was constant with increase of volume fraction of ZrC in the AA6061 alloy matrix with or without porosity (figure 3d). Without porosity in the composites, the tensile stress increased with increase of volume fraction of ZrC in AA6061 alloy matrix. 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 especially in the composites having 30%ZrC particles. Development of porosity and increased content of reinforcement particles reduced the plastic deformation of matrix at which point failure initiated.

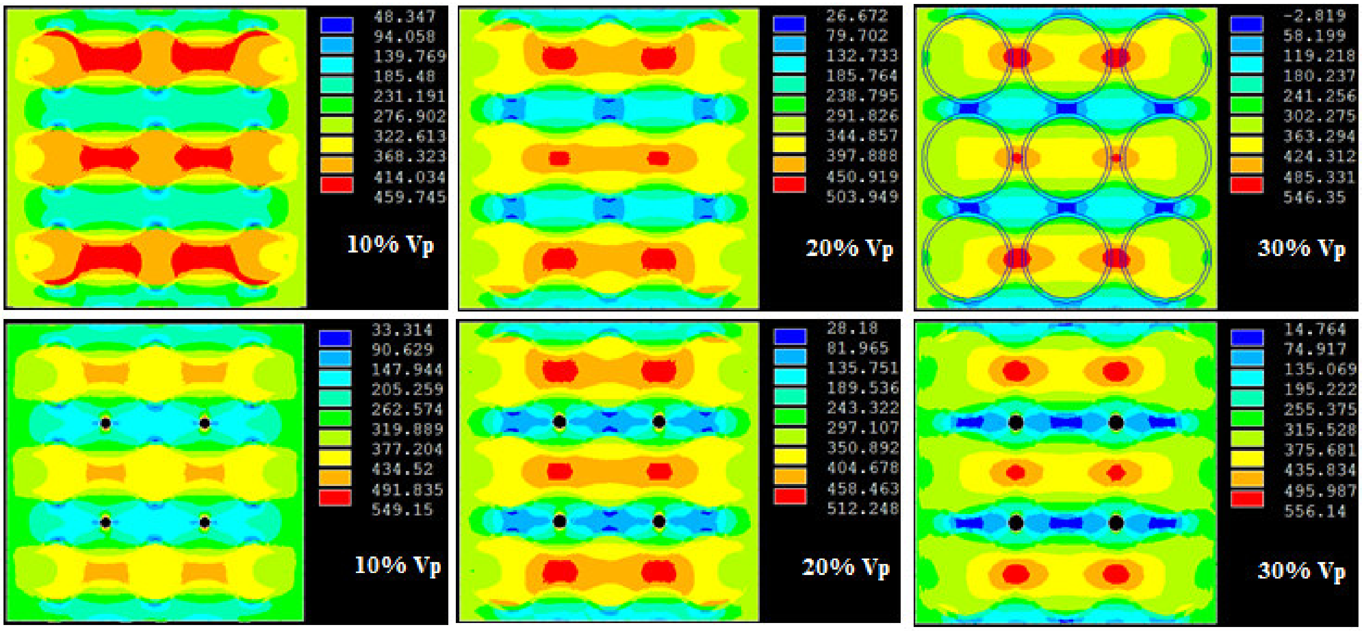

Figure 5: Images of tensile stresses obtained from FEA: (a) without porosity and (b) with porosity.

4. CONCLUSIONS

Porosity content was significantly linear with increasing percentage of ZrC particles in AA6061 alloy 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 reducing the plastic deformation of matrix.

REFERENCES

1. D. Brabazon, D.J. Browne, A.J. Carr, Mechanical stir casting of aluminium alloys from the mushy state: process, microstructure and mechanical properties, Materials Science and Engineering A326, 2002, pp. 370–381.
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. D. J. Lloyd, Particle reinforced aluminium and magnesium matrix composites, International Materials Reviews, 39, 1994, pp. 1-23.
5. 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.
6. 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.
7. 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.
8. 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.
9. A. M. Samuel, A. Gotmare, F.H. Samuel, Effect of solidification rate and metal feedability on porosity and SiC/Al2O3 particle distribution in an Al-Si-Mg (359) alloy, Composites science and technology, 53, 1995, pp. 301-315.
10. S. Madhav Reddy, A. C. Reddy, Clustering in Zirconium Oxide/AA1100 Alloy Particle-Reinforced Metal Matrix Composites, 4th International Conference on Composite Materials and Characterization, Hyderabad, India, 7-8 March 2003, pp. 182-187.
11. P. Laxminarayana, A. C. Reddy, Numerical Investigation of the Effect of Particle Clustering on the Micromechanical Properties of Titanium Nitride/AA4015 Alloy Particle-Reinforced Metal Matrix Composites, 4th International Conference on Composite Materials and Characterization, Hyderabad, India, 7-8 March 2003, pp. 193-196.
12. M. Kok, Production and Mechanical Properties of Al2O3 particle Reinforced 2024 Aluminium Composites, Journal of Materials Processing Technology, 16, 2005, pp. 381-387.
13. 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.

14. P. Laxminarayana, A. C. Reddy, Effect of Particle Spatial Distribution and Clustering on Tensile Behavior of Titanium Oxide/AA5050 Alloy Particle Reinforced Composites, 4th International Conference on Composite Materials and Characterization, Hyderabad, India, 7-8 March 2003, pp. 197-201.
15. J. W. Hutchinson, et al., Fundamentals of Metal Matrix Composites, 1993, pp. 158-173.
16. S. Madhav Reddy, A. C. Reddy, Effect of Particle Clustering on Micromechanical Properties of Boron Nitride/AA3003 Alloy Particle-Reinforced Metal Matrix Composites, 4th International Conference on Composite Materials and Characterization, Hyderabad, India, 7-8 March 2003, pp. 188-192.
17. Essa Zitoun, A. C. Reddy, Agglomeration of Nanoparticles into Network Aggregates in Zirconium Carbide/AA6061 Alloy Particle Reinforced Composites, 4th International Conference on Composite Materials and Characterization, Hyderabad, India, 7-8 March 2003, pp. 202-205.
18. P. K. Rohatgi, Low-Cost, Fly-Ash-Containing Alumi- num-Matrix Composites, JOM, 46, 1994, pp. 55-59.
19. Essa Zitoun, A. C. Reddy, Unit Cell Models for Clustering of Particles embedded in MgO Particle/AA8090 Alloy Metal Matrix Composites, 4th International Conference on Composite Materials and Characterization, Hyderabad, India, 7-8 March 2003, pp. 211-215.
20. 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.
21. Y. M. Youssef, R. J. Dashwood and P. D. Lee, Effect of Clustering on Particle Pushing and Solidification Behavior in TiB2 Reinforced Aluminum PMMCs, Composites Part A: Applied Science and Manufacturing, 36, 2005, pp. 747-763.
22. A. Chennakesava Reddy, Micromechanical Modelling of Interfacial Debonding in AA1100/Graphite Nanoparticulate Reinforced Metal Matrix Composites, 2nd International Conference on Composite Materials and Characterization, Nagpur, India, 9-10 April 1999, pp. 249-253.
23. A. Chennakesava Reddy, Cohesive Zone Finite Element Analysis to Envisage Interface Debonding in AA7020/Titanium Oxide Nanoparticulate Metal Matrix Composites, 2nd International Conference on Composite Materials and Characterization, Nagpur, India, 9-10 April 1999, pp. 204-209.
24. P. N. Bindumadhavan, T. K. Chia, M. Chandrasekaran, H. K. Wah, L. N. Lam and O. Prabhakar, Effect of Particle Porosity Clusters on Tribological Behavior of Cast Alu- minium Alloy A356-SiCp Metal Matrix Composites, Materials Science and Engineering: A315, 2001, pp. 217-226.
25. 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.
26. V. K. Prasad and A. C. Reddy, Tensile behavior of tempered AA5050/Al2O3 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.
27. D. M. Skibo, D. M. Schuster and L. Jolla, Process for Preparation of Composite Materials Containing Non-Metallic Particles in a Metallic Matrix, and Composite Materials, US Patent No. 4786467, 1988.
28. 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.
29. K. Swapna Sudha and A. C. Reddy, Tensile performance of heat treated AA2024/Al2O3 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.
30. C. Cui, et al., Review on fabrication methods of in situ metal matrix composites, Journal of Materials Science and Technology, 16, 2000, pp. 619-626.
31. 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.
32. 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.
33. 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.
34. 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.
35. B. Balu Naik, A. C. Reddy and T. K. K. Reddy, Finite element analysis of some fracture mechanisms, International Conference on Recent Advances in Material Processing Technology, Kovilpatti, 23-25th February 2005, pp.265-270.
36. 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.
37. Skolianos, S. 1996. Mechanical behavior of cast SiCp-reinforced Al-4.5%Cu-1.5%Mg alloy, Materials Science and Engineering. Vol. (A210): 76-82.
38. 8. Whitehouse, A.F. 2000. Creep of Metal Matrix Composites -Comprehensive Composite Materials Volume 3: Metal Matrix Composites. Clyne, T.W., Kelly, A., Zweben, C. (eds). Pergamon. UK.