Formation of Gas Porosity and Clustering in Stir Cast AA2024/Titanium Diboride Particle-Reinforced Metal Matrix Composites and Influence on Micromechanical Properties

[1]P. Rami Reddy and A. Chennakesava Reddy[2]

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

Abstract: *AA2024/TiB_2 metal matrix composites manufactured by stir casting practice and high pressure die casting process to investigate the effect of clustering and porosity on their micromechanical properties. Tension tests were conducted on specimens reinforced with different volume fractions of TiB_2. Two types of finite element models were proposed with and without clustering and porosity. The microstructures of AA2024/TiB_2 composites have revealed the occurrence of particle clustering and porosity. The stress intensities have decreased with increase of volume fraction of TiB_2 nanoparticles.*

Keywords: *AA2024 alloy, titanium diboride, unit cell, finite element analysis, clustering, porosity.*

1. INTRODUCTION

In cast metal-matrix composites, particle clustering is due to the combined effect of reinforcement settling and the rejection of the reinforcement particles by the matrix dendrites while these are growing into the remaining liquid during solidification [1]. Stir casting method is a relatively low cost liquid processing present to produce metal matrix composites and hence, this processing technique had been utilized in this study. There are several difficulties [2] in stir casting that are of concern, which are:

- porosity in the cast MMC,
- difficulty in achieving a uniform distribution of the reinforcement material,
- wettability between the two main substances, and
- chemical reactions between the reinforcement material and matrix alloy.

Although there is a qualitative understanding of the effects of clustering and porosity on the mechanical properties of composites, a quantitative assessment cannot be made in the absence of a detailed micromechanical modeling. Finite element analysis of a periodic unit cell was obtained from the traditional models developed for homogeneous composites and the overall composite behavior was computed by averaging the behavior of all cells [3-17].

In this paper, the two-dimensional simulations of the elasto-plastic deformation of composites reinforced with a homogeneous and isotropic distribution of spheres are extended to address the effect of clustering and porosity. The macroscopic response and the local stress and strain fields were computed for microstructures with clustering of particles and porosity, and compared with those of homogeneous composites with regular particle distributions. 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 titanium diboride (TiB_2) nanoparticles of average size 100nm. AA2024/ TiB_2 metal matrix composites were fabricated by the stir casting process and high pressure die casting technique (figure 2b) with pressure at 25 MPa. The test samples were machined to get flat-rectangular specimens 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 present work, a unit cell comprising of nine particles was implemented to analyze the micromechanical behavior AA2024/ TiB_2 metal matrix composites at three (10%, 20% and 30%) volume fractions of TiB_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 TiB_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.

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.

The upper-bound equation is given by

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

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 density of AA2024/ TiB_2 metal matrix composites increased as shown in figure 1a with increase of volume fraction of TiB_2 nanoparticles. This is due to difference in densities of AA2024 alloy matrix and TiB_2 nanoparticles. The densities of AA2024 alloy matrix and TiB_2 nanoparticles are, respectively, 2.80 g/cc and 4.52 g/cc.

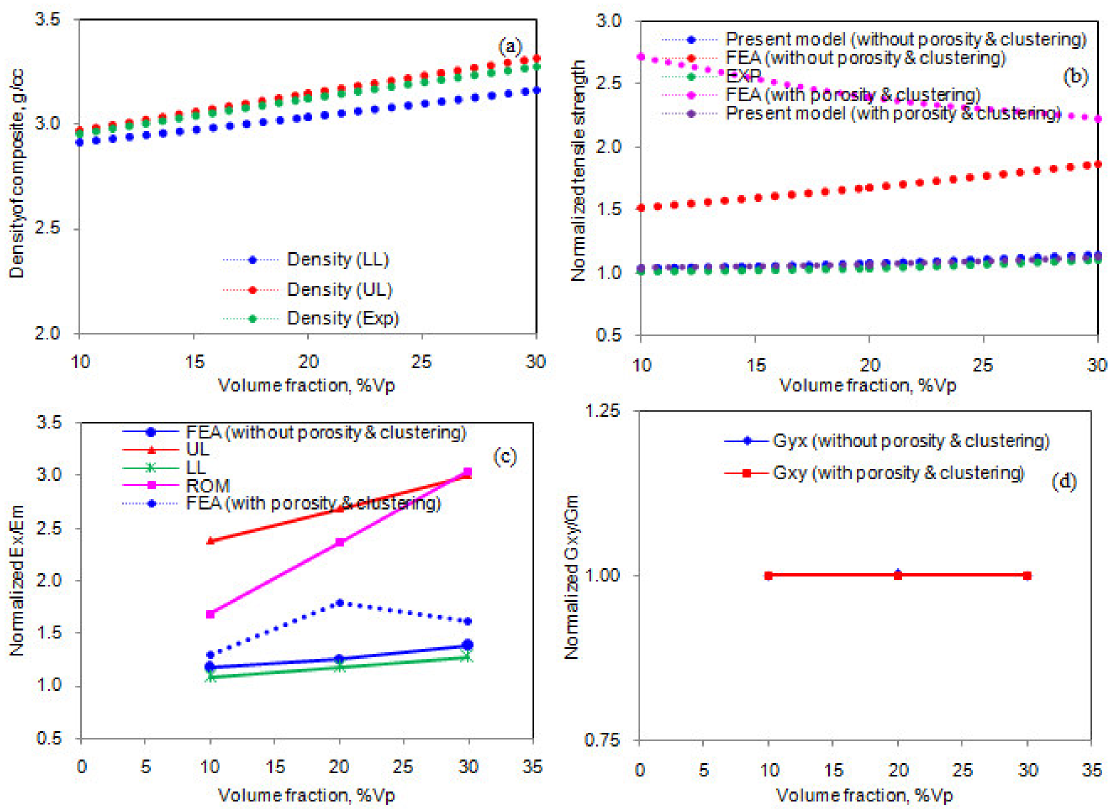

Figure 1: Effect of volume fraction on (a) density (b) normalized tensile stress, (c) normalized tensile elastic modulus and (d) normalized shear modulus of AA2024/TiB_2 composites.

Addition of TiB_2 nanoparticles to AA2024 alloy matrix increased tensile strength without porosity and clustering as shown in figure 1b. As a result of stir casting process and high pressure die casting technique, the porosity and clustering of nanoparticles were resulted in AA2024/TiB_2 composites. Subsequently, the tensile strength decreased owing to porosity and clustering in AA2024/ TiB_2 metal matrix composites. Owing to the occurrence of stress concentrations at voids and clustered regions, 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. The normalized elastic modulus increased with increase of volume fraction of TiB_2 nanoparticles in AA2024 alloy matrix without porosity and clustering in the composites; while it decreased with increase of volume fraction of TiB_2 nanoparticles above 20 vol.% in AA2024 alloy matrix with porosity and clustering (figure 1c). The normalized shear modulus is constant with increase of volume fraction of TiB_2 with and without porosity and clustering (figure 1d).

In all the finite element models (figure 2), the amount of porosity and volume of clustering were maintained constant. Without porosity and clustering in the composites, the stress intensities are nearly constant irrespective of increase in the volume fraction of TiB_2 in AA2024 alloy matrix (figure 2a). With porosity and clustering in the composites, the stress intensities were high in the composites. But, the stress intensity decreased with increase of volume fraction of TiB_2 (figure 2b). In general, the tensile strength increases with increase of volume fraction of particle reinforcement in the metal matrix composites. At high volume fractions of TiB_2, the stress intensities were suppressed by the increase in the tensile strength of AA2024/TiB_2 composites.

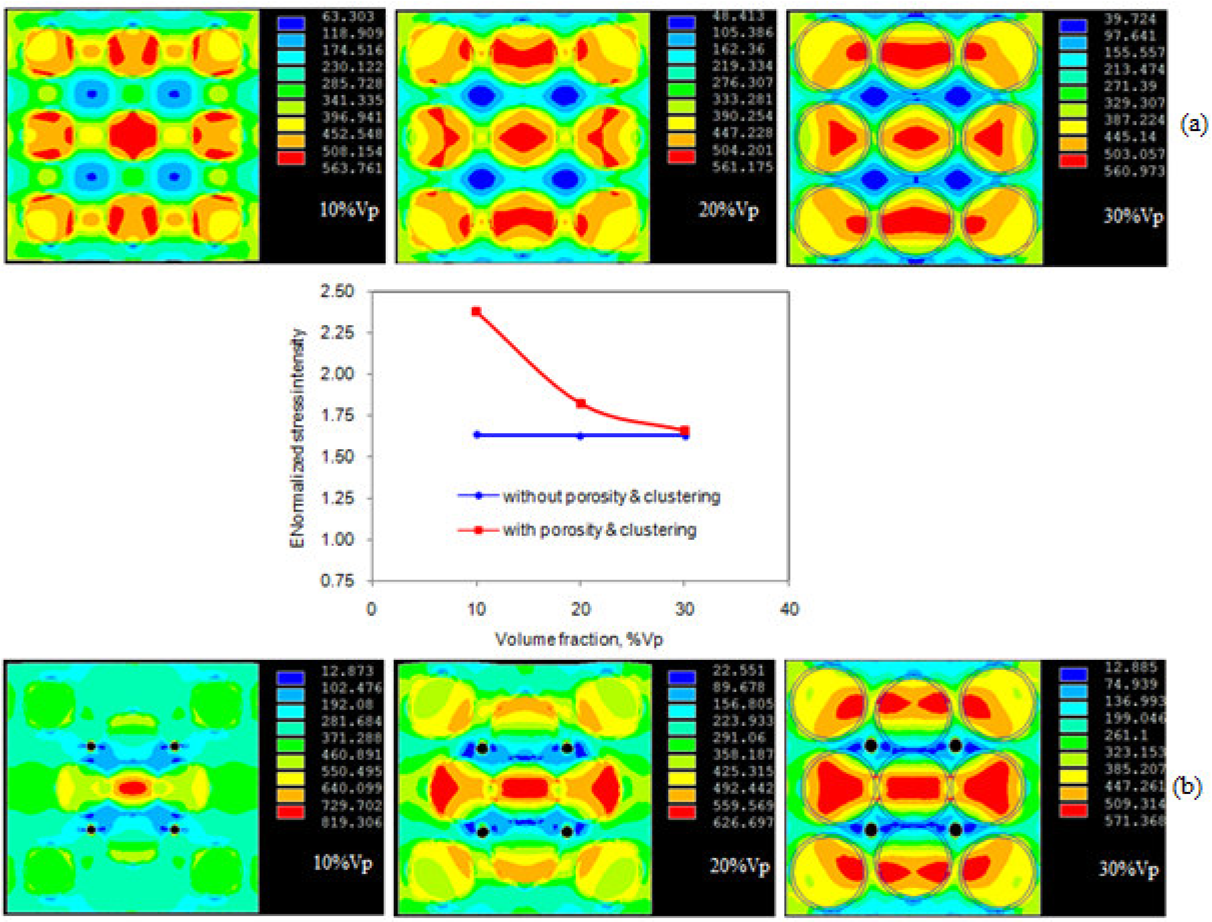

Figure 2: Images of stress intensities obtained from FEA: (a) without clustering and porosity and (b) with clustering and porosity.

During experimentation, the formation of necking was not observed in the tensile samples before failure and that the fracture strain of the composites was much lower than that of the AA2024 alloy matrix. As seen figure 3, the clustered particles and voids are the sites for damage accumulation ahead of the crack. The interface of the clustered particles is the preferred location of the voids. The predominant fracture mode of AA2024/TiB_2 metal matrix composites is cluster cracking and cracks originating from the porosity voids. The cracking occurs at an early stage of loading. Since the ductility of the composites is low, it is reasonable to assume that the cracks through the fractured clusters and porosity voids obey the fracture mechanics approach, and have a plane strain plastic zone. The plastic zone size increases with increasing load, and failure of the composite occurs when the plastic zones of adjacent cracks coalesce. Thus, clustering of TiB_2 nanoparticles and porosity voids make negative contributions to the strength of the AA2024/TiB_2 metal matrix composites.

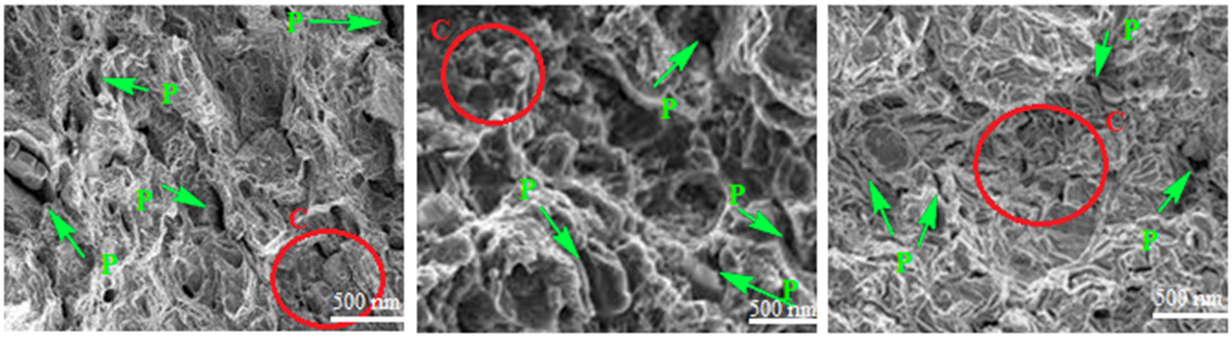

Figure 3: SEM images of tested specimens showing porosity and clustering of particles.

4. CONCLUSION

In AA2024/TiB_2 metal matrix composites, the voids are typically located at the interface of clustered particles. The cracks clearly has originated from the voids and clustered regions. The rate of strength computed from the finite element analysis is in good agreement with the experimental results. The stress intensities decreased with the increase of volume fraction of TiB_2 in the AA2024 alloy matrix.

REFERENCES

1. D. J. Lloyd, Particle reinforced aluminium and magnesium matrix composites, International Material Reviews, 39, 1994, pp. 1-23.
2. J. Hashim, L. Looney, M. S. J. Hashmi, Metal Matrix Composites: Production by the Stir Casting Method, Journal of Materials Processing Technology, 92-93, 1999, pp. 1-7.
3. 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.
4. 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.
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. 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.
10. 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.
11. 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.
12. 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.

13. 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.
14. 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.
15. 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.
16. 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.
17. 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.
18. S. Madhav Reddy, A. Chennakesava Reddy, Effects of Porosity on Mechanical Properties of Zirconium Oxide/AA1100 Alloy Metal Matrix Composites, 5th National Conference on Materials and Manufacturing Processes, Hyderabad, 9-10 June 2006, pp. 124-128.
19. Essa Zitoun, A. Chennakesava Reddy, High Pressure Die Casting Process on Micromechanical Properties of AA2024/Boron Carbide Metal Matrix Composites, 5th National Conference on Materials and Manufacturing Processes, Hyderabad, 9-10 June 2006, pp.129-133.
20. Essa Zitoun, A. Chennakesava Reddy, Micromechanical and Porosity Studies of Cast AA3003/ Boron Nitride Metal Matrix Composites, 5th National Conference on Materials and Manufacturing Processes, Hyderabad, 9-10 June 2006, pp. 134-138.
21. 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.
22. 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.
23. A. C. S. Kumar, A. Chennakesava Reddy, Effect of Cold Rolling on Porosity and Micromechanical Properties of AA6061/Zirconium Carbide Metal Matrix Composites, 5th National Conference on Materials and Manufacturing Processes, Hyderabad, 9-10 June 2006, pp. 149-153.
24. S. Madhav Reddy, A. Chennakesava Reddy, Effect of Reinforcement Loading on Porosity and Micromechanical Properties of AA7020/Graphite Metal Matrix Composites, 5th National Conference on Materials and Manufacturing Processes, Hyderabad, 9-10 June 2006, pp. 154-158.
25. A. C. S. Kumar, A. Chennakesava Reddy, Microstructure and Properties of Liquid Metal Processed MgO Reinforced AA8090 Metal Matrix Composites, 5th National Conference on Materials and Manufacturing Processes, Hyderabad, 9-10 June 2006, pp. 159-163.
26. 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.
27. 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.