Evaluation of Thermal Expansion of Al/B_4C Metal Matrix Composites

A. Chennakesava Reddy

Associate Professor, Department of Mechanical Engineering, Vasavi College of Engineering, Hyderabad, India
dr_acreddy@yahoo.com

Abstract: The thermal expansion behavior of aluminum matrix composites reinforced with boron carbide nanoparticles was measured between 30 and 300°C and compared to theoretical models. The results revealed that the nanoparticle volume fraction had significant effect on the thermal expansion behavior of the composites. For the composites with lower nanoparticle volume faction, their coefficient of thermal expansion (CTE) is determined by a stress relaxation process.

Keywords: Metal matrix composites, thermal expansion, boron carbide.

1. INTRODUCTION

Particle reinforced metal matrix composites have been the subject of extensive study in the past thirty years due to a need for lightweight structural materials [1-7]. Even though our understanding of composite mechanical behavior has progressed significantly over the past decade [8-15], the definition of coefficient of thermal expansion (CTE) still remains challenging in part due to the materials studied [16]. For most applications of Al-MMCs, CTE is a key parameter that needs to be carefully considered and tailored. Previous studies primarily focused on materials reinforced with micrometer-sized particles, long fibers and whiskers [17, 18]; little attention has been paid to the materials with nanometer-sized reinforcing particles.

The objective of this paper was to evaluate the thermal expansion behavior of aluminum metal matrix composites reinforced with nanoscale boron carbide (B_4C) particles. The effect of volume fraction of B_4C nanoparticles was also examined.

2. MATERIALS METHODS

Pure Al powder of 100 µm with 99.9% purity and B_4C powders of 100 nm were used as the starting materials. Pure powders of Al and B_4C, in the desired volume fractions, were mixed together by high-energy ball milling for 20 h to ensure the uniform mixing. The mixing was carried out in argon atmosphere to minimize the contamination. The obtained powder mixtures were then sintered to bulk specimens by hot pressing at 800 °C with a pressure of 50 MPa in vacuum, followed by quickly cooling to room temperature in 30 min. In this study, four different composites were prepared (Table 1).

Table 1: Composition of metal matrix composites

Composite	Composition, vol.%	
	Al	B_4C
AL-BC-1	90	10
AL-BC-2	85	15
AL-BC-3	80	20
AL-BC-4	75	25

The thermal expansion was then measured with a dilatometer (DIL 802) between 100 and 300°C at heating and cooling rates of 5°C/min in argon. With this instrument the difference in length between the specimen to be investigated and a reference sample is measured, which results in a resolution of ± 0.01 µm. The sample holder (pushrod) is made of sapphire (figure 1). Specimens with a diameter of 5 mm and length of 10 mm were used for CTE measurement. The instantaneous CTE at a given temperature was calculated using the following equation:

$$CTE = \frac{\partial}{\partial T}\left(\frac{\Delta L}{L}\right) \quad (1)$$

where L is the length of the specimen and T the temperature.

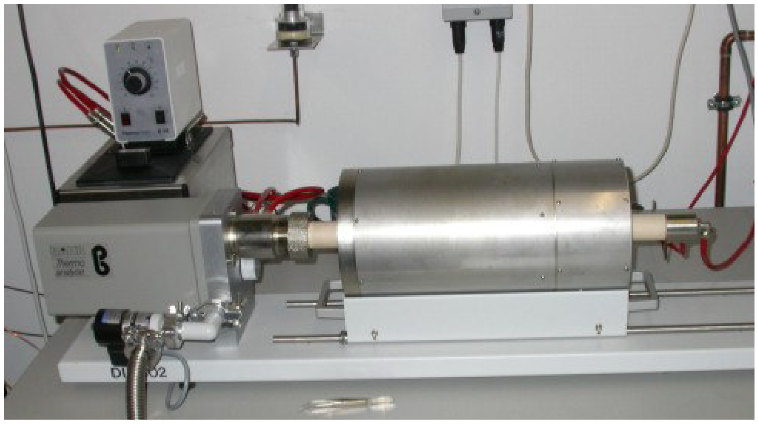

Figure 1: The differential dilatometer.

3. RESULTS AND DISCUSSION

The CTE obtained from the heating and cooling as a function of temperature is plotted in figure 1 for all materials. The CTE measured during the heating cycle increases with increasing temperature between 30 and 300°C as shown in figure 2. However, the CTE measured during the cooling cycle decreases continuously with decreasing temperature (figure 2). In addition, there is significant difference between CTE - temperature curves measured in the heating and the cooling cycles. This is due difference in CTE and thermal conductivities of pure Al matrix and B_4C nanoparticles. For the CTE of the composites containing lower concentration nanoparticles (AL-BC-1 and AL-BC-2), the rate of increase is higher than that of composites containing higher concentration nanoparticles (AL-BC-3 and AL-BC-4).

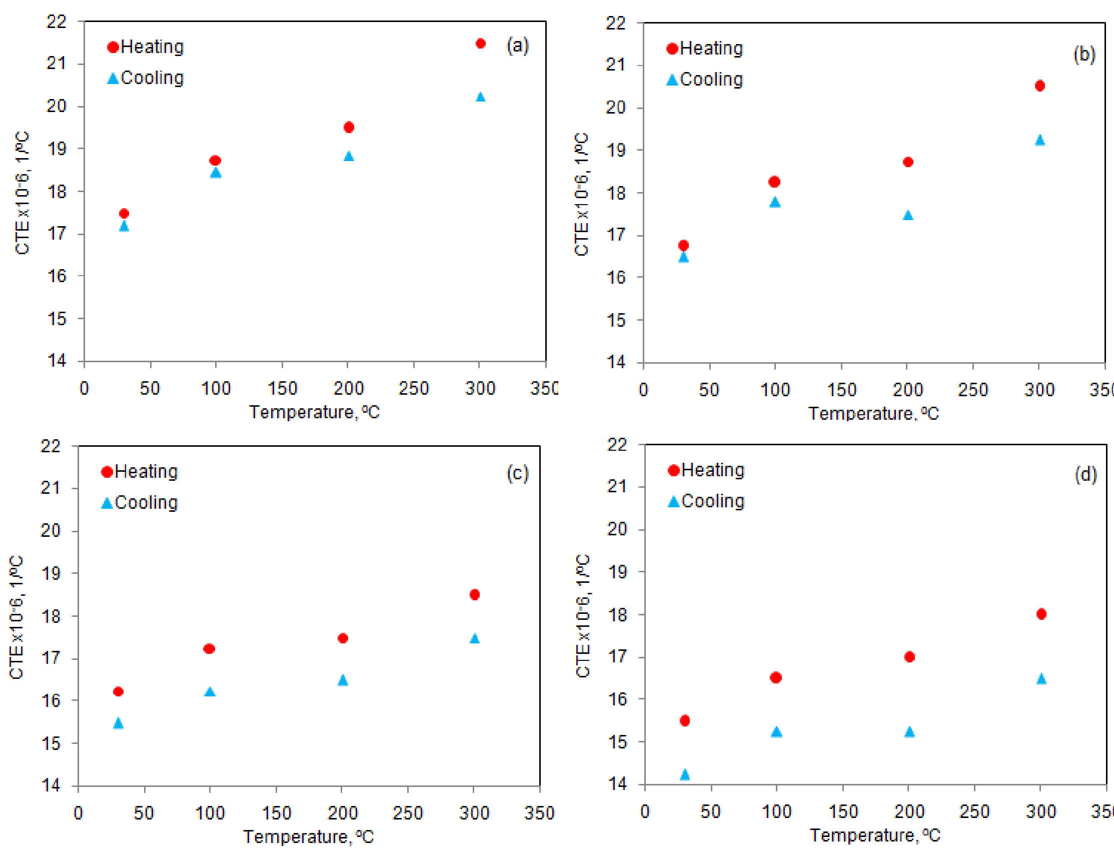

Figure 2: Coefficient of thermal expansion as a function of temperature for: (a) AL-BC-1, (b) AL-BC-2, (c) AL-BC-3 and (d) AL-BC-4.

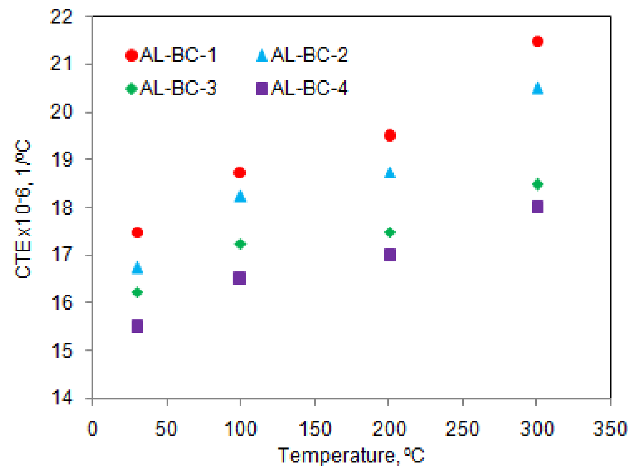

Figure 3: Compare the CTE of different composites.

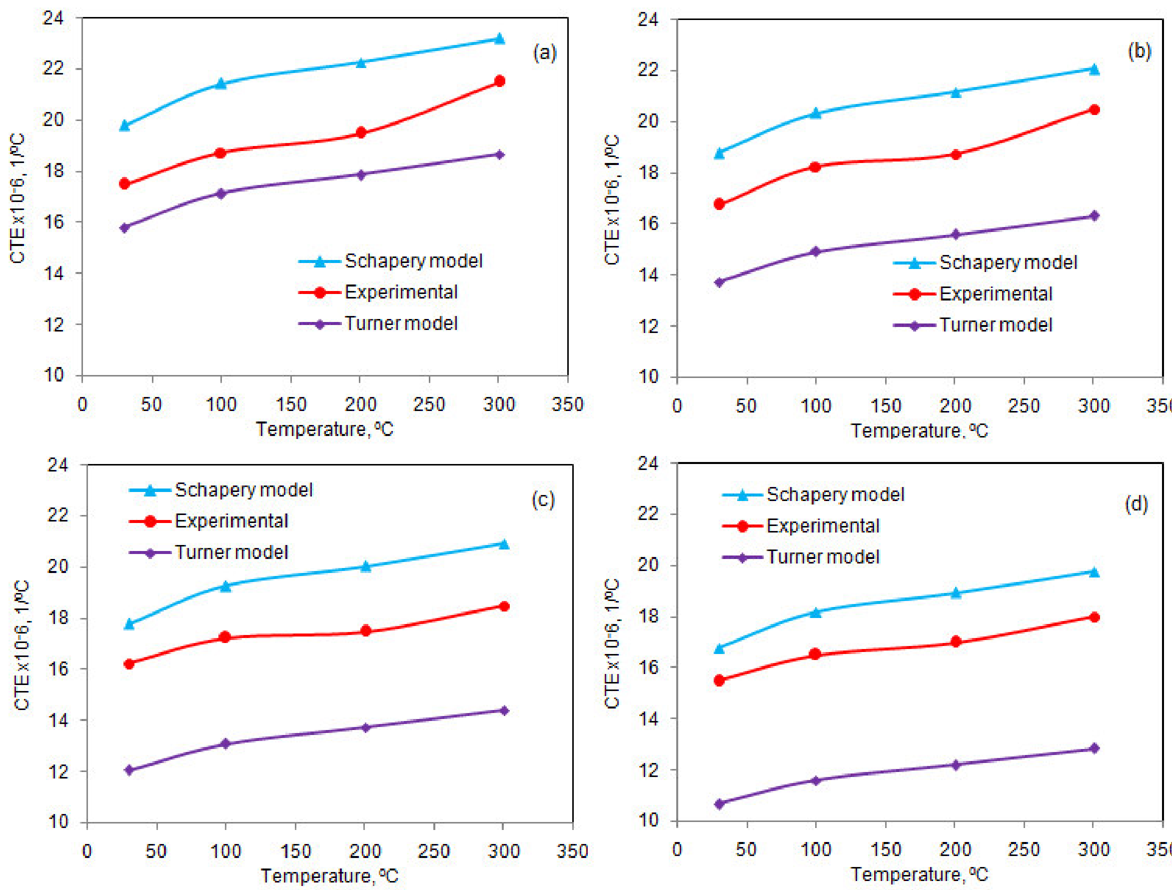

Figure 4: Coefficient of thermal expansion as a function of temperature compared with Schapery and Turner models for: (a) AL-BC-1, (b) AL-BC-2, (c) AL-BC-3 and (d) AL-BC-4.

Figure 3 compares the thermal expansion behavior of the four samples obtained from the heating cycle. It can be seen that the CTE value decreases with increase in volume fraction of B_4C nanoparticles. Thermal expansion generally decreases with increasing bond energy. The bond energy is low for the composites having high volume fraction of B_4C nanoparticles. For the composite materials, residual stresses resulted from thermal mismatch between the matrix and the reinforcement play a key role in determining the thermal expansion behavior. It is believed that the maximum values observed for samples AL-BC-1 and AL-BC-2 during the heating cycle were caused by the fast relaxation of residual stresses.

Further analysis of the thermal expansion behavior of the composites was done by comparing the experimental results with theoretical models. Several models have been proposed for estimating the CTE of the metal-matrix composite [17, 18]. By assuming that only uniform hydrostatic stresses exist in the phases, Turner [17] proposed that the CTE of a particular composite can be described by

$$\alpha_c = \frac{\alpha_m V_m K_m + \alpha_r V_r K_r}{V_m K_m + V_r K_r} \quad (2)$$

where α is CTE, V the volume fraction, K the bulk modulus, and the subscripts c, m, and r refer to the composite, matrix and reinforcement, respectively. On the other hand, by considering both hydrostatic and shear stresses, Schapery [18] is expressed as

$$\alpha_c = V_r\alpha_r + V_m\alpha_m + \left(\frac{4G_m}{K_c}\right)\left[\frac{(K_c-K_r)(\alpha_c-\alpha_r)V_r}{4G_m+3K_r}\right] \quad (3)$$

where G is shear modulus and K_c the bulk modulus of the composite given by:

$$K_c = \frac{\frac{V_r K_r}{4G_m+3K_r}+\frac{V_m K_m}{4G_m+3K_r}}{\frac{V_r}{4G_m+3K_r}+\frac{V_m}{4G_m+3K_r}} \quad (4)$$

Figure 4 compares the experimental results with the theoretical models for all four composites. It is seen that the experimental CTE results lower than the results obtained Schapery model. Also, the experimental CTE results higher than the results obtained Turner model. Such difference caused by the nanoparticle concentration can be explained by their effect on residual stresses. When the composites are cooled down from high temperatures, the thermal mismatch between the matrix and the reinforcement can result in residual stresses. These stresses are predominantly tensile in the matrix and compressive in the reinforcement. The increase in temperature during CTE measurement can relax such stresses, leading to the decrease in CTE.

4. CONCLUSION

In this research, the thermal expansion behavior of Al-based composites reinforced with boron carbide nanoparticles has been studied. The results reveal that the volume fraction of nanoparticle can have significant effect on thermal expansion behavior of the composites. The composites with higher nanoparticle volume fraction have the CTE closer to the theoretical value.

REFERENCES

1. A. Chennakesava Reddy, Evaluation of Debonding and Dislocation Occurrences in Rhombus Silicon Nitride Particulate/AA4015 Alloy Metal Matrix Composites, 1st National Conference on Modern Materials and Manufacturing, Pune, India, 19-20 December 1997, pp. 278-282.
2. A. Chennakesava Reddy, Interfacial Debonding Analysis in Terms of Interfacial Tractions for Titanium Boride/AA3003 Alloy Metal Matrix Composites, 1st National Conference on Modern Materials and Manufacturing , Pune, 19-20 December, 1997.
3. A. Chennakesava Reddy, Assessment of Debonding and Particulate Fracture Occurrences in Circular Silicon Nitride Particulate/AA5050 Alloy Metal Matrix Composites , National Conference on Materials and Manufacturing Processes, Hyderabad, India, 27-28 February 1998, pp. 104-109.
4. A. Chennakesava Reddy, Local Stress Differential for Particulate Fracture in AA2024/Titanium Carbide Nanoparticulate Metal Matrix Composites, National Conference on Materials and Manufacturing Processes, Hyderabad, India, 27-28 February 1998, pp. 127-131.
5. 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.
6. 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.
7. H. B. Niranjan, A. Chennakesava Reddy, Computational Modeling of Interfacial Debonding in Fused Silica/AA7020 Alloy Particle-Reinforced Metal Matrix Composites, 3rd International Conference on Composite Materials and Characterization, Chennai, India, 11-12 May 2001, pp. 222-227.
8. H. B. Niranjan, A. Chennakesava Reddy, Nanoscale Characterization of Interfacial Debonding and Matrix Damage in Titanium Carbide/AA8090 Alloy Particle-Reinforced Metal Matrix Composites, 3rd International Conference on Composite Materials and Characterization, Chennai, India, 11-12 May 2001, pp. 228-233.
9. S. Sundara Rajan, A. Chennakesava Reddy, Assessment of Temperature Induced Fracture in Boron Nitride/AA1100 Alloy Particle-Reinforced Metal Matrix Composites, 3rd International Conference on Composite Materials and Characterization, Chennai, India, 11-12 May 2001, pp. 234-239.

10. S. Sundara Rajan, A. Chennakesava Reddy, Estimation of Fracture in Zirconia/AA2024 Alloy Particle-Reinforced Composites Subjected to Thermo-Mechanical Loading, 3rd International Conference on Composite Materials and Characterization, Chennai, India, 11-12 May 2001, pp. 240-245.
11. P. M. Jebaraj, A. Chennakesava Reddy, Finite Element Predictions for the Thermoelastic Properties and Interphase Fracture of Titanium Nitride /AA3003 Alloy Particle-Reinforced Composites, 3rd International Conference on Composite Materials and Characterization, Chennai, India, 11-12 May 2001, pp. 246-251.
12. P. M. Jebaraj, A. Chennakesava Reddy, Effect of Thermo-Mechanical Loading on Interphase and Particle Fractures of Titanium Oxide /AA4015 Alloy Particle-Reinforced Composites, 3rd International Conference on Composite Materials and Characterization, Chennai, India, 11-12 May 2001, pp. 252-256.
13. 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.
14. 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.
15. A. Chennakesava Reddy, Significance of Testing Parameters on the Wear Behavior of AA1100/B_4C Metal Matrix Composites based on the Taguchi Method, 3rd International Conference on Composite Materials and Characterization, Chennai, 11-12 May 2001, pp. 276-280.
16. A. Chennakesava Reddy, Prediction of CTE of Al/TiB_2 Metal Matrix Composites, 3rd International Conference on Composite Materials and Characterization, Chennai, 11-12 May 2001, pp. 270-275.
17. E.H. Kerner, Proceedings of the Physical Society, 69, 1956, pp. 808-813.
18. R.A. Schapery, Journal of Composite Materials, 4, 1968, pp. 380-404.