Thermal Expansion Studies on Aluminum Matrix Composites with Different Reinforcement Volume Fractions of Si_3N_4 Nanoparticles

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Abstract: The thermal expansion behavior of aluminum matrix composites reinforced with silicon nitride 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. The hysteresis between the heating and cooling cycles and to the retention of residual strain are the results of the plastic deformation or yielding of materials.

Keywords: Metal matrix composites, thermal expansion, silicon nitride.

1. INTRODUCTION

Particulate-reinforced composites have become increasingly attractive in recent years for their high-strength and creep-resistant properties [1-8]. An external load (force) applied to a composite is partly borne by the matrix and partly by the reinforcement. The load carried by the matrix across a section of the composite is given by the product of the average stress in the matrix and its sectional area [9-18]. Because the residual stresses due to cooling from the consolidation temperature are an important issue in composite materials. Variations in ceramic material properties with temperature increases above room temperature are typically detrimental from a design point of view; with increases in temperature causing decreases in strength, moduli, thermal conductivity, electrical resistivity, and increases in thermal expansion coefficient, and dielectric loss factor. Room temperature material property values are useful for identifying a number of different materials that could be feasibly used, but failure to use temperature-dependent data in simulations can lead to inadequate designs, due to the simultaneous deterioration of many properties [19, 20].

The aim of this paper was to estimate the thermal expansion behavior of aluminum metal matrix composites reinforced with nanoscale silicon nitride (Si_3N_4) nanoparticles. The effect of volume fraction of Si_3N_4 nanoparticles was also examined.

2. MATERIALS METHODS

Pure Al powder of 100 µm with 99.9% purity and Si_3N_4 nanoparticles of 100 nm were used as the starting materials. Pure powders of Al and Si_3N_4, 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	Si_3N_4
AL-SN-1	90	10
AL-SN-2	85	15
AL-SN-3	80	20
AL-SN-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:

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

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

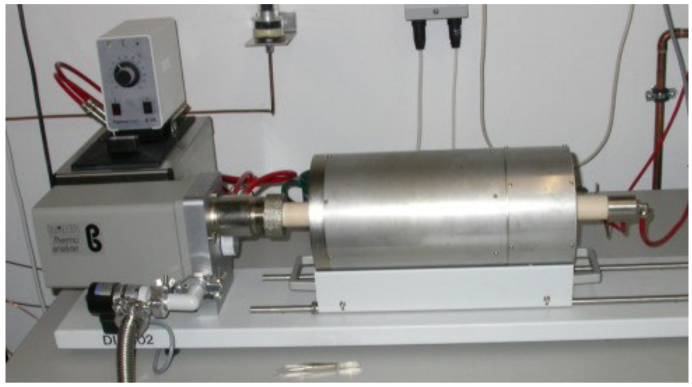

Figure 1: The differential dilatometer.

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). At high temperatures, there is significant difference between CTE during the heating and the cooling cycles. For the CTE of the composites containing lower concentration nanoparticles (AL-SN-1 and AL-SN-2), the rate of increase is higher than that of composites containing higher concentration nanoparticles (AL-SN-3 and AL-SN-4). The hysteresis between the heating and cooling cycles and to the retention of residual strain are the results of the plastic deformation or yielding of materials.

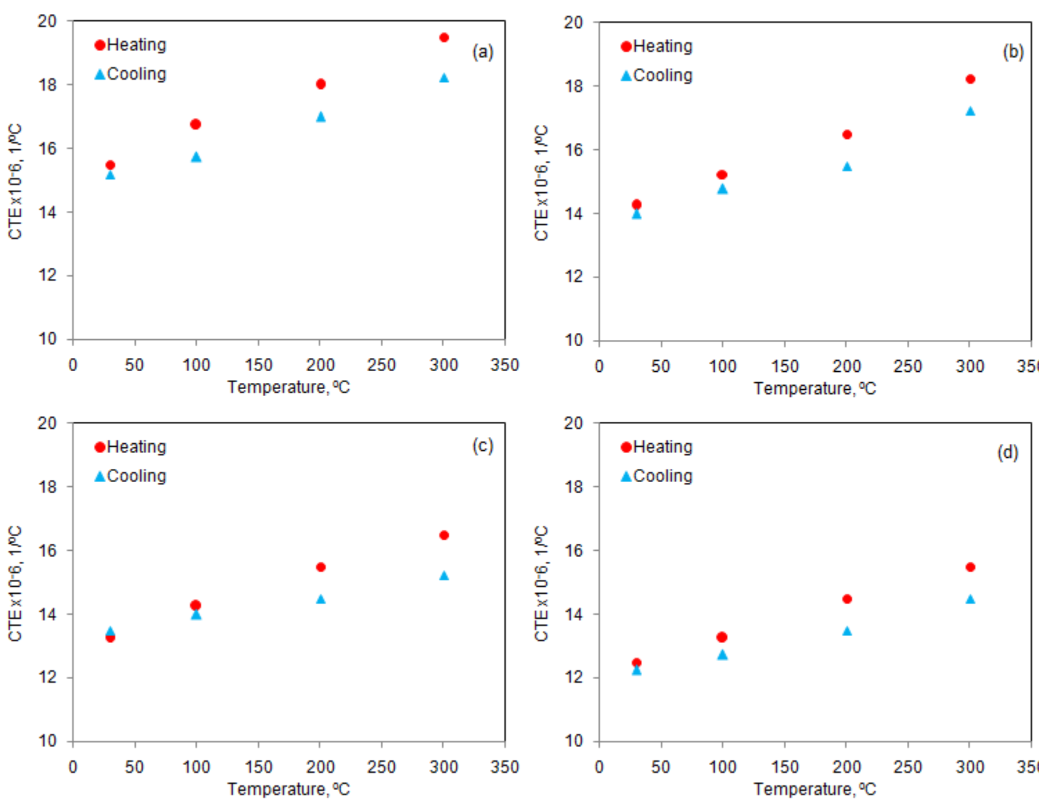

Figure 2: Coefficient of thermal expansion as a function of temperature for: (a) AL-SN-1, (b) AL-SN-2, (c) AL-SN-3 and (d) AL-SN-4.

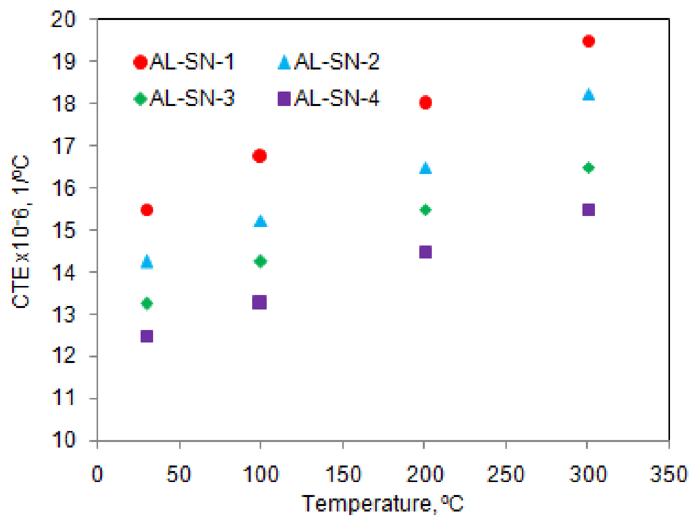

Figure 3: Compare the CTE of different composites.

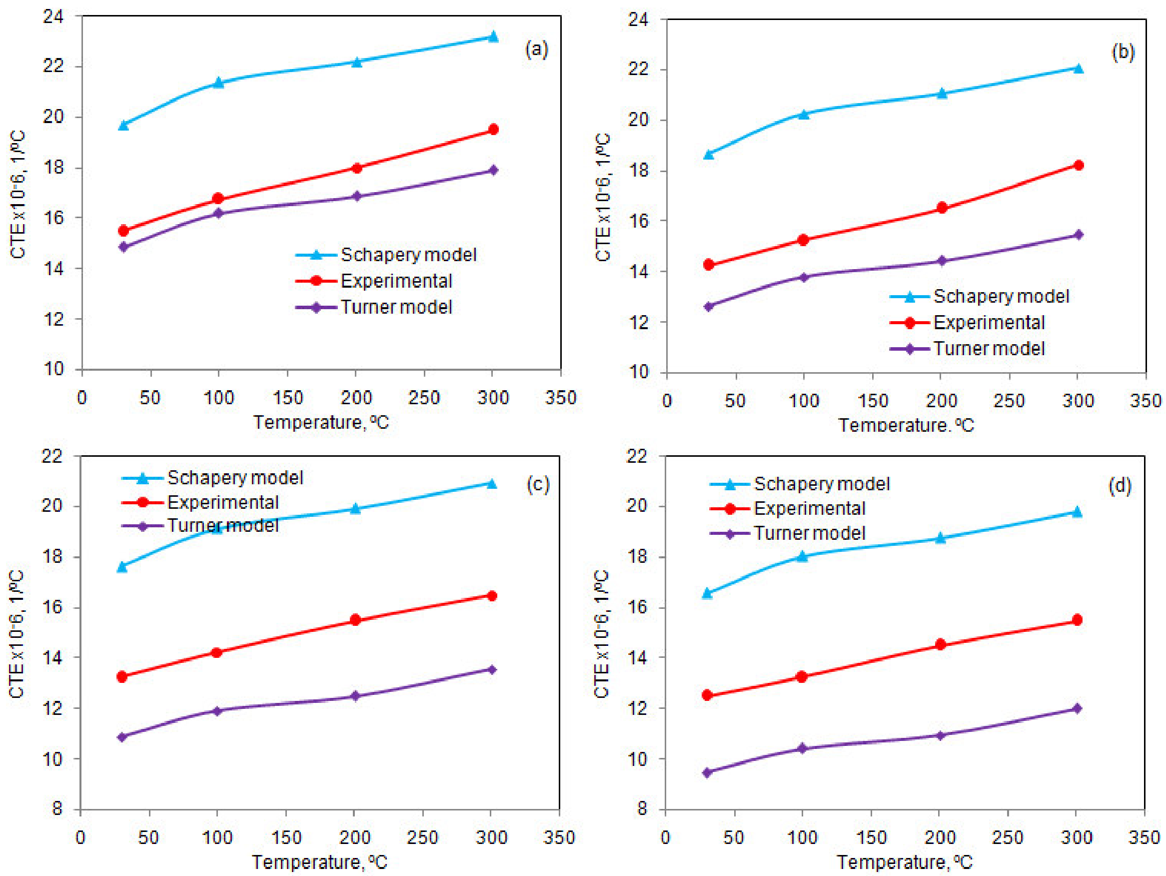

Figure 4: Coefficient of thermal expansion as a function of temperature compared with Schapery and Turner models for: (a) AL-SN-1, (b) AL-SN-2, (c) AL-SN-3 and (d) AL-SN-4.

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 Si_3N_4 nanoparticles. The bond energy is low for the composites having high volume fraction of Si_3N_4 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-SN-1 and AL-SN-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

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

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

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

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

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

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 are closer to the results obtained Turner model. 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 silicon nitride 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 by the Turner model.

REFERENCES

1. 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.
2. 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.
3. 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.
4. 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.
5. 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.
6. 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.

7. 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.
8. 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.
9. B. Kotiveera Chari, A. Chennakesava Reddy, Finite Element Modeling and Experimental Validation of Interphase Debonding and Particle Fracture in Titanium Carbide/AA1100 Alloy, 3rd National Conference on Materials and Manufacturing Processes, Hyderabad, India, 22-25 February 2002, pp. 156-161.
10. B. Kotiveera Chari, A. Chennakesava Reddy, Interphase Cracking in Titanium Nitride/2024 Alloy Particle-Reinforced Metal-Matrix Composites, 3rd National Conference on Materials and Manufacturing Processes, Hyderabad, India, 22-25 February 2002, pp. 162-167.
11. V. V. Satyanarayana, A. Chennakesava Reddy, Computation of Interphase Separation and Particle Fracture of Titanium Oxide/3003 Particle Reinforced Composites: The Role of Thermo-Mechanical Loading, 3rd National Conference on Materials and Manufacturing Processes, Hyderabad, India, 22-25 February 2002, pp. 168-173.
12. V. V. Satyanarayana, A. Chennakesava Reddy, Micromechanical Modeling of Reinforcement Fracture in Zirconium Carbide/4015 Particle-Reinforced Metal-Matrix Composites , 3rd National Conference on Materials and Manufacturing Processes, Hyderabad, India, 22-25 February 2002, pp. 174-178.
13. 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.
14. 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.
15. Ch. Rajanna, A. Chennakesava Reddy, Effects of Interphase and Interface Characteristics on the Tensile Behavior of Boron Nitride/7020 Particle Reinforced Composites Subjected to Thermo-Mechanical Loading, 3rd National Conference on Materials and Manufacturing Processes, Hyderabad, India, 22-25 February 2002, pp. 188-191.
16. Ch. Rajanna, A. Chennakesava Reddy, Modeling of Interphases in SiO2/AA8090 alloy Particle -Reinforced Composites under Thermo-Mechanical Loading Using Finite Element Method, 3rd National Conference on Materials and Manufacturing Processes, Hyderabad, India, 22-25 February 2002, pp. 192-195.
17. 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.
18. A. Chennakesava Reddy, Wear Resistant Titanium Boride Metal Matrix Composites, 3rd National Conference on Materials and Manufacturing Processes, Hyderabad, 22-25 February 2002, pp. 201-205.
19. 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.
20. A. Chennakesava Reddy, Evaluation of Thermal Expansion of Al/B_4C Metal Matrix Composites, 3rd National Conference on Materials and Manufacturing Processes, Hyderabad, 22-25 February 2002, pp. 196-200.
21. E.H. Kerner, Proceedings of the Physical Society, 69, 1956, pp. 808-813.
22. R.A. Schapery, Journal of Composite Materials, 4, 1968, pp. 380-404.