Thermal Expansion of Al Matrix Composites Reinforced with TiN Nanoparticles

A. Chennakesava Reddy

Professor, Department of Mechanical Engineering, JNTUH College of Engineering, Hyderabad

Abstract: The thermal expansion behavior of aluminum matrix composites reinforced with TiN nanoparticles was measured between 30 and 400°C and compared to theoretical models. The thermal expansion was then measured with a dilatometer (DIL 802) between 100 and 400°C at heating and cooling rates of 5°C/min in argon. 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 concentration, their coefficient of thermal expansion (CTE) is determined by a stress relaxation process. While for the composites with higher nanoparticle concentration, their CTE is determined by a percolation process.

Keywords: Metal matrix composites, coefficient of thermal expansion, titanium nitride.

1. Introduction

The development of aluminum based metal matrix composites is attracting a lot of interest from materials engineers in developing countries. Important properties of these composites such as high strength and modulus complemented with the excellent high temperature resistance represent these materials as appropriate candidates for automotive and aerospace applications. Reinforcement by particles has proved to be particularly beneficial since it offers composite materials having almost isotropic properties at low cost [1]. A number of other reinforcing materials such as such as Al_2O_3 [2], SiC [3], SiO_2 [4], Si_3N_4 [5], B_4C [6], TiC [7], TiN [8], ZrC [9], MgO [10], and BN [11] have been incorporated in Al using molten metal method.

One of the important aspects of metal matrix composites is the effect of thermal residual stresses on the properties of the materials. When metal matrix composites are fabricated at a certain high temperature and cooled to the room temperature, residual thermal stresses are induced into the matrix and reinforcement because of the significant difference between the coefficient of thermal expansion (CTE) of the two constituents [12]. The interaction of the matrix with the surface of the reinforcement inclusion during curing, restricts the free segmental and molecular mobility of the matrix and thus creates a constrained layer with different mechanical and physical properties of the composite. The thermal expansion coefficient of a particle reinforced composite material for aluminum-titanium nitride presented in this paper.

2. Materials and Methods

Pure Al powder of 100 μm with 99.9% purity and titanium nitride (TiN) powders of 100 nm were used as the starting materials. Pure powders of Al and ZrO_2, 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 (figure 3) 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	TiN
AL-TN-1	95	5.0
AL-TN-2	90	10.0
AL-TN-3	85	15.0
AL-TN-4	80	20.0
AL-TN-5	75	25.0

The thermal expansion was then measured with a dilatometer (DIL 802) between 100 and 400°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. Specimens with a diameter of 5 mm and length of 10 mm were used to measure CTE. 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. All of the specimens were tested from 30°C to 400°C for heating cycle and 400°C to 30°C during cooling cycle at 10°C/min. This temperature range was selected so as to include the entire usable range of the Al/TiN metal matrix composites, without the formation of liquid phase in the matrix.

3. Results and Discussion

The relative thermal expansion behavior of Al/TiN metal matrix composites measured at temperatures varying from 30 °C to 400 °C are shown in figure 1. The CTE curve for the heating cycle shows linear increase with increase in temperature, while for the cooling cycle it shows a nonlinear decrease with decrease in temperature. These heating and cooling curves exhibit some hysteresis residual strain, which increases with increase in volume % of the TiN reinforcement. The CTE of the composites decreases with increase in volume fraction of reinforcement.

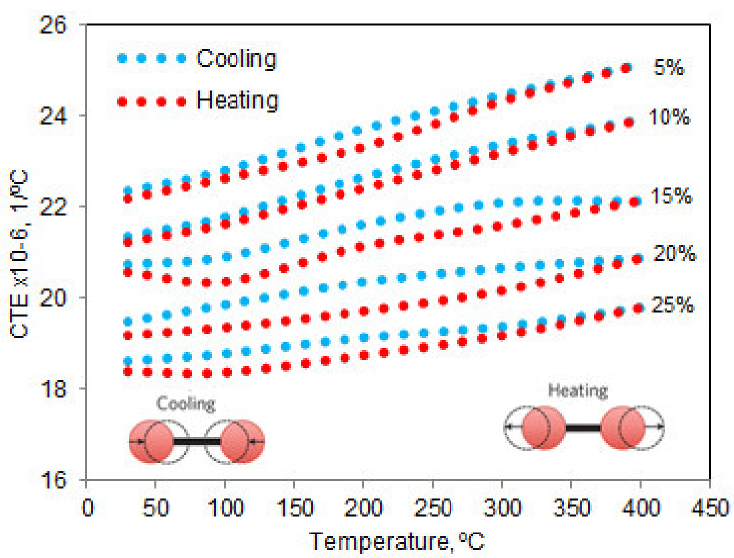

Figure 1: Coefficient of thermal expansion as a function of temperature.

When the composites are cooled down from high temperatures, the thermal mismatch between the matrix and the reinforcement will 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.

Further analysis of the thermal expansion behavior of the composites was done by comparing the experimental results with theoretical models. Many analytical and semi-empirical formulas have been derived to evaluate the effective coefficient of the linear thermal expansion of different types of heterogeneous composites [13-15]. The rule-of-mixture models are derived from the assumption of uniform strain or stress of the composite structure.

$$\alpha_c = \alpha_r V_r + \alpha_m V_m \quad (2)$$

Turner model [13] takes into account the mechanical interaction between the phases in the heterogeneous composite material.

$$\alpha_c = \frac{\alpha_m V_m K_m + \alpha_r V_r K_r}{V_m K_m + V_r K_r} \quad (3)$$

Another model for particulate composites is given by Kerner [14], which accounts for both shear and isostatic stresses developed in the component phases, and gives the CTE for the composite as:

$$\alpha_c = \alpha_m V_m + \alpha_r V_r + V_m V_r (\alpha_r - \alpha_m) \frac{K_r - K_m}{V_m K_m + V_r K_r + 3K_m K_r / 4G_m} \quad (4)$$

Schapery [15] used elastic energy principles to derive bounds for effective CTEs of anisotropic composites made from isotropic constituents. The lower and upper bounds for the effective coefficients are given by

$$\alpha_c^u = \alpha_m V_m + \alpha_r V_r + \frac{4G_m}{K_c} \frac{(K_c - K_r)(\alpha_m - \alpha_r) V_r}{4G_m + 3K_r} \quad (5)$$

$$\alpha_c^l = \alpha_m V_m + \alpha_r V_r + \frac{4G_r}{K_c} \frac{(K_c - K_m)(\alpha_r - \alpha_m) V_m}{4G_m + 3K_m} \quad (6)$$

where a is the CTE, v is the volume fraction, K is the bulk modulus, G is the shear modulus, and subscripts c, m, r refer to the composite, matrix and particle respectively.

Figure 2 compare the experimental results with the theoretical models for all five metal matrix composites. In all the cases, the upper bound of composite CTE is Kerner's model and the lower bound of composite CTE is Turner's model. This is owing to Turner's model is based on the fact that only uniform hydrostatic stresses exist in the phases, while the stresses inside the composite are very complex. Kerner's model, which assumes spherical particles, may underestimate the actual constraints in the composite. Shapery derived the effective coefficient of thermal expansion of isotropic composites employing extreme principles of thermo-elasticity. Schapery's upper bound represents that the reinforcing phase is isolated, while Schapery lower bound and Turner model represent the percolation situation. The CTE could be even lower than Schapery's lower bound at high temperatures. The measured CTE shows gentler rise than that of theoretical CTE, from 30°C to 400°C. This could be explained by taking into account the porosity present and the debonding between the matrix and the reinforcement in these samples. The presence of voids provides the space for the expanding metal matrix and lowers the effective thermal strain.

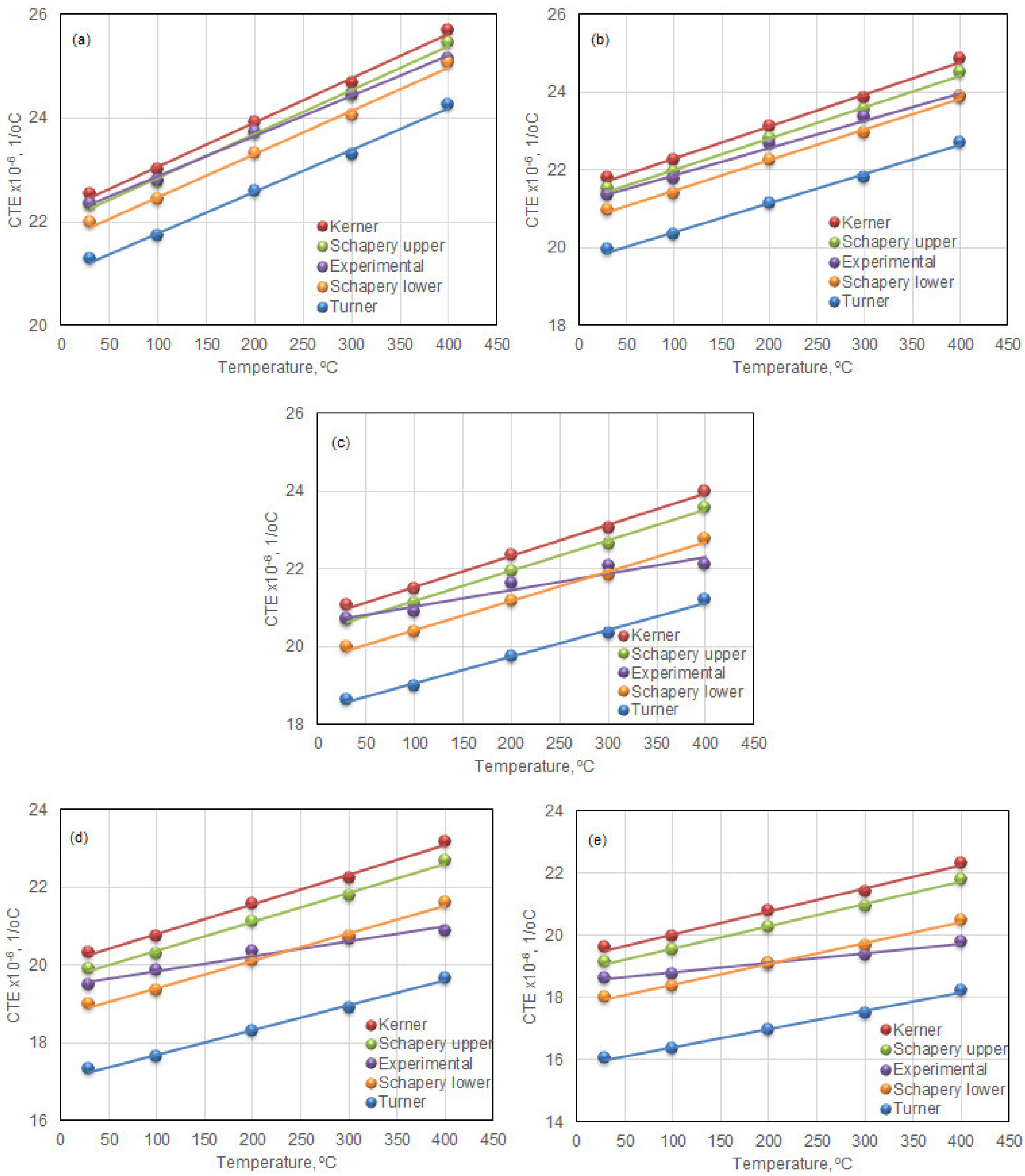

Figure 2: Coefficient of thermal expansion as a function of temperature: (a) Al/5%TiN, (b) Al/10%TiN, (c) Al/15%TiN, (d) Al/20%TiN and (e) Al/25%TiN.

4. Conclusions

In this research, the thermal expansion behavior of Al-based composites reinforced with TiN 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 concentration have the CTE closer to the theoretical value. The CTE of the composites consisting of low volume fraction of TiN is controlled by the relaxation of residual stresses. On the other hand, the CTE of the composites containing a high volume fraction of nanoparticles is controlled by a percolation effect.

References

[1] A. C. Reddy, Evaluation of mechanical behavior of Al-alloy/SiC metal matrix composites with respect to their constituents using Taguchi techniques, i-manager's Journal of Mechanical Engineering, 1(2), 31-41, 2011.

[2] A. C. Reddy, Evaluation of mechanical behavior of Al-alloy/Al_2O_3 metal matrix composites with respect to their constituents using Taguchi, International Journal of Emerging Technologies and Applications in Engineering Technology and Sciences, 4(2), 26-30, 2011.

[3] A. C. Reddy, Tensile fracture behavior of 7072/SiCp metal matrix composites fabricated by gravity die casting process, Materials Technology: Advanced Performance Materials, 26(5), 257-262, 2011.

[4] A. C. Reddy, Combined Loading and Micromechanical Analysis of AA5050 Alloy-Silicon Oxide Particle-Reinforced Metal Matrix Composites, 5th International Conference on Modern Materials and Manufacturing, Bangalore, 6-7 December 2013, 373-378.

[5] M. Mastanaih, A. C. Reddy, Exploitation of Reinforcement in Revision of Wear Behavior of AA1100/Si3N4 Metal Matrix Composites, 5th International Conference on Modern Materials and Manufacturing, Bangalore, 6-7 December 2013, 379-383.

[6] V. K. Reddy, A. C. Reddy, Wear performance of AA4015/Boron Carbide Metal Matrix Composites, 5th International Conference on Modern Materials and Manufacturing, Bangalore, 6-7 December 2013, 384-388.

[7] M. Mastanaih, A. C. Reddy, Influence of Reinforcing Particle Size on Tribological Properties of AA6061-Titanium Carbide Microcomposites, 5th International Conference on Modern Materials and Manufacturing, Bangalore, 6-7 December 2013, 389-393.

[8] V. K. Reddy, A. C. Reddy, Role of Reinforcing Particle Size in the Wear Behavior of AA6061-Titanium Nitride Composites, 5th International Conference on Modern Materials and Manufacturing, Bangalore, 6-7 December 2013, 394-398.

[9] V. B. Reddy, A. C. Reddy, Sliding Wear by Hard and Micro-Particles of AA2024-Zirconium Carbide Metal Matrix Composites, 5th International Conference on Modern Materials and Manufacturing, Bangalore, 6-7 December 2013, 399-403.

[10] T. K. K. Reddy, A. C. Reddy, Wear Performance of Magnesia as Reinforcement of AA2024 Metal Matrix Composites, 5th International Conference on Modern Materials and Manufacturing, Bangalore, 6-7 December 2013, 404-408.

[11] A. C. Reddy, Study of Factors Influencing Sliding Wear Behavior of Hexagonal Boron Nitride Reinforced AA6061 Metal Matrix Composites, 5th International Conference on Modern Materials and Manufacturing, Bangalore, 6-7 December 2013, 409-413.

[12] A. C. Reddy, Effect of Phase Transformation from h-BN to c-BN on Nanoparticle Fracture Tendency in AA8090/h-BN Particle-Reinforced Metal Matrix Composites, 5th International Conference on Modern Materials and Manufacturing, Bangalore, 6-7 December 2013, 365-372.

[13] P.S. Turner, Thermal Expansion Stresses in Reinforced Plastics, Journal of Research of the National Bureau of Standards, 37, 239-250, 1946.

[14] E.H. Kerner, The elastic and thermo-elastic properties of composite media, Proceedings of the Physical Society, 69, 808–813, 1956.

[15] R. A. Schapery, Thermal expansion coefficients of composite materials based on energy Principles, Journal of Composite Materials, 2, 380-404, 1968.