Effect of TiC Nanoparticles on the Coefficient of Thermal Expansion Behavior of the Aluminum Metal Matrix Composites

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Abstract: The thermal expansion behavior of aluminum matrix composites reinforced with TiC 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. The hysteresis between the heating and cooling cycles was negligible in Al/TiC composites.

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

1. INTRODUCTION

Aluminum metal matrix composites reinforced with discontinuous phases in the forms of whiskers, fibers, and particulates exhibit magnify strength values at higher temperatures, low coefficient of friction and thermal expansion, good wear resistance and stiffness compared to base alloys [1-10]. The reinforcing material consists of discontinuous phase embedded in a continuous phase, whereas the matrix material consists of only continuous phase. The discontinuous phase much harder and stronger than continuous phase [11-23]. Several ceramic reinforcements have been identified for Aluminum (Al)-based metal matrix composites, but recently titanium carbide (TiC) has gained attention over others due to its high hardness, stiffness and wear resistance [24].

Aluminum metal matrix composites find a number of applications such as automobile brake systems, cryostats, microprocessor lids, space structures, rocket turbine housing and fan exit guide vanes in gas turbine engines. These applications require operation at varying temperature conditions ranging from high to cryogenic temperatures. Coefficient of thermal expansion (CTE) mismatch between the reinforcement phase and the aluminum matrix results in the generation of residual thermal stress by virtue of fabrication [25-29]. These thermal stresses increases with increasing volume fraction of the reinforcement and decreases with increase in interparticle spacing. Thermal cycling enhances plasticity at the interface resulting in deformation at stresses much lower than their yield stress. Low and stable coefficient of thermal expansion can be achieved by increasing the volume fraction of the reinforcement.

The present investigation was undertaken to study CTE behavior of aluminum metal matrix composites reinforced with TiC. The thermal expansion was determined using dilatometer (DIL 802) between 100 and 300°C subjected to heating and cooling cycles. The effect of volume fraction of TiC nanoparticles was also examined.

Table 1: Composition of metal matrix composites

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

2. MATERIALS METHODS

Pure Al powder of 100 µm with 99.9% purity and TiC nanoparticles of 100 nm were used as the starting materials. Pure powders of Al and TiC, 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). 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.

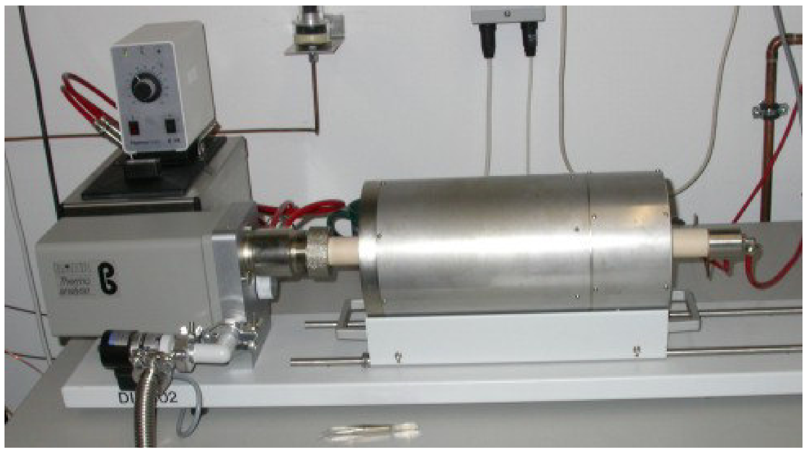

Figure 1: The differential dilatometer.

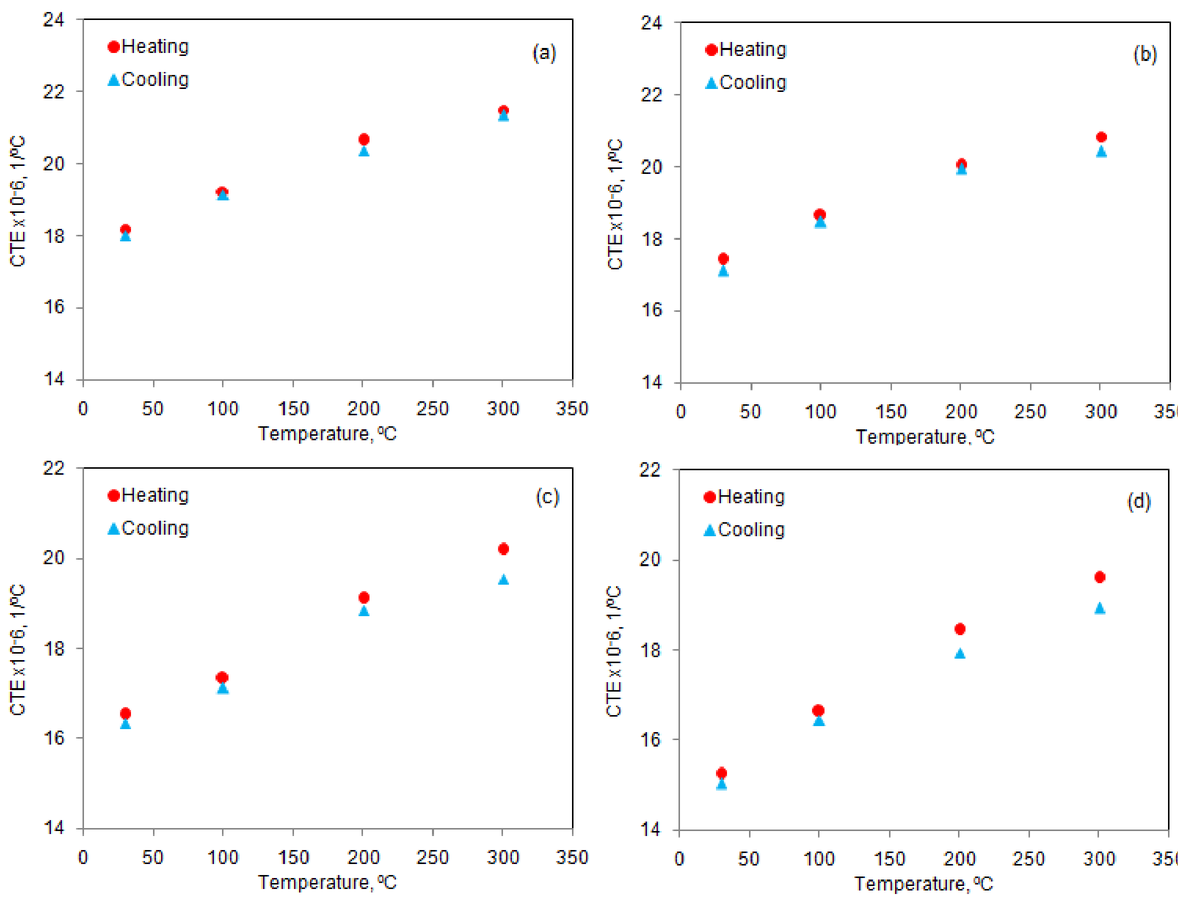

Figure 2: Coefficient of thermal expansion as a function of temperature for: (a) AL-TIC-1, (b) AL-TIC-2, (c) AL-TIC-3 and (d) AL-TIC-4.

3. RESULTS AND DISCUSSION

The CTE obtained from the heating and cooling as a function of temperature is plotted in figure 2 for all the composites. 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. The crystalline structure of TiC is face-centered cubic (FCC). The hysteresis between the heating and cooling cycles is negligible owing to the stable crystalline structure of TiC. 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 TiC nanoparticles. This is due CTE mismatch between Al and TiC.

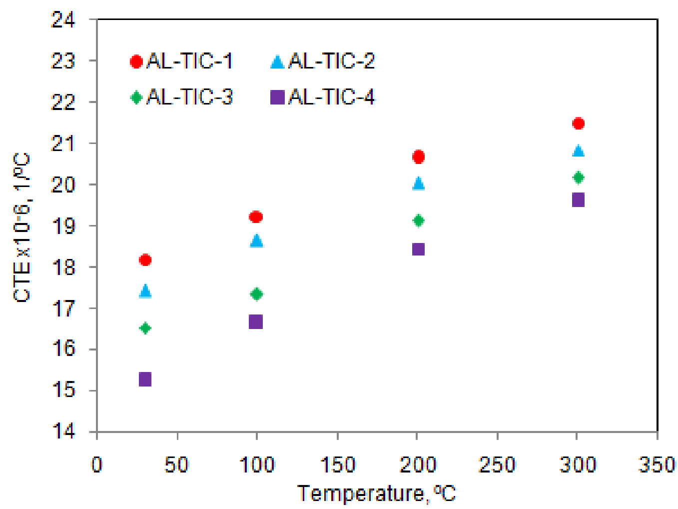

Figure 3: Compare the CTE of different composites.

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 [26-29]. By assuming that only uniform hydrostatic stresses exist in the phases, Turner [21-22] 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 [26-29] 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. The experimental CTE results are in between the results obtained Schapery and Turner models. When the composites are cooled down from high temperatures, the thermal mismatch between the matrix and the reinforcement can result in residual stresses. The titanium carbide nanoparticles are in hydrostatic state and their surrounding matrix phase suffers a compressive radial stress. On the other hand, in case of higher weight % of reinforcement, the average inter-particle spacing is significantly influenced. However, the Al matrix alloy phase with a higher CTE should undergo shrinking on cooling, resulting in a tensile residual stress development. During heating and cooling cycles, the matrix alloy covers the particulate and shrinks.

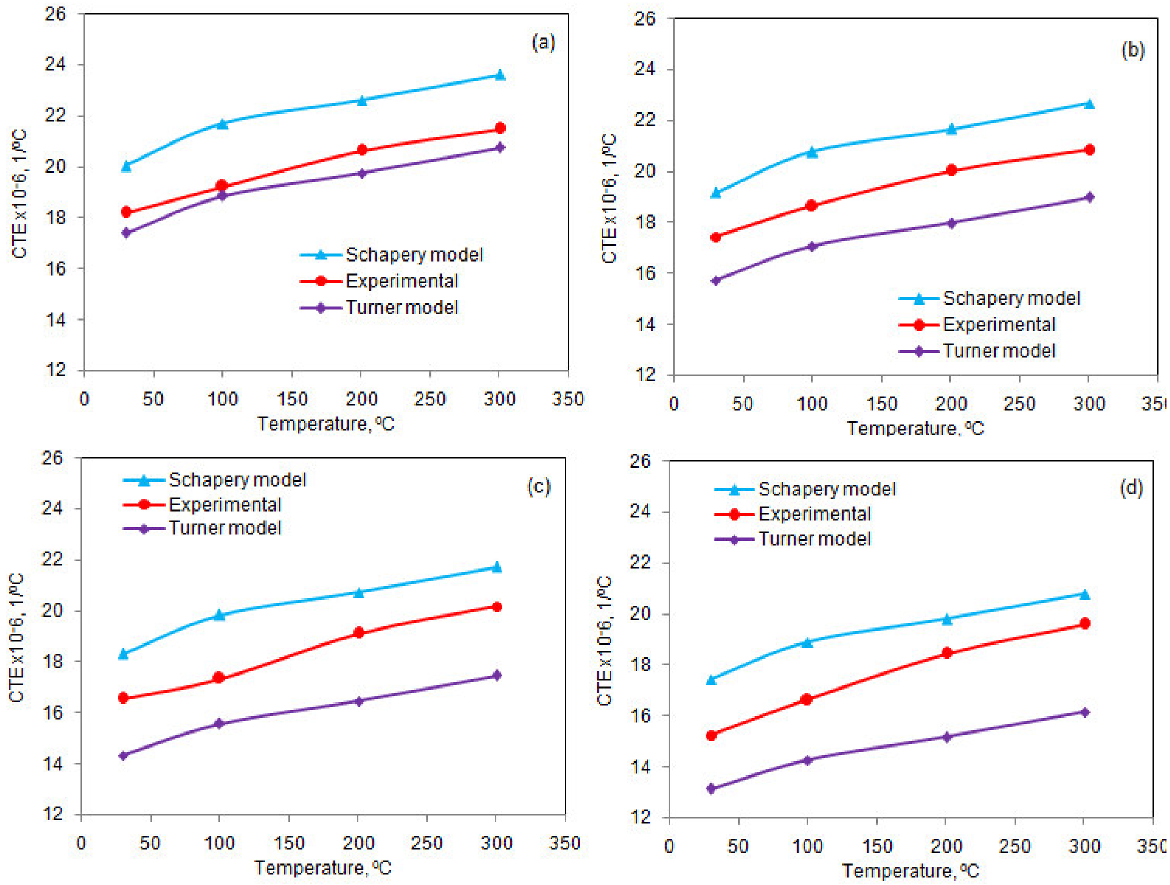

Figure 5: Coefficient of thermal expansion as a function of temperature compared with Schapery and Turner models for: (a) AL-TIC-1, (b) AL-TIC-2, (c) AL-TIC-3 and (d) AL-TIC-4.

4. CONCLUSION

In this research, the thermal expansion behavior of Al-based composites reinforced with TiC 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 hysteresis in CTE between heating and cooling cycles is negligible in Al/TiC composites.

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