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Thermal Expansion Behavior of Aluminum Matrix Composites Reinforced with Fused Quartz Nanoparticles

A. Chennakesava Reddy

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

Abstract: The thermal expansion behavior of aluminum matrix composites reinforced with fused quartz 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 a random network of aggregated clusters based on cristobalite, trydimite, and quartz with dimensions of a few nanometers.

Keywords: Metal matrix composites, thermal expansion, fused quartz.

1. INTRODUCTION

Metal matrix composites reinforced by nano-particles are very promising materials, suitable for a large number of applications. These composites consist of a metal matrix filled with nano-particles featuring physical and mechanical properties very different from those of the matrix [1-8]. The nano-particles can improve the base material in terms of wear resistance, damping properties and mechanical strength. In the literature, different kinds of matrix metals have been coupled with several types of nanometric phases. Ceramic compounds (SiC, Al_2O_3, etc.), intermetallic materials and carbon allotropes were used to reinforce Al, Mg, Cu and other metals and alloys [9-17].

Since vitreous silica is a low-thermal-expansion material, its shape and size remain constant with changing temperature, unlike most glasses and inorganic materials. Recent study on the thermal expansion of vitreous silica has been restricted to synthetic fused silica [18]. A comparison between fused quartz produced by melting natural quartz powder and synthetic fused silica will provide useful information on the glass structure because there should be a structural difference between these two types of vitreous silica; the former has optically observable grain structure, but the latter does not have such a structure [19]. To avoid thermal instability a low coefficient of thermal expansion (CTE) over a wide temperature range, since internal stresses that occur during solidification and cool-down depend strongly on CTE [20-22].

It is the aim of the present work to develop such materials which can potentially reduce residual stresses in metal matrix composites significantly while maintaining or even improving all other properties (strength, toughness, corrosion and wear resistance). The thermal expansion was determined of the aluminum metal matrix composites reinforced with nanoscale silicon oxide (SiO_2) nanoparticles. The effect of volume fraction of SiO_2 nanoparticles was also examined.

Table 1: Composition of metal matrix composites

Composite	Composition, vol.%	
	Al	SiO_2
AL-SO-1	90	10
AL-SO-2	85	15
AL-SO-3	80	20
AL-SO-4	75	25

2. MATERIALS METHODS

Pure Al powder of 100 μm with 99.9% purity and SiO_2 nanoparticles of 100 nm were used as the starting materials. Pure powders of Al and SiO_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 by hot pressing at 800 ^{o}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^{o}C at heating and cooling rates of 5^{o}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.

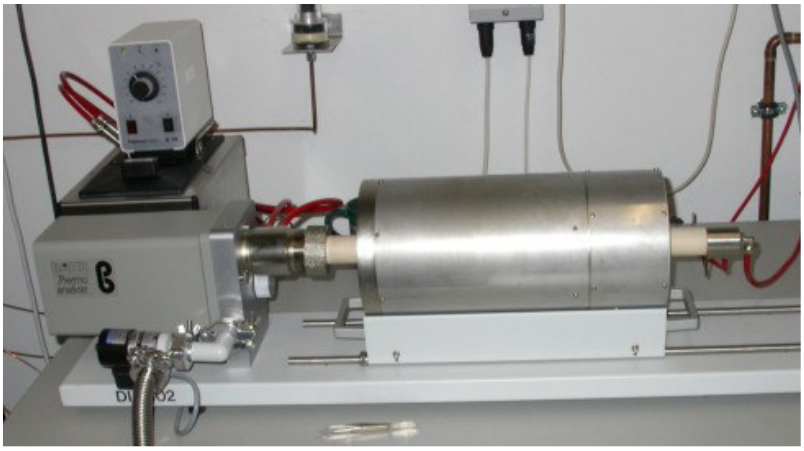

Figure 1: The differential dilatometer.

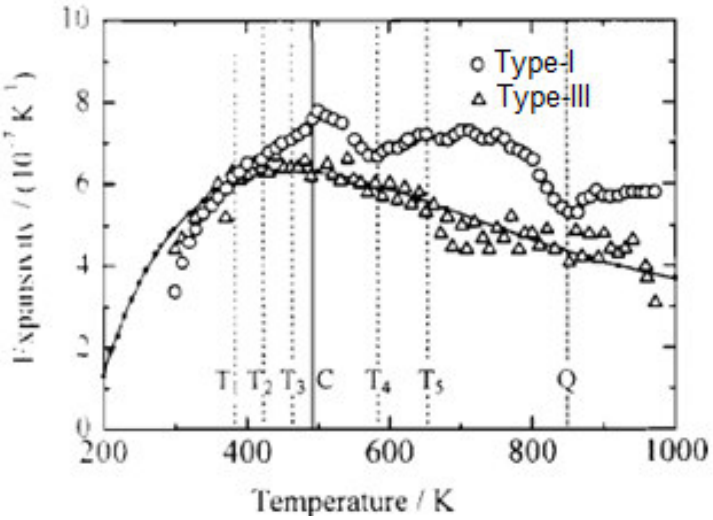

Figure 2: Linear thermal expansion curve of two types of silica, type-I and type-III. The phase transition points of silica crystals: solid line (C), cristobalite: dashed line (Q), quartz: and dotted line (T_1, T_2, T_3, T_4 and T_5): tridimites.

3. RESULTS AND DISCUSSION

Type-I is fused quartz produced by electrical melting of natural quartz powder. Type –III is synthetic fused silica produced by hydrogen-oxygen flame hydrolysis of $SiCl_4$. Type-I silica shows a sharp peak at 500 K, and minima at 580 and 850 K (figure 2). In the temperature range of 650-750 K, several small peaks and valleys also appeared. For

type-I silica, the scatter of the data seems to be smaller than that for type-III silica. In the present work, type-I fused quartz was used. Type-I fused quartz exhibits a different temperature dependence than does type-III fused silica. The crystalline forms of silica which are stable at room temperature are quartz, cristobalite, tridimite. Crystalline quartz exhibits α to β phase transition at 846 K. This temperature corresponds to a minimum in the expansion curve of type-I silica (indicated by the dashed line Q). Cristobalite exhibits a low-to high-temperature phase transition at 493 K. This temperature corresponds to the maximum of the dilatation curve of type-I silica (solid line C). The phase transition of tridymite is more complicated. The transition points in tridymite are at 383 K (T_1), at 423 K (T_2), at 464 K (T_3), 583 K (T_4) and 653 K (T_5).

The CTE obtained from the heating and cooling as a function of temperature is plotted in figure 1 for all the composites. The CTE measured during the heating cycle increases with increasing temperature between 30 and 300^{o}C as shown in figure 3. However, the CTE measured during the cooling cycle decreases continuously with decreasing temperature (figure 3). At high temperatures, there is significant difference between CTE during the heating and the cooling cycles. This deviation for the CTE of the composites containing lower concentration nanoparticles (AL-SN-1 and AL-SN-2) is smaller than that of composites containing higher concentration nanoparticles (AL-SN-3 and AL-SN-4). The hysteresis between the heating and cooling cycles is owing to the dilatation curve of type-I silica which has several peaks and valleys corresponding to the phase transition temperatures of crystalline silica i.e., quartz (853 K), cristobalite (493 K), and tridymite (580 K).

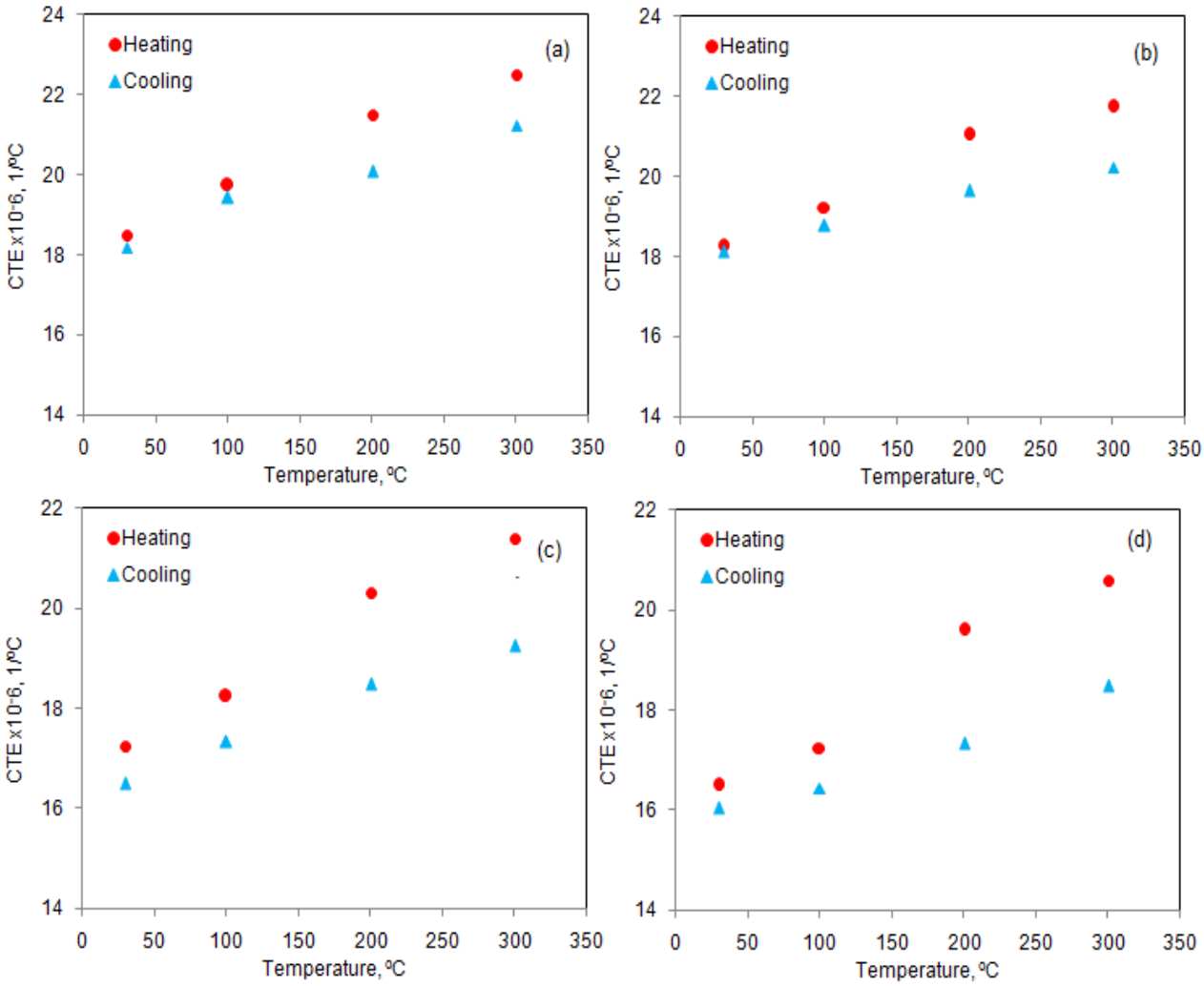

Figure 3: Coefficient of thermal expansion as a function of temperature for: (a) AL-SO-1, (b) AL-SO-2, (c) AL-SO-3 and (d) AL-SO-4.

Figure 4 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 SiO_2 nanoparticles below 150°C. The bond energy is low for the composites having high volume fraction of SiO_2 nanoparticles.

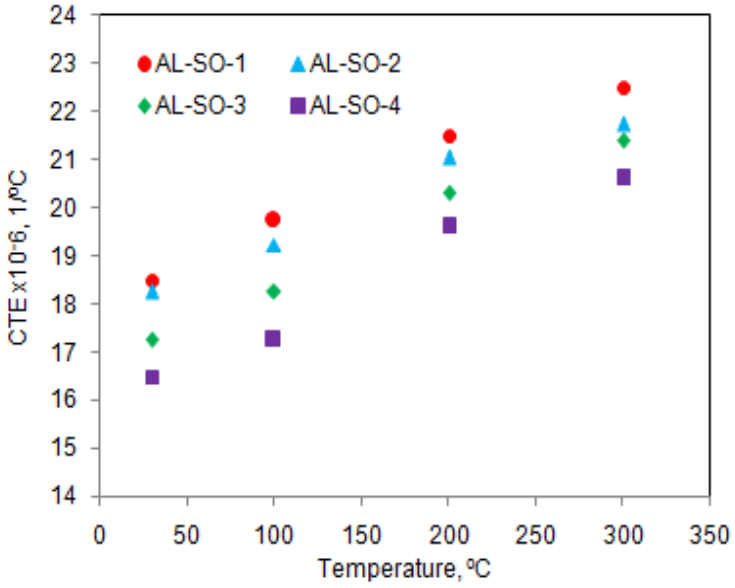

Figure 3: Compare the CTE of different composites.

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 [21-22]. 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

$$\alpha_c = \frac{\alpha_m V_m K_m + \alpha_r V_r K_r}{V_m K_m + V_r K_r} \tag{2}$$

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 [21-22] is expressed as

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

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

$$K_c = \frac{\frac{V_r K_r}{4G_m + 3K_r} + \frac{V_m K_m}{4G_m + 3K_r}}{\frac{V_r}{4G_m + 3K_r} + \frac{V_m}{4G_m + 3K_r}} \tag{4}$$

Figure 5 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. Above 150°C the experimental CTE values are higher than those values computed from the Turner model. This is on account of a random network of aggregated but strained clusters based on cristobalite, trydimite, and quartz with dimensions of a few nanometers. These nanoscale crystalline regions are connected by disordered regions. These structures exhibit short-range order which is difficult to detect by diffraction methods.

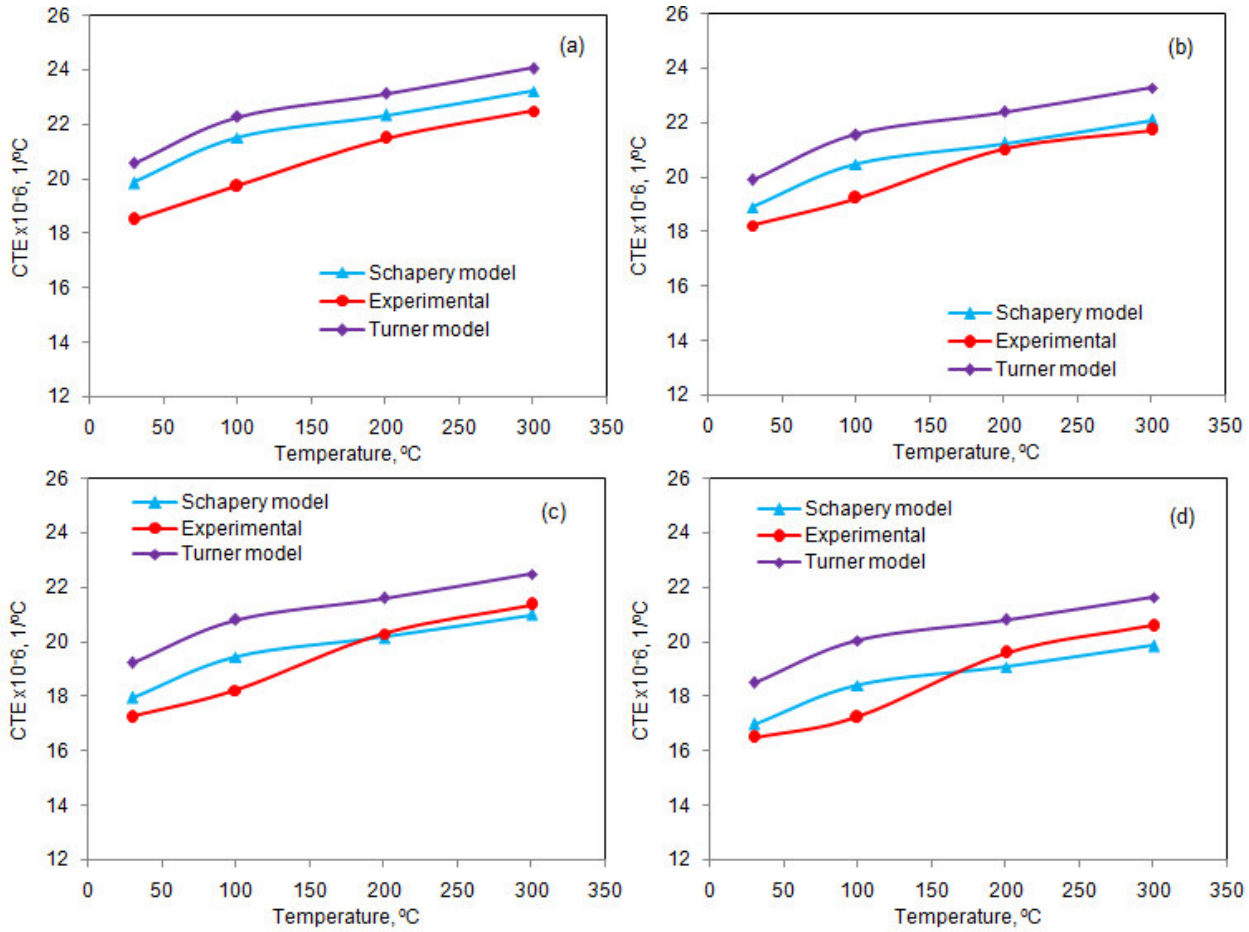

Figure 5: Coefficient of thermal expansion as a function of temperature compared with Schapery and Turner models for: (a) AL-SO-1, (b) AL-SO-2, (c) AL-SO-3 and (d) AL-SO-4.

4. CONCLUSION

In this research, the thermal expansion behavior of Al-based composites reinforced with fused quartz 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.

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