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Effects of particle size on the thermal expansion behavior of SiCp/Al composites

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Abstract The coefficients of thermal expansion (CTEs) of 20 vol% SiCp/Al composites fabricated by powder metallurgy process were measured and examined from room temperature to 450 °C. The SiC particles are in three nominal sizes 5, 20 and 56μm. The CTEs of the SiCp/Al composites were shown to be apparently dependent on the particle size. That the larger particle size, the higher CTEs of the composites, is thought to be due to the difference in original thermal residual stresses and matrix plasticity during thermal loading. At low temperature, the experimental CTEs show substantial deviation from the prediction of the elastic analysis derived by Kerner and rule of mixture (ROM), while the Kerner's model agrees relatively well at high temperatures for the composite with the larger particle size.

Introduction

Silicon carbide particle reinforced aluminum (SiCp/Al) composites exhibit high specific strength and specific modulus. In addition, they have excellent thermo-physical properties such as low coefficients of thermal expansion and high thermal conductivity. In recent years, some theoretical models such as Turner's [1], Kerner's [2] and Eshelby [3] models were employed to discuss the thermal expansion behavior of the composites. However, the predicted results are partly matched to the experimental results for metal matrix composites (MMCs). These discrepancies can be partly attributed to the fact that none of the models in [1, 2] takes into account the effects of thermal residual stresses and plasticity in the matrix which inevitably occurs in the matrix during temperature change [4, 5].

It is generally known that considerable amount of thermal mismatch stresses would generate during cooling from fabrication temperature to room temperature due to the large difference in CTEs between the metal matrix and ceramic reinforcement. These stresses are usually subject to degradation by relaxation mechanisms such as local and global dislocation movements [6–8]. The thermal residual stresses exhibit as compressive stresses in the reinforcement and tensile stresses in the matrix, and the magnitude of these stresses vary with the characteristics of reinforcement, matrix metal and the thermal processing history. In the matrix, dislocations and residual stresses interact with each other, and the in-situ material properties of the matrix may differ appreciably from those of the corresponding bulk metal. The amount of residual stresses and dislocation density relates to the content, type, shape and sizes of the particles. They affect the properties of the composites, including the mechanical strength and thermal expansion behavior.

The effects of particle size on the CTEs of MMCs have been reported recently [9–12]. Xu et al. [9] observed that the CTEs of the TiC/Al XD^{TM} composites decrease with decreasing the particle size. They used a phenomenological approach to predict the CTEs of the composite. The predicted values agreed well with the experimental results. Elomari et al. [10] also observed that the CTEs of the SiCp/Al composites decrease with decreasing the particle size. It was suggested that the effect of the particle size on the CTEs is due to silicon oxides with a very low CTEs formed on the surface layers of SiC particles. However,

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Ma et al. [11] and Arpón et al. [12] reported no significant effects of particle size on the thermal expansion behavior of the composites. Until now, the mechanism of the effect of particle size on the CTEs of the SiCp/Al composites is not well understood. Therefore, it is of theoretical or experimental importance to make clear the effects of particle size on the CTEs of the SiCp/Al composites.

The purpose of this study is to investigate the effects of particle size on the CTEs of the 20 vol% SiCp/Al composites fabricated by a powder metallurgy technique. The CTEs measurement was performed from 25 °C to 450 °C by using a Netzsch DIL402C.

Experimental procedure

In this work, commercial pure aluminum powder (1100Al, Northeast Light Alloy Co. Ltd, China) with an average diameter of 10 μm was used as the matrix and polycrystalline α-SiC particles (QingZhou Hengtai Micro_powder Co. Ltd, China) with the average diameter of 5 μm, 20 μm and 56 μm were used as reinforcement. The average size and size distribution of SiCp were determined by the GSL-101BI laser particle size analyzer. The SiC particle size parameters are summarized in Table 1. The SiCp/Al composites containing 20% volume fraction of SiC particles were fabricated by a powder metallurgy technique. The process involved dry blending of the SiC particles with the Al powder in a mechanical mill for 12 h followed by hot pressing at 650 °C in a vacuum furnace. Then the hot pressed billets were extruded at 420 °C with the extrusion ratio of 16:1. The composites produced in this way using SiCp of varying size were designated as MMC5, MMC20 and MMC56, respectively. The pure aluminum specimen was fabricated in a similar manner.

Microstructure examination was carried out by means of optical microscopy (Olympus PMG-3). Representative microstructure of the MMC56 is shown in Fig. 1. It exhibits a uniform distribution of particles.

Specimens for CTEs testing with the dimension of Φ6 mm × 20 mm were machined from the extruded composites rods. The CTEs measurements were performed from 25 °C to 450 °C at a heating rate of 5 °C/min using a Netzsch DIL402C dilatometer.

Table 1 Particle size parameters

Composites	Average particle size (μm)	Standard deviation
MMC5	5.21	0.21
MMC20	20.99	0.23
MMC56	55.64	0.18

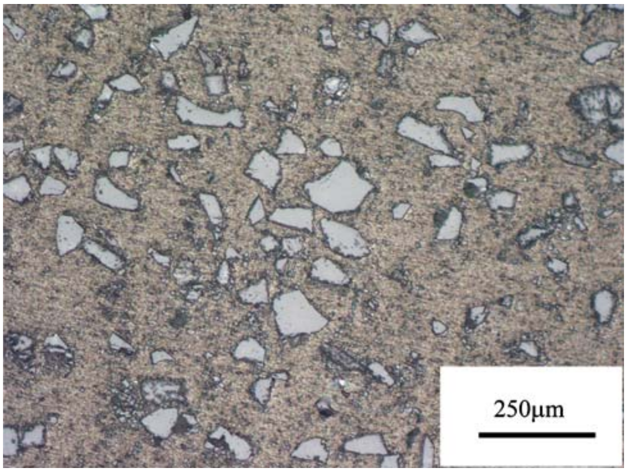

Fig. 1 Optical microstructure of specimen MMC56

Results and discussion

Figure 2 shows the values of the CTEs as a function of temperature for SiCp/Al Composites with different particle size. It is evident that the CTEs of the composites increase with increasing particle size. The CTEs of the composites with the larger particles increase more rapidly with temperature than those with the smaller particle-sizes. It can also be seen that the variation of CTEs with the particle size is very marked for temperatures over 150 °C, whereas such variation is much smaller below 150 °C. The CTE values for Al and composites are low at temperature below about 100 °C may be due to instrumental errors. Due to temperature fluctuations in the system at low temperature it is not possible to obtain accurate CTE data for temperatures less than 100 °C [13].

The thermal loading history of the composites is shown in Fig. 3. Considerable amount of thermal mismatch

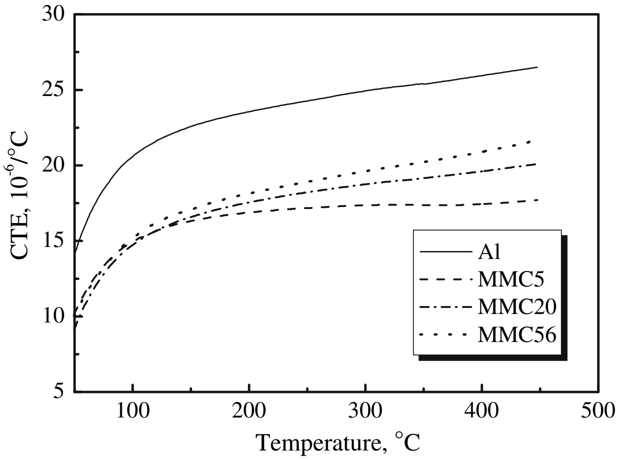

Fig. 2 CTEs versus temperature for the pure Al specimen and the SiCp/Al composites with various SiCp size

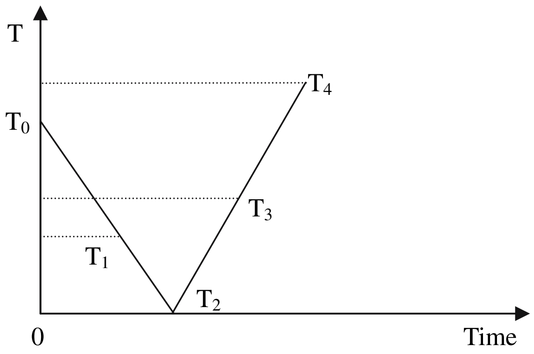

Fig. 3 Applied thermal load history

stresses would generate during cooling from the fabrication temperature (T_0) to room temperature (T_2) due to the large difference in CTEs between the Al matrix and SiC particle. During cooling, the ductile matrix will initially yield at a temperature T_1. During reheating from T_2, reversed plasticity will occur at a certain temperature (T_3). The evolution of plastic zones during thermal loading history is schematically illustrated in Fig. 4.

In the following sections 'Thermally induced plastic deformation' and 'Thermal residual stresses' are considered qualitatively the effects of the thermal plastic deformation and of residual stresses on the thermal expansion of the present composites of varying particle sizes. The measured values of CTE for the composites are tentatively compared to estimations following the classical ROM and Kerner's models in 'Kerner and ROM models'.

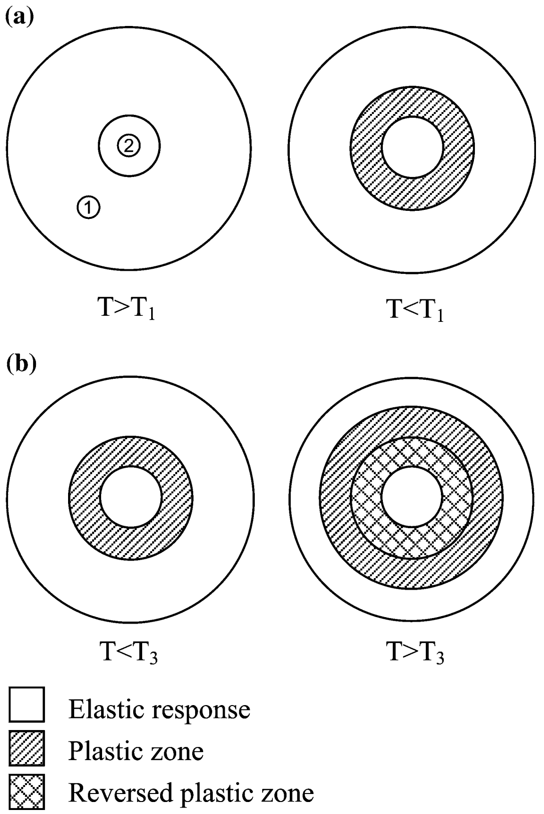

Fig. 4 The evolution of plastic zones during thermal loading history: ① matrix, ② particle

Thermally induced plastic deformation

Thermally induced plastic deformation has been extensively investigated [14–17]. Recently, Olsson [18] extended the earlier studies by Brooksbank and Andrews [19] who studied the evolution of residual stress evolving around spherical inclusions embedded in a hollow sphere of the elastic-ideally plastic matrix in response to temperature changes from an initially stress-free state. Analytical expressions of the macroscopic thermal straining of the composites ε_c are given by Olsson et al. [18]. For the purely elastic response, it follows that

$$\varepsilon_c = \left[\alpha_m + \frac{(\alpha_p - \alpha_m)\cdot f}{\left(1 - \frac{2M}{3}(1-f)\right)}\right]\cdot \Delta T \tag{1}$$

where f is the particle volume fraction, m is the elastic mismatch parameters, α is the coefficients of thermal expansion, ΔT is the temperature change. The subscripts c, p and n stand for the composite, particle and matrix, respectively. Here M is given by

$$n = \frac{E_m}{(1-\nu_m)}\left[\frac{(1-2\nu_m)}{E_m} - \frac{(1-2\nu_p)}{E_p}\right] \tag{2}$$

where E is the Young's modulus, ν is the Poisson ratio.

For imposed temperature levels in the elastic–plastic range, the thermal strain is [18]:

$$\varepsilon_c = \alpha_m \Delta T + f\left(\frac{r_p}{a}\right)^3 \frac{\sigma_y(1-\nu_m)}{E_m}\Phi,\quad \Phi = \mathrm{Sign}\{(\alpha_p - \alpha_m)\Delta T\} \tag{3}$$

where a is the radius of the particle, r_p is the radius of the plastic zone, σ_y is the yield strength of the matrix material. The function Sign(x) is defined as $x/|x|$ for $x \neq 0$ and 0 for $x = 0$. The relationship (3) between the thermal strain and the change of temperature is in general non-linear. Therefore, the thermal expansion coefficient becomes a complicated function of temperature once plastic flow occurs in the matrix.

The change in macroscopic thermal expansion ε of the composite with the thermal load history can be explained by using Fig. 5. At the fabrication temperature (T_0), it is supposed that there is no thermal mismatch strain in the matrix. Upon cooling, considerable amount of thermal strain would generate due to the large difference in CTEs

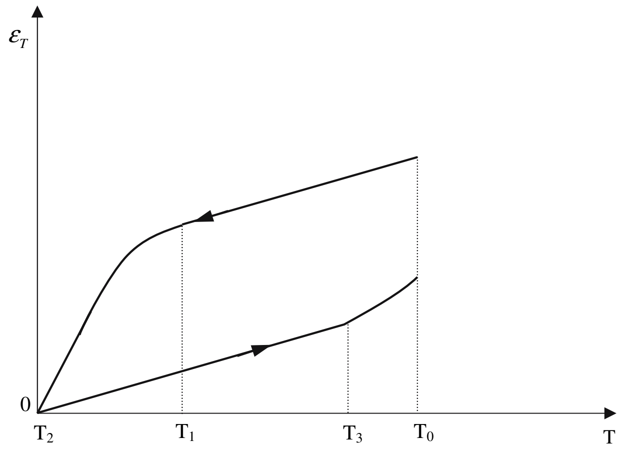

Fig. 5 Schematic illustration of the variation in composite thermal strain during thermal loading

between the metal matrix and ceramics reinforcement. The thermal strain ε follows the linear elastic solution of Eq. 1. As temperature decreases, non-linear deformation due to the onset of plastic flow in the matrix occurs at a temperature T_1 and the thermal strain can be calculated by Eq. 3.

During reheating for CTEs testing ($T_2 \rightarrow T_0$), at first, the thermal strain follows the linear elastic solution of Eq. 1, but at a temperature T_3, a reversed plastic zone starts to develop. It can be observed that there is a residual thermal strain at temperature T_0, which is caused by the no reversed plasticity developed during the thermal loading. It can also be seen from Fig. 5 that the plastic deformation causes the CTEs of the composites ($d\varepsilon/dT$) are larger than in the elastic case. It is consistent with the Finite Element Method results investigated by Shen [17].

Thermal residual stresses

The thermal residual stresses present in the MMCs in the as-made state, also affect the CTEs of the composites. The experimental [20, 21] results show that the thermal residual stress results in low CTEs of the composite. The residual stresses in both the matrix and reinforcing particles could affect the overall CTEs of the SiCp/Al composites. The tensile stress on the matrix could enlarge the distance of the Al atom [20]. During the subsequent heating process, the tensioned matrix expands at a lower rate than the unstrained zones due to the enlarged atom distance, leading to the much lower CTEs of composite. On the other hand, the compressive stresses on the reinforcement would enhance the restriction effect of SiC particles on the matrix and will probably lower the CTEs of the SiCp/Al composite.

When analyzing the thermal strain state of the composites, it should be born in mind that the in-situ material properties of the matrix may differ appreciably from those of the corresponding bulk metal due to cooling from elevated temperature can result in local yielding and work hardening [22]. From a microscopic point of view, plastic deformation in metallic materials reflects the collective behavior of a vast number of dislocations. When a material is deformed, dislocations are generated, moved, and stored, and the storage causes the material to work harden. Dislocations become stored for one of the two reasons: they accumulate by trapping each other in a random way, or they are required for compatible deformation of various parts of the material constrained within its surroundings [23]. The dislocations that are mutually trapped are referred to as statistically stored dislocations, ρ_S. The dislocations that are stored due to incompatibility in deformation are called geometrically necessary dislocation, ρ_G. It can be related to an effective strain gradient η as [24]:

$$\rho_G = 2\eta/b \tag{4}$$

where b is the Burgers vector. For aluminum: $b = 0.286$ nm.

In the case of MMCs, the incompatibility in deformation between the plastically deforming matrix and rigid particles leads to the creation of strong strain gradient in the metallic matrix. Thus, for a given plastic flow, the smaller particle size, which induces smaller particle interparticle distance, should lead to a greater strain gradient in the composites matrix, which, in turn, results in a greater ρ_G.

In Tayor-based nonlocal theory (TNT) of plasticity [23], the density of geometrically necessary dislocations ρ_G is treated as a nonlocal variable expressed in terms of an integral average of plastic strain. The flow stress of the matrix σ_m^* is given by:

$$\sigma_m^* = \sqrt{(\sigma_m)^2 + 27\sqrt{\frac{5}{2}}\beta^2\mu^2\frac{b}{a}f^{1/3}\varepsilon} \tag{5}$$

where σ_m is the flow stress of the pure Aluminum, β is an empirical constant, μ is the shear modulus of the matrix, and, 2a is the particle diameter. For aluminum: $\beta = 0.3$, $\mu = 26$ GPa.

From Eq. 5, it can be noted the flow stress of the matrix increases with decreasing the particle size. During cooling from fabrication temperature to ambient temperature, the relaxation of the thermal stresses will be harder for composites with small particle. The residual stresses increase with decreasing particle size. During reheating for CTEs testing, the higher flow stress of the matrix in the composite with the smaller particles will restrain the plastic deformation in the matrix.

Geometrically necessary dislocations and residual thermal stresses interact with each other easily and affect the properties of composites much more seriously, and thus the CTEs of composites should be lower. Smaller particle results in larger total geometrically necessary dislocations ρ_G and the thermal residual stresses. Therefore, the CTEs of the composites should decrease with decreasing particle size.

Kerner and ROM models

According to Kerner's model, the CTEs of MMCs is given as follows:

$$\alpha_c = \bar{\alpha} + f(1-f)(\alpha_p - \alpha_m)\frac{K_p - K_m}{(1-f)K_m + fK_p + (3K_pK_m/4G_m)} \tag{6}$$

where the rule of mixture (ROM) value is given by $\bar{\alpha} = (1-f)\alpha_m + f\alpha_p$, K and G are the bulk and shear modules. Because α_p is smaller than α_m, the posterior term contributes a negative value to this equation as a strain constrain term. Hence, the predicted α_c is small than that $\bar{\alpha}$.

The comparison among the theoretical calculations based on ROM and Kerner's model, and experimental results of the composites CTEs is shown in Fig. 6. The data used in the calculations are extracted from previous experimental works [25]. A summary of the elastic constants and CTEs of the composite constituents is provided in Table 2. It can be seen that both models can not capture the effects of particle size on the CTEs of the composites. At low temperature, the experimental results of CTEs show substantial lower than from the prediction of the ROM and Kerner's model, while the Kerner's model agrees relatively well at high temperature. These discrepancies can be qualitatively understood by noting that none of those two models takes into account the effect of thermal residual stress and matrix plasticity. The ROM assumes there is no stress transfer between reinforcements and the matrix through interfaces. Thus it predicts the highest CTEs of composites. During cooling, internal stresses will be developed due to the large difference in CTEs and Yong's modulus between the Al matrix and the SiC particles. It can inhibit the expansion of the composite and lead to the lower CTEs of the composite. As the temperature increase, the residual stress is gradually released and has less of an effect on the thermal response of the composites, and the matrix plasticity will increase CTEs of the composites. The thermal residual stress and dislocation density, and their interaction, result in the complex CTEs response and particle size effect in the composites. Although the particle alignment for larger particles can also affect the CTE values of the composites, the average aspect ratio is only 1.0–1.5 for larger particles and nearly 1.0 for smaller particles, the particle alignment effects will smaller than particle size effects. In this paper, we only emphasize the particle size effects. The particle alignment effects, for the different particle size, will be considered in our future sturdy.

Conclusions

By incorporating the thermal residual stresses and matrix plasticity in the composites, the effects of particle size on the thermal expansion coefficients of SiCp/Al composites are reasonably well explained, and the following conclusions have been drawn.

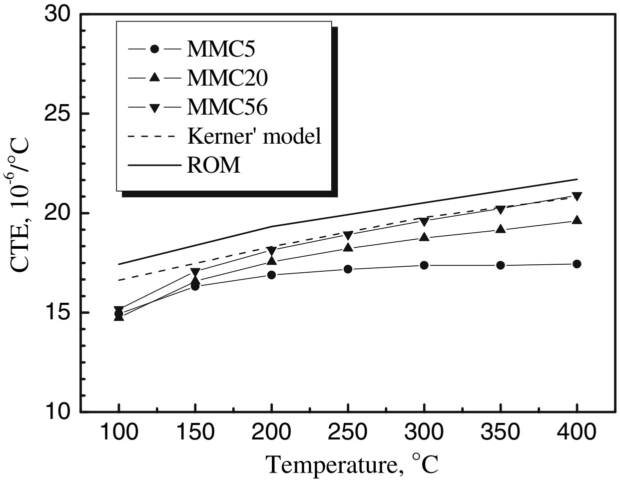

Fig. 6 Comparison of the mean CTEs of the SiCp/Al composites predicted by ROM and Kerner's model

Table 2 Temperature-dependence of the properties of the composite constituents

T (°C)	SiC				Al			
	E (GPa)	G (GPa)	K (GPa)	CTEs (× 10^{-6}°C^{-1})	E (GPa)	G (Gpa)	K (GPa)	CTEs (× 10^{-6}°C^{-1})
50	450	192	227	4.5	72.03	27.2	68.28	21.8
100	450	192	227	4.5	70.66	26.6	68.55	22.4
200	450	192	227	4.5	65.90	24.7	66.21	23.9
300	450	192	227	4.5	63.73	24.1	59.79	25.9
400	450	192	227	4.5	49.16	18.1	60.96	27.8

1. The particle size has certain influence on the thermal expansion behavior of the SiCp/Al composites investigated in the present study. The composite containing small particle shows lower CTEs and lower increasing rate with temperature. The relative higher residual thermal stresses, generated within the composite containing the smaller particles, associated with high strain gradient, should be responsible for the observed difference in CTEs of the investigated composites under various particle sizes.
2. At low temperature, the experimental CTEs of the composites show substantial deviation from the prediction of the ROM and Kerner's model, while the Kerner's model agrees relatively well at high temperature for the composite with the larger particle size.

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