Study on Thermophysical Properties of medium volume fraction SiCp/Al composites

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Abstract. In this paper, the SiC particle size and volume fraction were studied for the thermophysical properties of medium volume fraction SiCp / Al composites. The thermal expansion coefficients (CTEs) of 30%, 35% and 40% SiCp / Al composites were prepared by powder metallurgy techniques from room temperature to 400 °C. The SiC particles have sizes of 3, 8, 15, 25 and 40 μm. The experimental results show that when the volume fraction of SiC particles is the same, the larger the particle size, the higher the CTE of the composite. As the volume fraction of SiC particles increases, the thermal expansion coefficient of the composite decreases. The Schapery model can be used as a good predictive model for medium volume fractional SiCp / Al composite CTE.

1. Introduction
Silicon carbide particle reinforced aluminum alloy (SiCp / Al) composites have excellent mechanical properties and thermophysical properties. Its low coefficient of thermal expansion is the main research objective [1]. The coefficients of thermal expansion (CTEs) vary with the volume fraction of SiC particles. In addition, the size of the SiC particles also affects the CTE of the composite. Although many studies have been conducted in the past [2, 3, 4, 5], there is no uniform conclusion on the effect of SiC particle size on composite CTE. The purpose of this study was to investigate the effect of particle size and volume fraction on the CTE of medium volume fractions (30%, 35%, and 40%) of SiCp / Al composites. In order to provide composite samples having different volume fractions or SiC particle sizes, composite materials were prepared using a powder metallurgy route.

2. Experimental Procedures
In this work, commercial 2024 aluminum alloy powders(Al-4.5Cu-1.2Mg) with an average size of 10 μm were used as the matrix. The aluminum alloy powders were dry mixed thoroughly with SiC particles. An average particle size of SiC reinforcement were 3, 8, 15, 25 and 40 μm, and the volume fraction of reinforcement were 30%, 35 and 40%, respectively. The mixed powders involved in a mechanical mill for 2 hours, then the mixed powders were sintered using a vacuum hot pressing (VHP) technique. Hot pressure was 80 MPa and holding pressure time was 3 h. The CTEs of the specimen were determined by the thermal radiometer (LINSEIS DILL76). Sample size was Φ8 x 12 mm, Both surface of the sample parallel strictly. The heating rate is 5 °C/min. Microstructure examination was carried using microscopy(OM) and scanning electron microscope(SEM).
3. Results and discussion

3.1. Microstructure examination

Figure 1 shows the metallographic structure of SiCp/Al composites with different SiC particle size and volume fraction. The black part is SiC particles and the white part is aluminium matrix. It can be seen from figure 1(a) and figure 1(f) that SiC particles of SiCp (3μm)/Al composites have obvious agglomeration phenomena, and from figure 1 (b), figure 1 (c), figure 1 (g) and figure 1 (h), it can be seen that SiC particles are basically uniformly distributed in the composites with slight agglomeration. It can be seen from figure 1 (d) and figure 1 (e) that the distribution of SiC particles is more uniform. The finer the SiC particles are, the easier they are to form clusters.

Representative microstructures of the different SiCp/Al composites were shown in figure 2. Be seen from the figure 2, there is a uniform distribution of SiC particles. Figures 2 (b), (c), (d) correspond to EDS diagrams at point A, B and C in figure 2 (a), respectively. EDS analysis showed that most of the white particles in the matrix were Al-Cu alloy phase, some of the white particles near SiC particles were Al-Cu-Mg alloy phase, and the brown matrix was mainly α-Al.

![Figure 1. Metallographs showing 30% SiCp/Al distribution in the composites with various SiCp sizes of (a) 3μm, (b) 8μm, (c) 15μm, (d) 25μm, and (e) 40μm; 35% SiCp/Al composite with varying SiC particles size of (f) 3μm, (g) 8μm, (h) 15μm, and (i) 40% SiCp/Al composite with SiC particles size of 15μm](image)

3.2. The influence of volume fraction on the CTEs

The CTE is the important thermal physical properties for the optical/instrument level materials. Figure 3 showed the experimental data of the CTEs and the calculated values with four kinds of theory models (Kerner[6], Turner[7], ROM and Schapery[8]) under the temperature range from 20°C to 100°C for the different volume fraction of SiCp(15μm)/Al composite. From the figure 3, the changes of the CTEs predicted by the four kinds of models are in consistent with the variation of SiC particle volume fraction, the CTEs decrease with the increasing of the volume fraction of SiC particle. A large number of SiC phase with low expansion coefficient can effectively inhibit matrix expansion with the increase of SiC particle volume fraction. It is the most effective way to achieve low expansion coefficient by adjusting the volume fraction of SiC particles.
Figure 2. EDS energy spectra of composite (a)SEM micrograph;(b)EDS of A;(c)EDS of B;(d)EDS of C.

The theoretical calculating value of the CTE using Kerner model is higher than experimental value, this is mainly due to that the SiC particles are supposed to be spherical in Kerner model, but actually the SiC particles used in the experiment are irregular shape. So, the estimate values are generally larger than the actual measured values. Turner model considered the tensile stress, compressive stress, shear stress, the internal stress and deformation in practical influence factors, so its theoretical calculation value is lower than the experimental value. Comprehensive comparison, Schapery model can predict preferably the CTEs of SiCp/Al composites.

In addition to small SiC particles can effectively lower the thermal expansion coefficient, the interface of SiC particles and aluminum alloy matrix can also constraint the thermal expansion behavior. When the volume fraction of SiC particles increase, increasing interfaces will also reduce the CTEs of composites.

Figure 4 shows the trend of temperature versus CTE for different SiC volume fractions of SiCp / Al composites. The CTE of SiCp / Al composites with different SiC volume fractions increases with increasing temperature. When the temperature exceeds 100 °C, the CTE increases rapidly, and when the temperature exceeds 350 °C, the thermal expansion slows down.

3.3. The influence of SiC particle size on the CTEs

Figure 5 is the change of CTE for SiCp/Al composite with different SiC particle size when temperature ranges from 50 to 400°C. Adding 30% SiC particles into the composite can obviously decrease the CTEs, and the CTEs increase with the increasing of the temperature. The CTEs remain increasing when the SiC particle sizes increase from 3μm to 40μm. The CTEs of the SiCp/Al composite were influenced by the SiC particle size at the whole stage, the CTEs decrease with the decreasing of SiC particles size. For the small size SiC particles reinforced SiCp/Al composite, the increase rate of the CTEs has a slight decrease with increasing temperature. The CTE value of SiC particle is $4.2 \times 10^{-6}$/K, its value is around one fifth of the CTE value of pure Al. The CTE of SiCp/Al composite was mainly decided by the matrix and the SiC particle, and largely affected by interface of SiC particle and Al matrix. The CTE of SiCp/Al composite tend to increase when the temperature rises. Firstly, the CTE of SiC particles and aluminum matrix increases when temperatures rise; secondly, transfer ability of the interface will decline, so the restraining effect of the SiC particle on Al matrix was weakened.
Figure 3. Theoretical predicted value and measured value of SiCp/Al composites with varied volume fraction of SiC particles.

Figure 4. The effect of temperature on the CTEs of SiCp/Al composites with different SiC volume fraction.

Figure 5. The change of CTE for SiCp/Al with different SiC particle size in temperature range from 50 to 400°C.

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3.4. The analysis of thermal expansion coefficient variation of composite

For the SiCp/Al composite, the CTEs between SiC particles and the Al matrix are very large in the process of heating, thermal stresses mostly due to the CTE mismatches between different constituents (SiC particle and matrix) [9]. The aluminum matrix suffer compressive stress and SiC particles suffer tensile stress, thermal residual stress will pass the interface between SiC particles and Al matrix to transfer stress and restrict the expansion of the matrix. SiC particle size effects on the CTE are mainly manifested in the interface area. Thermal residual stress reduced the CTE of the composite; meanwhile, plastic deformation emerged in the matrix has the important influence on the thermal strain behavior of the composite, thermoplastic deformation of the matrix increase the CTE of the composite.

According to the theory of Brooksbank [10] and Vaidya [11], when the particle size of SiC increases, the stress of the interface can be expressed as follows:

$$
\sigma = \sigma_{rm} - \sigma_{bm} = p \frac{0.5a^3/r^3 - 2V_p}{1 - V_p} \quad (1)
$$

Where, \( a \) is the particle radius, \( r \) represent the distance particle center to the outside of the aluminum matrix, \( s \) is the stress along the direction of diameter, \( is \) the circumferential stress, \( p \) is the interface pressure, and \( E \) represent respectively the poisson's ratio and young's modulus, \( V \) is the volume fraction of SiC particle, \( p \) represent particle, and \( m \) represent matrix, respectively.

From the formula (1) can be found that stress between SiC particles and the matrix are concerned with the volume fraction and particle size of SiC particles.

Thermal expansion changes of SiCp/Al composites can be divided into several parts. Part of variation of thermal expansion coefficient is the increment caused by the variation of atomic spacing with the rise of temperature, part of variation of thermal expansion coefficient is thermoplastic relaxation of the aluminum alloy matrix when the temperature changes, other part of variation of thermal expansion coefficient comes from the thermal residual stress within composite, the total variation can be expressed as:

$$
\Delta L = \Delta L_a + \Delta L_p - \Delta L_{RS} \quad (2)
$$

Where \( \Delta L \) is the total variation after the thermal expansion; \( \Delta L_a \) is the quantity of heat bilges cold shrink caused by atomic thermal motion; \( \Delta L_p \) is the variation produced by matrix plastic relaxation; \( \Delta L_{RS} \) is the specimen elongation due to the thermal residual stresses in composite. Considering all these effects, thermal residual stresses of composite containing small size SiC particles are larger, then \( \Delta L_{RS} \) is larger, and the expansion of the SiC particles in the matrix will play a constraints role. Meanwhile, because the yield strength is bigger, the thermal mismatch stress relaxation is relatively difficult to occur when the temperature changes, then the elongation \( \Delta L_p \) is smaller. Combining the above factors, the CTEs of the SiCp/Al composites are small when SiC particle size are small.

4. Conclusion

Thermal physical properties of the medium volume fraction SiCp/Al composite were mainly studied in this article. The effect of particle size and volume fraction of SiC particle on the CTEs are well explained in the composites, and the different theoretical prediction model was analyzed.

(1) The addition of SiC particles to the aluminum alloy matrix can effectively reduce the thermal expansion coefficient of the material. As the volume fraction of SiC particles increases, the CTE decreases. The change in CTE can be preferably predicted by the Schapery model.

(2) As the SiC particle size decreases, the CTE decreases. The SiC particle size can indirectly affect the thermal expansion behavior of the composite by affecting the thermoplastic deformation behavior and thermal residual stress.

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