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Effect of whisker volume fraction on the coefficient of thermal expansion and thermal conductivity of SiCw/6061Al composites

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SiC whisker reinforced aluminium alloy (SiCw/Al) composites are attractive as stuctural materials because of their high specific modulus and specific strength [1, 2]. The addition of SiC whisker results in a lower coefficient of thermal expansion (CTE) in comparison with that of aluminium alloy [3], while the density of the composite is almost the same as that of aluminium alloy, so SiCw/Al composites are very suitable for applications in engine components and space structures [4, 5]. In these applications, both a low CTE and a high thermal conductivity (λ) are required. Also, for applications in electronic packaging and precision optical instruments, a high ratio of λ to CTE (λ/CTE) is one of the necessary conditions. Therefore, it is very important to study the thermal behaviour, especially to clarify the conditions for achieving high λ/CTE.

One of the advantages of the SiCw/Al composites is that the CTE and λ of the composite can be adjusted by changing the whisker volume fraction (Vf). However, there is very little experimental data about the effect of Vf on the CTE and λ of the SiCw/Al composites [6, 7], and almost no research has been done about the effect of Vf on the value of λ/CTE. In this letter, the CTE and λ of the SiCw/Al composites for various Vf are examined with emphasis on the effects of Vf on λ/CTE. The squeeze casting route was adopted for fabricating the SiCw/6061Al composites using β-SiC whisker (TWS-100; diameter 0.2–1.0 μm, length 5–20 μm) as the reinforcement and commercial 6061 aluminium alloy as the matrix. The whisker volume fractions Vf were 0.13, 0.17, 0.20, 0.26 and 0.32. The SiCw/6061Al composites and 6061Al were solution treated at 520 °C for 1.5 h and aged at 150 °C for 9 h. The CTE of the 6061Al and SiCw/6061Al composites were measured using a push rod type dilatometer with a heating rate of 10 °C min^{-1}. The CTE values at 100 °C were used for analysis because the values at room temperature were less accurate. The specific heat (C_p) and thermal diffusibility (α) of the SiCw/6061Al composites were measured at room temperature and the thermal conductivity of the SiCw/6061Al composites was estimated by the method shown below.

Fig. 1 shows the effect of Vf on the CTE of the SiCw/6061Al composite, from which it can be seen that the CTE of composite decreases with increasing Vf. The CTE of the SiC whisker is only $3.0 \times 10^{-6}\,K^{-1}$, which is much lower than that of the 6061Al. According to the simple law of mixtures ($CTE_c = CTE_f Vf + CTE_m(1-Vf)$, where the subscripts c, f and m refer to composite, whisker and matrix, respectively), it is easy to understand qualitatively the decrease of the CTE of the composite with increasing Vf. However, the qualitatively calculated results by the law of mixtures do not match the experimental data as shown in Fig. 1, indicating that other factors such as size, shape and distribution of the reinforcement must be taken into account in the calculation.

In the present SiCw/6061Al composites fabricated by the squeeze casting route, the SiC whiskers were greatly damaged during the fabrication processes. Fig. 2 shows the size, shape and distribution of the

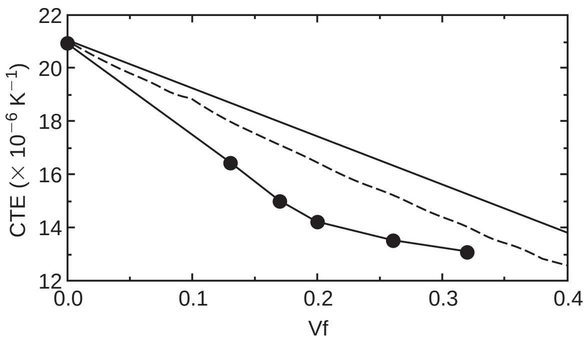

Figure 1 Effect of whisker fraction (Vf) on the CTE of the SiCw/6061Al composite. (——), law of mixtures; (– – –), Equation 2; (●), test value.

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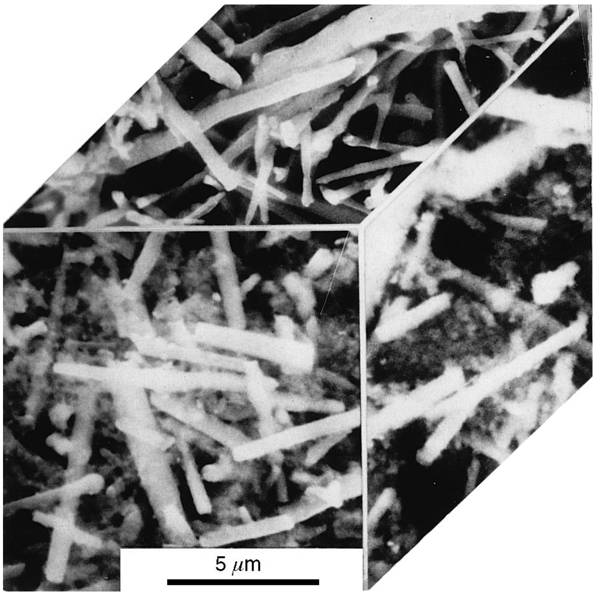

Figure 2 SEM micrograph showing the size, shape and distribution of the SiC whiskers in the SiCw/6061Al composite.

whiskers in the SiCw/6061Al composite used here. It can be seen that the SiC whiskers with average dimensions of 0.5 μm diameter $\times$ 5 μm length distribute uniformly and orientate randomly in the matrix. For this situation, Equation 1 [8] derived for particulate composites according to these structural parameters, based on the law of mixtures and the Eshelby theory, was adopted to a first approximation:

$$\mathrm{CTE_c} = \mathrm{Vf\ CTE_f} + (1 - \mathrm{Vf})(\mathrm{CTE_f} - \mathrm{CTE_m})$$
$$(K_f - K_m)[(1 - \mathrm{Vf})K_m + \mathrm{Vf}K_f + 3K_m K_f/(4\mu_m)]^{-1} \tag{1}$$

where K_m and K_f are the bulk modulus of matrix and fibre, respectively, and μ_m is the shear modulus of the matrix. For the T6 state SiCw/6061Al composites used here, the values of the above parameters are shown in Table I.

From Table I and Equation 1, the CTE of the T6 state SiCw/6061Al composites is expressed by:

$$\mathrm{CTE_c} = 21 - 18\mathrm{Vf} - 162\mathrm{Vf}(1 - \mathrm{Vf})(25 + 9\mathrm{Vf})^{-1}$$
$$(\times 10^{-6}\mathrm{K}^{-1}) \tag{2}$$

TABLE I Some parameters of the T6 state SiCw/6061Al composite used in this research

$\mathrm{CTE_f}$ (K^{-1})	$\mathrm{CTE_m}$ (K^{-1})	K_m (GPa)	K_f(GPa)	μ_m (GPa)
3.0×10^{-6}	21.0×10^{-6}	51.5	96.6	50.7

From Fig. 1 it can be seen that compared with the law of mixtures the values calculated from Equation 2 are closer to the experimental. However, there is still some deviation between the values from Equation 2 and the experimental data, possibly because the shape of the SiC whisker was assumed to be elliptical in the calculation, while the real shape is columnar. A more suitable equation should be developed to describe these experimental data.

The density (ρ), specific heat capacity (C_p) and thermal diffusibility (α) of the T6 state SiCw/6061Al composites with different Vf were measured at room temperature, and the results are shown in Table II. With increasing Vf, the density of the composite increases, while the specific heat and thermal diffusibility decrease. Thermal conductivity (λ) of the SiCw/6061Al composite was calculated using:

$$\lambda = \rho C_p \alpha$$

The calculated results are shown in Table II, indicating that the thermal conductivity of the SiCw/6061Al composite decreases with increasing Vf. The reason for this could be as follows. In this research, as the thermal conductivity was measured at room temperature, it depends mainly on the average free distance of the electrons of the matrix alloy. In the SiCw/Al composite, the resistance and scatter function of the SiC–Al interfaces, grain boundaries and dislocations in the matrix will reduce the average free distance of the electrons of the matrix alloy. In the squeeze-cast SiCw/6061Al composites, the amount and density of the SiC–Al interfaces, grain boundaries and dislocations in the matrix increase with increasing whisker volume fraction. Therefore, with increasing Vf, the average free distance of the electrons of the matrix decreases, resulting in the decrease of the thermal conductivity of the SicW/6061Al composite with increasing Vf as shown in Table II.

The present results indicate that the whisker volume fraction is very effective on the thermal conductivity and CTE of the SiCw/6061Al composites. From Fig. 1 and Table II it can be seen that with increasing Vf, both CTE and thermal conductivity of the SiCw/6061Al composite decrease.

Fig. 3 shows the thermal conductivity to CTE ratio (λ/CTE) of the T6 state SiCw/6061Al composites with different whisker volume fractions. With increasing Vf from 0 to 0.2, the λ/CTE ratio increases, and when the Vf is higher than 0.2, the λ/CTE ratio decreases with increasing Vf. Thererfore, it is

TABLE II Density (ρ), specific heat capacity (C_p), thermal diffusibility (α) and thermal conductivity (λ) of the T6 state SiCw/6061Al composites with different Vf

Vf	ρ ($\times 10^3$ kg mm^{-3})	C_p (J kg K)	α ($\times 10^{-4}$ m^2 s^{-1})	λ (Wm^{-1} K^{-1})
0.13	2.76	847	0.63	147.3
0.17	2.78	795	0.62	137.0
0.20	2.80	781	0.60	131.3
0.26	2.83	745	0.57	121.7
0.32	2.86	733	0.54	113.2

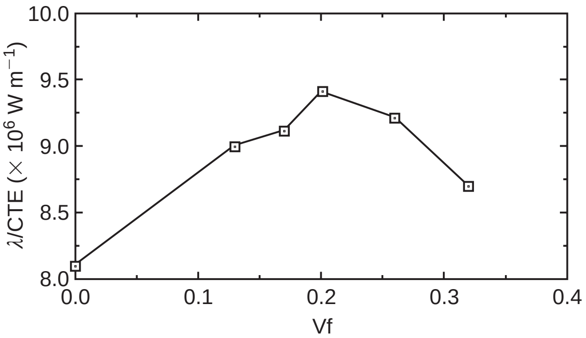

Figure 3 Effect of Vf on the thermal conductivity to CTE ratio (λ/CTE) of the SiCw/6061Al composite.

suggested that in maximizing the thermal conductivity to CTE ratio (λ/CTE) of the squeeze-cast SiCw/6061Al composites, the whisker volume fraction should be about 0.2. This is the first finding in this field.

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