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Thermal expansion of isotropic Duralcan metal–matrix composites

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The thermal expansion behaviour of Duralcan composites having a matrix of hypoeutectic Al–Si alloy containing SiC reinforcements ranging from 10–40 vol% was investigated. The coefficient of thermal expansion (CTE) of the MMCs was measured between 25 and 350 °C by a high-precision thermomechanical analyser, and compared to the predictions of three theoretical models. At low temperature, the experimental CTEs show substantial deviation from the predictions of the elastic analysis derived by Schapery, while the Kerner model agrees relatively well at high temperature. The overall measured CTE, in the range of 25–350 °C, as a function of the volume fraction of SiC is well predicted using Schapery's lower bound. We interpret these features as being an effect of reinforcement phase geometry and the modified microstructure derived from the Duralcan process and subsequent heat treatments. © *1998 Kluwer Academic Publishers*

1. Introduction

Metal matrix composites (MMCs) have emerged as a class of materials capable of advanced structural, aerospace, automotive, electronic, thermal management, and wear applications. These alternatives to conventional materials provide the specific mechanical properties necessary for cryogenic and elevated temperature applications. In many cases, the performance of MMCs is superior in terms of improved physical, mechanical, and thermal properties. The performance advantage of aluminium alloys reinforced with various ceramics such as SiC and Al_2O_3 is their tailored mechanical, physical, and thermal properties that include low density, high specific strength, high specific modulus, good fatigue response, control of thermal expansion, high abrasion and wear resistance [1, 2]. Tailorability for specific applications is one of the greatest attractions of MMCs. Thus, these composites are gaining rapid prominence in aerospace [3], automotive, electronic [4] and energy sectors. For instance, low coefficient of thermal expansion (CTE) and high thermal conductivity are desirable properties for applications such as heat sink and radiator panels for satellite structures and space shuttles [5]. Furthermore, MMC material is being successfully used as diecast components, which include pistons [6, 7], cylinder liners, connecting rods [8], brake drums and even engine blocks. The interest in this composite stems from its high specific strength and stiffness, low thermal expansion, high thermal conductivity and improved tribiological properties.

The CTE of MMCs has been recognized as one of the important thermomechanical properties because the thermal stability can be a critical issue in the design of components subjected to temperature variations. Tailoring the CTE is an important consideration in minimizing the expansion–contraction mismatch or to maintain specific dimensional tolerances between components subjected to various temperature gradients. In addition, a thermal expansion study of MMCs is required in order for thermal stresses to be investigated for particular applications such as electronic packaging.

In recent years, extensive numerical and analytical research has been performed on thermomechanical properties, such as CTE, of Al/SiC composites and on the dependence of such properties on processing parameters [9, 10]. For instance, it has been well established from numerical investigations that geometrical variables, such as the concentration, size, shape, and spatial distribution (architecture) of the ceramic particles in the aluminium matrix can substantially influence the thermal expansion behaviour of particle-reinforced MMCs. However, detailed experimental

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TABLE I Chemical composition of aluminium alloy matrices

	Si	Fe	Cu	Mn	Mg	Ti	Zn	All other elements	Al
A359	8.50–9.50	0.20 max.	0.20 max.	0.45–0.65	0.45–0.65	0.20 max.	–	0.03 max. 0.10 total	Bal.
A360	9.50–10.50	0.80–1.20	0.20 max.	0.50–0.80	0.50–0.70	0.20 max.	0.03 max.	0.03 max. 0.10 total	Bal.

studies of such geometrical effects on the CTEs of MMCs have so far not been reported.

We explore, here, the effect of reinforcement volume fraction, which is known to exert a significant influence on the thermal expansion behaviour of isotropic MMCs matrix composites, as might be expected from a simple rule of mixtures. In this work, the thermal expansion behaviour of Duralcan composites having a matrix of hypoeutectic Al–Si alloy containing SiC reinforcements ranging from 10–40 vol % was investigated. The CTE of the MMCs was measured between 25 and 350 °C by a high-precision thermomechanical analyser (TMA), and compared to the predictions of three theoretical models.

2. Experimental procedures

2.1. Composite materials

The chemical compositions of the aluminium alloy matrices used in this study are given in Table I. The composite materials were received in the form of ingots from Duralcan Canada and MC-21 Incorporated, San Diego, CA. The specifications of the reinforcement particle and aluminium alloys used in this study are shown in Table II. The MMC materials were produced by the Duralcan^{tm} (Trademark, Alcan Aluminium Ltd, San Diego, USA) molten metal mixing process [11, 12]. The composites were permanent mould cast and then heat treated to the T4 condition (solution treated at 550 °C for 1 h then quenched in water followed by room-temperature ageing for a minimum of 2 d). Fig. 1 shows scanning electron micrographs of polished sections of the SiC/Al composites. All composites exhibit a uniform particle distribution which seems to be responsible for the isotropic nature of mechanical and physical properties. At low volume fraction, the reinforcing particles are very effective in nucleating new grains within the aluminium matrix, and stabilizing the resulting fine grain size. Quantitative metallography analysis of the composites were examined with a light microscope interfaced with the IBAS 2000 system. Typically, 20 fields of about 100 particles per filed were investigated. This system enabled the data acquisition for the SiC particles, including location of the particle centroid in the field, particle area and aspect ratio (ratio of maximum and minimum particle diameter). Aspect ratio distribution histograms of SiC particulate for all four material systems accumulated during image analysis are shown in Fig. 2. The SiC particulate is irregular in shape having an average aspect ratio of 1.4–2.2 with the rare occurrence of larges shards of much greater convexity. The average SiC particle size in the 10 vol% composite is 9.3 μm (600 grit), and at 20, 30 and 40 vol% 13 μm (500 grit). The aluminium alloy matrix has a fine uniform grain size of the order of the interparticle spacing (5–40 μm depending on volume fraction). Energy dispersive X-ray analysis in the SEM revealed no unusual second phases other than those associated with the Al–Si–Mg matrix and the typical trace elements. No evidence of chemical reaction between the matrix and the SiC particulate was noted. No particle cracking is apparent and essentially no porosity is present in the composite material.

TABLE II Properties of reinforcement particles and aluminium matrices

	Density (g cm^{-3})	Yield stress (MPa)	Maximum plastic strain (%)	Thermal conductivity (W m^{-1} k^{-1})
SiC	3.2	303	0	80–200
A359	2.685	207–262	3–5	138
A360	2.63	170	3.5	113

2.2. TMA test

The average dimension of the specimens for TMA testing was 10 mm × 5 mm × 1.5 mm. Coupons were cut form the cast materials using a diamond saw and were polished using 1 μm diamond phase. More than four samples of each composite were tested to verify reproducibility of the experimental data. CTE measurements were performed from 25–350 °C at 10 °C min^{-1} using a commercial thermomechanical analysis equipment (model TMA 2940, Dupont, USA). The thicknesses of the samples were measured with increased sensitivity (0.01 μm) using the standard expansion probe. The TMA apparatus measures linear or volumetric changes in the dimensions of a specimen as a function of time, temperature and force. The dimensional change of the sample is measured with a linear variable differential transformer (LVDT) that has an output which is proportional to the linear displacement of the core caused by changes in sample dimensions. The samples were placed in a chamber where atmosphere quality can be controlled. An inert gas (helium) was blown into the chamber at a rate of 40 ml min^{-1}. A thermocouple adjacent to the sample ensures accurate measurements of the sample temperature. The final output is a plot of per cent linear change (PLC) versus time, temperature or force. TMA

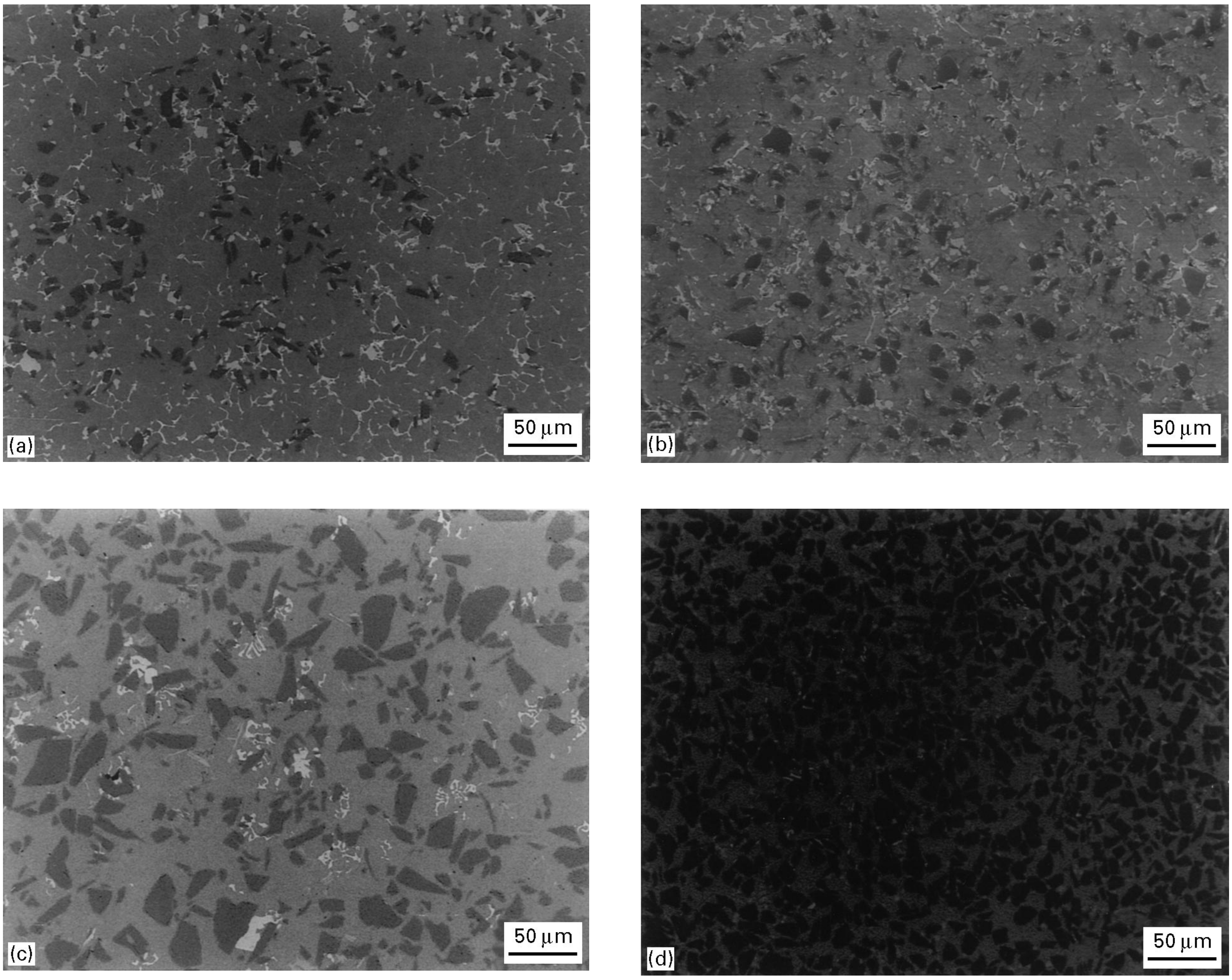

Figure 1 Microstructures of Duralcan SiC/Al MMCs: (a) 10% SiC, (b) 20% SiC, (c) 30% SiC, and (d) 40% SiC.

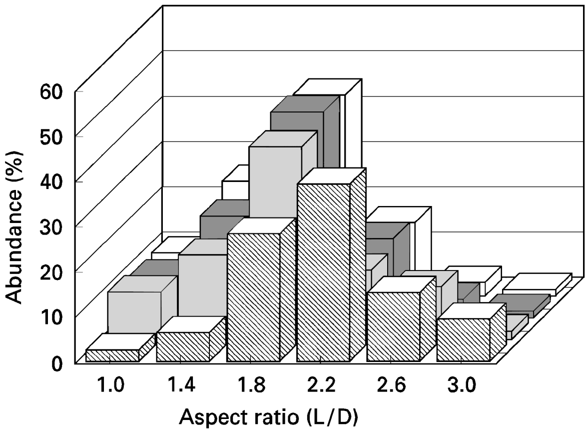

Figure 2 Aspect ratio histograms of SiC particulate for Duralcan composites. ▨ 10%, ░ 10%, ■ 30%, □ 40%

standard data analysis software was used to evaluate instantaneous and average CTEs of the composites tested. In this study, average CTEs were determined at intervals of 50 °C based on the calculated slope fit between two selected temperatures using PLC versus temperature curves.

3. Results

The precision of the TMA measurement technique was established by repeated test of the same composite specimen as well as various aluminium alloys. The experimental results of the dimensional change with temperature of the four silicon carbide-reinforced composites are shown in Fig. 3a. For a given temperature, the dimensional change decreases with reinforcement volume fraction. In addition, the slope of the dimensional change versus temperature curves becomes shallower for the entire temperature interval as the reinforcement volume fraction increases from 10% to 40%. Note that all thermal expansion versus temperature responses of the composites are not linear.

The effect of reinforcement volume fraction on thermal expansion behaviour of Duralcan composite for various temperature ranges is shown in Fig. 3b. As expected from Fig. 3a, the CTE strongly depends on volume fraction of SiC for a given temperature range. The composite reinforced with 40% SiC exhibits the lowest CTE around 10 p.p.m. $^{\circ}C^{-1}$ at 25–50 °C which is about 2.2 times that of monolithic SiC. It is evident that the measured CTE shows, for each Duralcan composite, similar variations with temperature, but with a substantial increase in the CTE value, by about 6 p.p.m. $^{\circ}C^{-1}$, as the temperature range increases from 25–50 °C to 300–350 °C. This effect of temperature is expected, because the temperature dependence of CTE for each aluminium alloy [13, 14], as illustrated in Table III, clearly points to a similar increase in CTE (5.4 p.p.m. $^{\circ}C^{-1}$).

4. Discussion

4.1. Theoretical models

The CTE of MMCs is generally difficult to predict because it is influenced by several factors such as reinforcement volume fraction, fabrication process and the nature of the composite constituents. Several models have been proposed for predicting the CTE of particle-reinforced MMCs. Among those, there are worth mentioning due to their simplicity and good accuracy: Turner [15], Kerner [16], and Schapery [17] models.

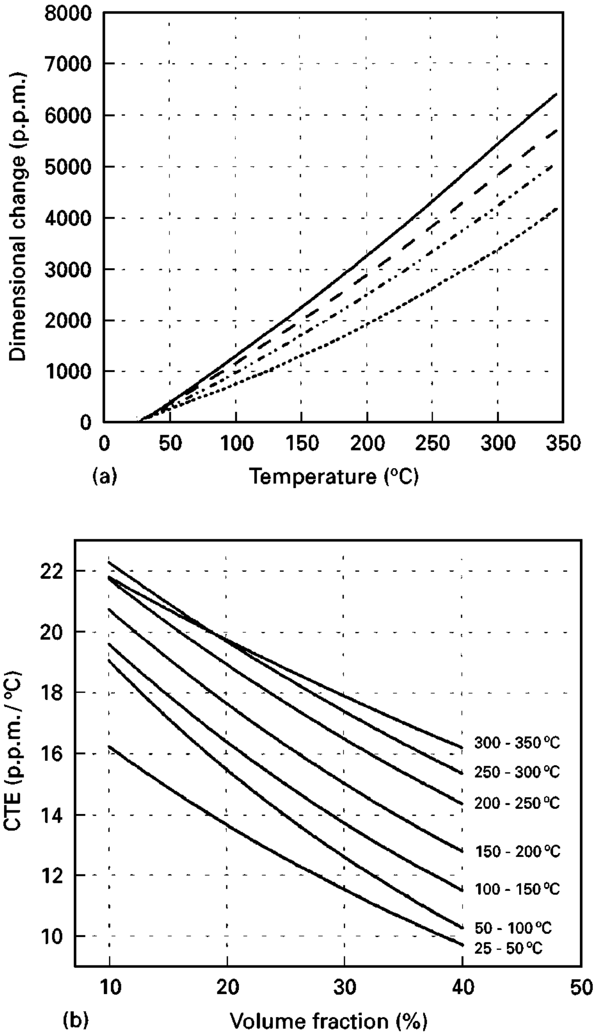

Figure 3 Thermal expansion behaviour of SiC composites: (a) dimensional changes versus temperature, (—) 10% SiC, (– – –) 20% SiC, (–·–) 30% SiC, (–––) 40% SiC temperature, and (b) CTE versus temperature.

4.1.1. Turner's model

The Turner model assumes homogeneous strain throughout the composite and uses a balance of internal average stresses to derive the thermal expansion of the composite. In this model, each constituent is assumed to change dimensions with the temperature changes at the same rate as the composite. Neglecting shear deformation, we can write the stresses acting on the matrix and the particles using the volume strain and bulk modulus

$$\sigma_i = (\beta_c - \beta_i)\, K_i \Delta T \qquad i = p, m \tag{1}$$

where β is the volumetric coefficient of thermal expansion, K the bulk modulus and subscripts c, p and m refer to the composite, particle and matrix, respectively. The resultant force acting on any cross-section of the composite must be zero for equilibrium such that

$$\sigma_p A_p + \sigma_m A_m = 0 \tag{2}$$

where A_p and A_m are the cross-sectional areas of the particles and the matrix, respectively. For a homogeneous distribution of the reinforcing particles, the cross-sectional areas become proportional to the volume fraction of each constituent such that Equation 2 becomes

$$\sigma_p V_p + \sigma_m V_m = 0 \tag{3}$$

Substituting this last equation into Equation 1 and knowing that the volumetric CTE is related to the linear CTE by $\alpha = \beta/3$, the CTE of the composite becomes

$$\alpha_c = \frac{\alpha_p V_p K_p + \alpha_m V_m K_m}{V_p K_p + V_m K_m} \tag{4}$$

4.1.2. Kerner's model

The Kerner model assumes that the reinforcement is spherical and wetted by a uniform layer of matrix; thus the CTE of the composite is stated to be identical to that of a volume element composed of a spherical reinforcement particle surrounded by a shell of matrix,

TABLE III Temperature-dependence of the properties of the composite constituents

T (°C)	SiC				A359				A360			
	E (GPa)	*G* (GPa)	*K* (GPa)	CTE (μm °C^{-1})	*E* (GPa)	*G* (GPa)	*K* (GPa)	CTE (μm °C^{-1})	*E* (GPa)	*G* (GPa)	*K* (GPa)	CTE (μm °C^{-1})
25	450	192	227	4.5	70.4	26.9	68.4	21.1	71.4	27.2	69.4	21.2
50	450	192	227	4.5	70.3	26.8	68.3	21.8	71.2	26.9	69.1	21.6
100	450	192	227	4.5	69.4	25.5	68.1	22.3	70.2	26.2	68.6	22.4
150	450	192	227	4.5	68.7	25.2	67.5	22.7	69.4	25.4	68.2	22.9
200	450	192	227	4.5	68.2	24.7	66.3	23.6	68.4	25.1	67.2	23.2
250	450	192	227	4.5	66.4	23.9	63.2	24.5	67.1	24.2	63.8	24.3
300	450	192	227	4.5	65.9	23.1	59.2	25.3	66.4	23.6	60.4	25.4
350	450	192	227	4.5	65.3	22.1	61.6	26.2	65.9	22.9	60.7	25.9

both phases having the volume fraction present in the composite. This model gives the composite CTE as

$$\alpha_c = \bar{\alpha} + V_p(1 - V_p)(\alpha_p - \alpha_m) \times \frac{K_p - K_m}{(1 - V_p)K_m + V_pK_p + (3K_pK_m/4G_m)} \quad (5)$$

where the rule of mixtures if given by $\bar{\alpha} = (1 - V_p)\alpha_m + V_p\alpha_p$, K and G are the bulk and shear moduli, V is the volume fraction, and α is the coefficient of thermal expansion.

The bulk modulus is calculated using the standard relationship

$$K = \frac{E}{3(3 - E/G)} \quad (6)$$

4.1.3. Schapery's model

Among the several formulae that have been suggested for the calculation of the thermal expansion coefficients of composite materials taking into account the stress interaction between components is that of Schapery who has derived the effective CTE of isotropic composites, by employing extremum principles of thermoelasticity. The CTE value can be written as

$$\alpha_c = \alpha_p + (\alpha_m - \alpha_p)\frac{(1/K_c) - (1/K_p)}{(1/K_m) - (1/K_p)} \quad (7)$$

where α_c and K_c are the CTE and bulk modulus of the composite. Note that α_c depends on the volume fraction and phase geometry only through their effect on bulk modulus. This equation states an exact relation between the composite CTE and bulk modulus. However, only upper and lower bounds of K_c are determined in a given case (Hashin's bounds [18]). Thus, this expression will provide only bounds on CTE. The lower bound on bulk modulus is

$$K_c = K_m + \left[V_p \Big/ \left(\frac{1}{K_p - K_m} + \frac{V_m}{K_m + \frac{4}{3}G_m}\right)^{-1}\right] \quad (8)$$

The upper bound is obtained by interchanging indices m and p everywhere. The lower bound on K_c yields the upper bound on the composite CTE shown in Equation 7 (and vice versa). Note that this upper bound of the composite CTE was shown by Schapery to coincide with the CTE value determined using Kerner's model. This is not surprising, because Hashin's lower bound for bulk modulus is stated to be an exact result for an elastic composite, in which the reinforcement is a sphere coated with a uniform layer of the matrix.

Numerical values of parameters, E, K, G, and α, used for the computation of predicted composite CTE using Equations 4, 5 and 7 are extracted from previous experimental work [13, 14, 19–22]. The variation in Young's and shear moduli with temperature for pure aluminium was examined using dynamic mechanical analysis (DMA) and the temperature dependence of aluminium alloys CTE was studied using TMA. A summary of the elastic constants and CTE of the composite constituents is provided in Table III.

4.2. Comparison between the experimental and theoretical results

An advantage of the present theoretical calculations over the mean field theory, which consider the CTE constant over a given temperature range, is that it can take into account the temperature dependence of the CTE of Al/SiC Duralcan composites. Because we experimentally determined extensive data for the constituent phases of the composite materials [22, 23], it is possible to compare quantitatively the theoretical predictions with experimental results. Therefore, the predicted effects of reinforcement volume fraction on the CTE of composite materials do furnish worthwhile information for better understanding the composites thermal expansion behaviour.

The comparison between the theoretical calculations and experimental results of the composite CTE for the 10%–40% volume fraction range is shown in Fig. 4. At low temperature, the experimental CTEs show substantial deviation from the predictions of the elastic analysis derived by Schapery, because these are significantly lower than the elastic lower bound. This trend become more prominent as reinforcement volume fraction increases, while the Kerner model agrees relatively well at high temperature. Obviously, the low-temperature CTEs measured upon heating of the Duralcan composites are closer to the Turner model values than the elastic lower bound. The agreement with Turner and Schapery's lower-bound model is good at lower temperatures; as the temperature is increased, experimental results are seen to deviate from these predictions, presumably because of a change in the physical interaction between ceramic particles and the aluminium matrix. Kerner's model, which took into account both the normal and shear stresses between particles and particle and matrix, is a better fit at high temperature than those of Turner and Schapery. This feature was reported in previous work [17, 23] on pressure-infiltrated composites containing high volume fraction of reinforcement (56%). A good agreement with Kerner's model at high temperatures was found while the CTEs in the low-temperature range agreed relatively well with the values predicted by Turner and Schapery's equation.

The average CTE between 25 and 350 °C as a function of reinforcement volume fraction is given in Fig. 5. Knowing the equation of the experimental CTE as a function of temperature (second-order polynomial best-fit curve) from Fig. 4, we can compute the experimental average CTE using the following general relationship

$$F_{\text{avg}} = \frac{1}{T_2 - T_1}\int_{T_1}^{T_2} F(T)\,\mathrm{d}T \quad (9)$$

where T_1 and T_2 represent the limits of the temperature interval. In addition, theoretical predictions of the average CTE versus volume fraction curves were obtained using the average values of the constituent

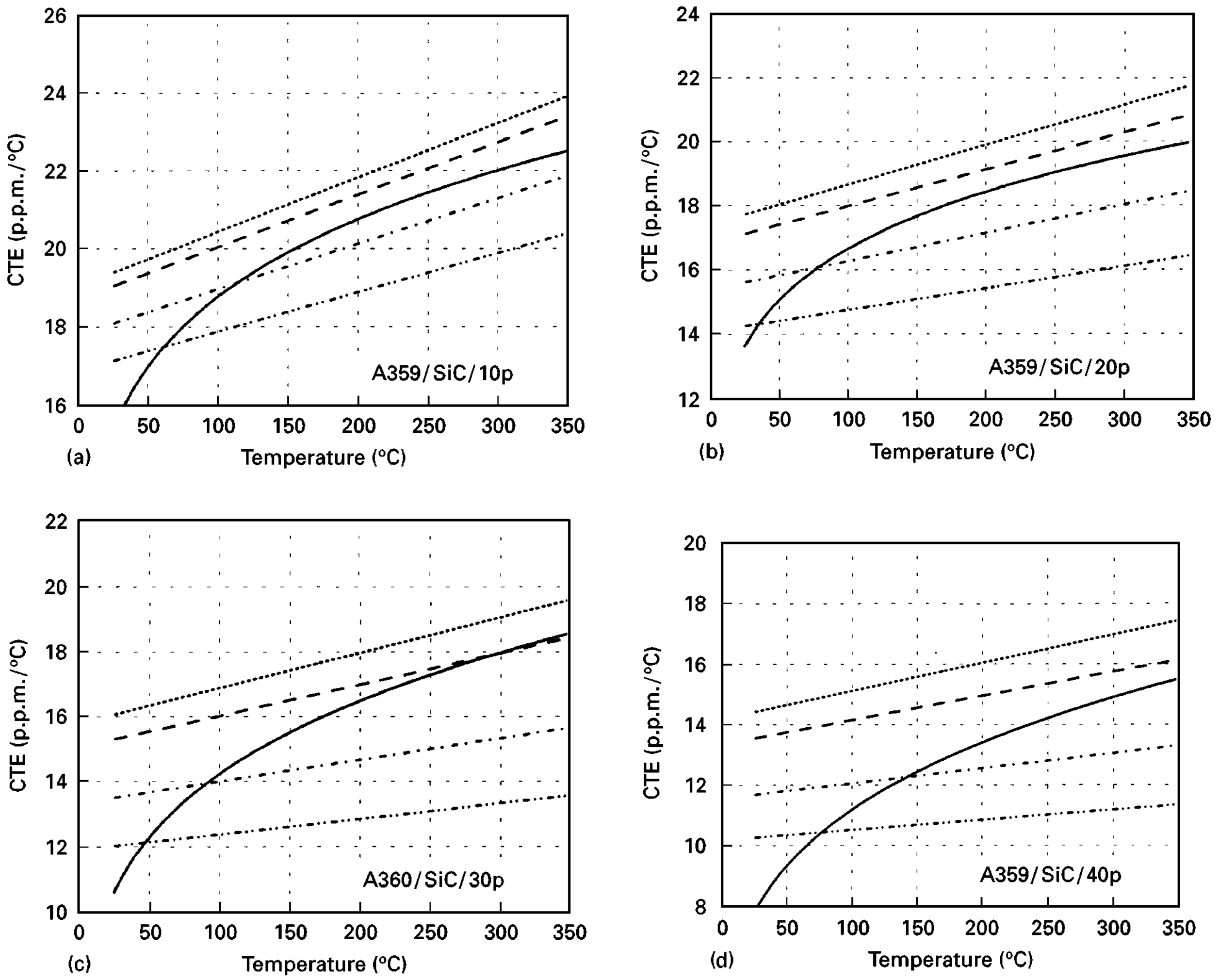

Figure 4 Comparison of the measured CTE of Duralcan SiC/Al composites with the theoretical predictions. (—) Experimental, (–––) Kerner [16], (- - - -) ROM, (—·—) Schapery [17], (–-–) Turner [15]. (a) A359/SiC/10P, (b) A359/SiC/20P, (c) A360/SiC/30P, (d) A359/SiC/40P.

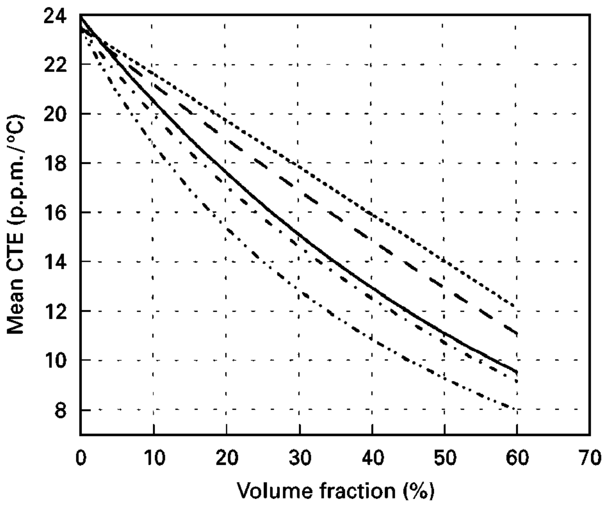

Figure 5 Comparison of the mean CTE of Duralcan SiC/Al composites with theory for 25–350 °C temperature range. (—) Experimental, (···) ROM, (---) Kerner [16], (-·-) Schapery [17], (-–-) Turner [15].

properties given in Table III over the same temperature interval. The average CTEs of the four composites of the present study were combined with those of Balch *et al.* [15] and Elomari *et al.* [23], for Al/56% SiC and Al/47% SiC composites, respectively. This experimental average CTE curve provides an excellent approximation of the expansion behaviour of SiC/Al composites over 25–350 °C temperature range. The overall measured CTE as a function of the volume fraction of SiC, in the range of 0–60%, is shown in Fig. 5, as well as the predictions of Kerner, Schapery and Turner. Although the influence of ceramic concentration on the CTE is consistent, the thermal expansion behaviour is well predicted using Schapery's lower bound, up to 60% SiC phase. This trend is not surprising because particle shape has a significant effect on the CTE of Al–SiC composites. Indeed, the results of finite element analysis indicate that for spherical particles, the Kerner model provides the weakest constraint, while high aspect ratio particles (>1) give the strongest constraint on the matrix [24]. Therefore, Kerner's model, which assumed spherical particles, may underestimate the constraints actually offered in real composites. The previous argument applies to any two-phase material composed of constituents with distinct properties. For example, it was reported experimentally [25], in WC–Co alloys, that the constraint imposed on the binder phase depends strongly on the aspect ratio and concentration of cobalt phase.

In summary, the thermal expansion behaviour of Duralcan composites is the result of a complex interaction between the SiC particulate reinforcement and the aluminium matrix microstructure. The composite is not a homogeneous monolithic structure but a mixture of a continuous aluminium matrix and discontinuous particulates each having significantly different mechanical and thermal properties across a thin interface. The mismatch in CTE between the particles and the matrix results in the generation of localized stresses at the particle interfaces during the solidification of the composite, as well as the solution treatment and quenching step of the heat-treatment cycle. It is possible that these stresses may, in part, be responsible for the very low CTE measured in all composite samples at low temperatures. At higher temperatures, these localized stresses (strains) relax and should have less of an effect on the thermal response of the composites. The CTE of metal matrix composites is further influenced by its discontinuous microstructure. On a fine scale, the MMC may be viewed as having a complex defect structure. The aluminium matrix grains can be extremely small due to the limiting effect of the reinforcing phase. As a result, there is a high concentration of grain boundaries. There is also a large number of particle–matrix interfaces, typical of particle-reinforced composites. The high incidence of these planar discontinuities can result in strain and dislocation generation at the interfaces during the heating cycle due to the property mismatch. This complex defect microstructure and dislocation cells at the interfaces are though to affect strongly the CTE of metal matrix composites. The interplay of these effects and others, less understood and more poorly defined, result in the complex CTE response discussed above.

5. Conclusion

The geometry and volume fraction of the reinforcing ceramic phase in Duralcan MMC appear to be the major factors in the determination of composite thermal expansion coefficients. SiC particle-reinforced Duralcan composites show similar thermal expansion behaviour over the temperature range tested and appear to be more stable in that range. At low temperature, the experimental CTEs show substantial deviation from the predictions of the elastic analysis derived by Schapery, while the Kerner model agrees relatively well at high temperature. The Duralcan composites, as demonstrated in this study, exhibit a greater dimensional stability and are well suited for applications such as electronic packaging which require low and tailorable CTEs that do not noticeably increase within the usage temperature range.

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