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Thermal Expansion of an SiC Particle-Reinforced Aluminum Composite[1]

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Using a push-rod dilatometer, we measured between 76 and 390 K the thermal expansion of a particle-reinforced-composite wrought plate obtained by powder-metallurgy methods. The particles, 30% by volume, consisted of monocrystals of α-SiC with sizes near 10 μm. The matrix consisted of a 6061 aluminum alloy with original particle sizes near 20 μm. We found the perpendicular thermal expansivity, α_3, higher by 26% than the in-plane thermal expansivity, $\alpha_1 \simeq \alpha_2$. These values differ from a rule-of-mixture prediction by -3 and -23%, respectively. All three α_i components lie outside the Rosen–Hashin bounds. Levin's isotropic model agrees within 10% with the α_1–α_2–α_3 average. Both the anisotropy and the bounds violation result from microstructural non-homogeneity arising from processing. Rosen and Hashin's transverse-isotropic-symmetry relationships account approximately for these effects by introducing the anisotropic elastic constants. Using neutron diffraction, we determined that the SiC particles are textureless.

KEY WORDS: aluminum; composite; elastic constants; low temperatures; silicon carbide; thermal expansion; thermal expansivity.

1. INTRODUCTION

Thermal expansivity is an important physical–mechanical property. On one hand, it relates directly to fundamental anharmonic interatomic forces. The volume thermal expansivity is

$$\beta = (1/V)(\partial V/\partial T)_P \tag{1}$$

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It relates to the Helmholtz free energy, F, according to

$$\beta = -(1/B)(\partial^2 F/\partial V\, \partial T)_{T,V} \tag{2}$$

Here B denotes the isothermal bulk modulus, V the volume, P the pressure, and T the temperature. It relates to other important physical properties that include the elastic constants and the Grüneisen parameter. On another hand, β relates to key technological problems such as dimensional stability and internal strain.

Being a tensor property, thermal expansivity has six independent components in the least-symmetrical case. Most practical materials exhibit at least orthotropic symmetry, thus only three independent components. In crystals, the anisotropy arises from forces between atoms. In technological materials the macroscopic anisotropy arises from processing, from gradients in temperature or in mechanical deformation, for example.

For composites, the principal theoretical problem is, How can we calculate the macroscopic composite properties from those of its constituents and from the phase geometry? For thermal expansivity, Christensen [1] recently reviewed this subject. Hashin [2] described it in the context of a unified, rational treatment of the theory of fiber-reinforced composites.

The present study involved measurements of the thermal expansion of a particle-reinforced composite—SiC in 6061-Al alloy—and comparisons of observation with existing models.

2. MEASUREMENTS

2.1. Material

We obtained material from a commercial supplier in the form of 1-cm plates. The supplier started with commercially available Al-6061 and SiC particles. These powders were blended, compacted, and sintered to produce billets measuring $25 \times 30 \times 4$ cm. Billets were hot rolled at 700–783 K (800–950°F) with a thickness reduction per pass ranging from 10 to 50%. Rolled plates were subjected to a standard T6 heat treatment: solution treat at 800 K (980°F) for 2 h, water quench, and age at 436 K (325°F) for 18 h. Two SiC volume concentrations were produced: 20 and 30 percent. The present study considers only the latter composition. Figure 1 shows the microstructure. To determine whether the material exhibits texture in the SiC-particle orientation distribution, we used neutron diffraction to obtain pole figures. Figure 2 shows a typical result and that the SiC particles were essentially textureless.

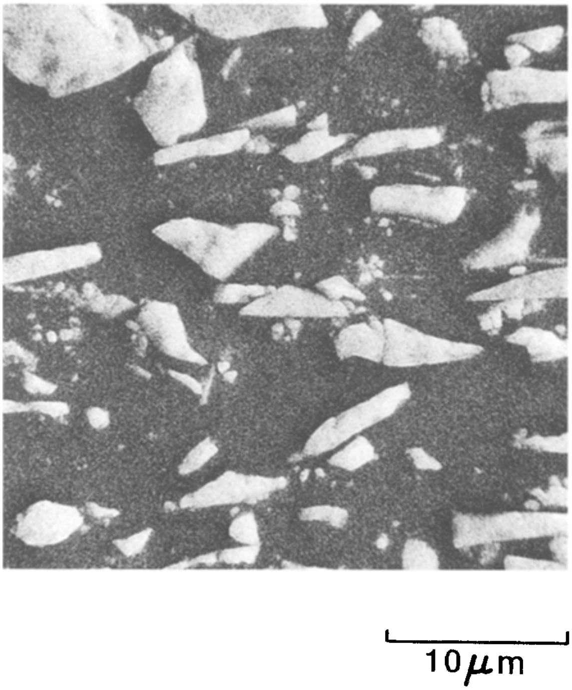

Fig. 1. Microstructure of studied SiC/Al composite containing 30 vol% particles, which ranged in size up to approximately 10 μm.

2.2. Measurement Method

Measurements were made with a concentric tube-type dilatometer. Specimens were cylinders 0.96 cm in diameter and 12.7 cm long. A platinum resistance thermometer placed into a specimen center hole from the base of the dilatometer provided the temperature measurement.

After cryostating, resistance wire wrapped about the outer silica tube heated the sample for above-ambient temperature studies. For below-ambient temperature measurements, the probe was placed in the ullage of a dewar containing liquid nitrogen.

Length change was detected by a linear variable displacement transducer (LVDT) excited by a 2500-Hz sinusoid at 2.5 V_{rms} and mounted directly on the end of the outer tube in the laboratory environment. The response was detected by a lock-in amplifier whose output voltage and phase indications were digitized into a desktop computer for subsequent analysis. As the specimen cooled from 400 to 76 K, temperature was

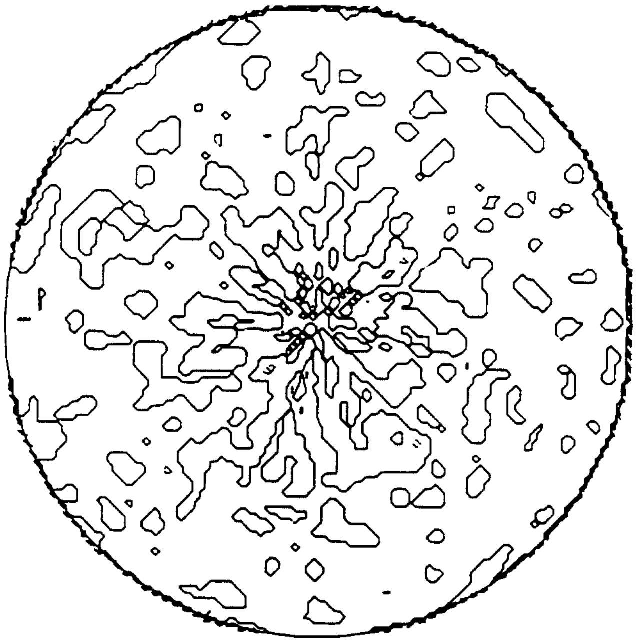

Fig. 2. Silicon-carbide-particle pole figure determined by neutron diffraction. Corresponding to a 2Θ diffraction angle of 28.5°, this result confirms that the hexagonal-crystal-structure SiC particles are textureless and contribute nothing to the anisotropic thermal expansivity. Pole figure obtained by Professor R. Reno (University of Maryland).

monitored continuously; sample length was recorded every kelvin. Calibrations against standard materials showed that our uncertainty in $\Delta L/L$ is 2×10^{-6}.

3. RESULTS

Figure 3 shows the length-change measurements for two in-plate directions, x_1 and x_2, and in a direction perpendicular to the plate, x_3. We take the plate rolling direction to be x_1. Both Fig. 3 and Table I give the linear thermal expansivity, α. This was obtained by fitting to the measurements the function

$$\Delta L/L = b/[\exp(t/T) - 1] \tag{3}$$

Here b and t are adjustable parameters. Elsewhere, Ledbetter [3] describes that t is approximately the Einstein characteristic temperature and that b relates to fundamental physical properties. Consistent with Eq. (1), the linear thermal expansivity is

$$\alpha = \frac{bt \exp(t/T)}{T^2[\exp(t/T) - 1]^2} \tag{4}$$

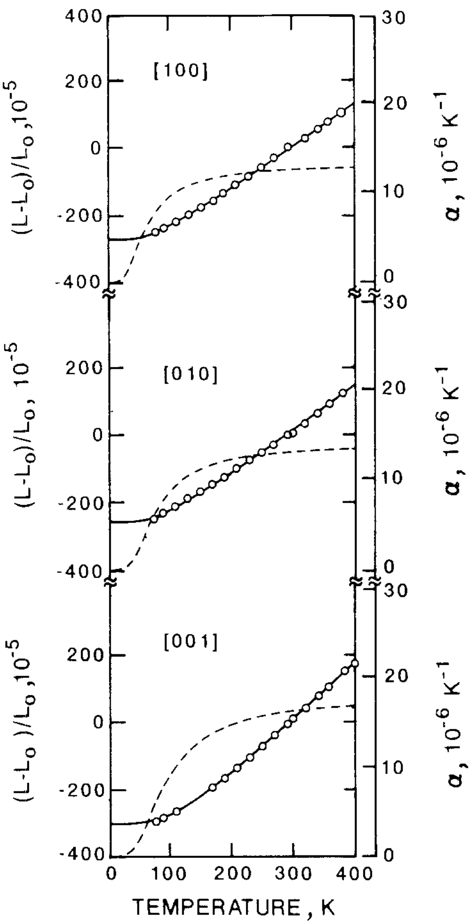

Fig. 3. Length change, $\Delta L/L$, and linear thermal expansivity, α, for the SiC–Al composites. Rolling direction = [100], transverse direction = [010], perpendicular to rolling plane = [001]. Curves represent Eqs. (3) and (4). Solid curve represents $\Delta L/L$; dashed curve represents α.

Table I. Ambient-Temperature Observed and Predicted Thermal Expansivities in Units of $10^{-6}\,K^{-1}$

Observed		Predicted: isotropic	
x_1	12.5	Rule of mixture	16.7
x_2	13.1	Levin model	15.3
x_3	16.2	Rosen–Hashin upper	15.7
Avg.	13.9	Rosen–Hashin lower	13.5
		Rosen–Hashin avg.	14.6
		Predicted: anisotropic	
		Rosen–Hashin: $x_1 = x_2$	14.2
		Rosen–Hashin: x_3	18.3

4. DISCUSSION

We compare the observations in Table I with predictions of simple existing theory. First, we consider a rule of mixture:

$$\bar{\alpha} = c_p \alpha_p + c_m \alpha_m \tag{5}$$

Here $\bar{\alpha}$ denotes effective macroscopic thermal expansivity, c volume concentration, p particle, and m matrix. Because α_p and α_m differ considerably, we expect Eq. (5) to give only a rough prediction, which serves, nevertheless, as a useful guideline. From Touloukian et al. [4], $\alpha_p = 3.3 \times 10^{-6}\,K^{-1}$. As shown in Table I, the rule-of-mixture prediction agrees within 20% with the observed α_1–α_2–α_3 average. This prediction differs 31% from α_1 and 3% from α_3.

In 1967, Levin [5] gave, for the case where both the composite and its constituents are isotropic, an explicit expression for the thermal expansivity:

$$\alpha = \bar{\alpha} + \frac{\alpha_m - \alpha_p}{\dfrac{1}{B_m} - \dfrac{1}{B_p}} \left[\frac{1}{B} - \overline{\left(\frac{1}{B} \right)} \right] \tag{6}$$

Here B denotes bulk modulus and

$$\overline{\left(\frac{1}{B} \right)} = \frac{c_m}{B_m} + \frac{c_p}{B_p} \tag{7}$$

Here nonsubscripted variables denote the macroscopic composite.

Levin's relationship contains the necessary elastic constants that must enter the problem because strain couples not only to the temperature gradient but also to stress through Hooke's law. Ledbetter and Datta [6] recently reported that $B_m = 74.9$ GPa and $B = 97.9$ GPa for this composite. From Schreiber and Soga [7], $B_p = 233.4$ GPa. Thus, as shown in Table I, Levin's model differs only 10% from the observed α_1–α_2–α_3 average. But it fails to account for anisotropy.

For the case where the composite is isotropic, but its constituents are anisotropic, Rosen and Hashin [8] gave "best possible" bounds:

$$\bar{\alpha} + y \geqslant \alpha \geqslant \bar{\alpha} + x \tag{8}$$

Here

$$x = \frac{4G_p(B_p - B_m)(\alpha_p - \alpha_m)\, c_p c_m}{3B_p B_m + 4G_p \bar{B}} \tag{9}$$

and

$$y = \frac{4G_m(B_p - B_m)(\alpha_p - \alpha_m)\, c_p c_m}{3B_p B_m + 4G_m \bar{B}} \tag{10}$$

where

$$\bar{B} = c_p B_p + c_m B_m \tag{11}$$

Table I shows that the arithmetic average of these bounds agrees within 5% with the observed α_1–α_2–α_3 average. But all three α_i lie outside the Rosen–Hashin bounds.

The 27% anisotropy coupled with the Rosen–Hashin bounds violation suggests that this composite is nonhomogeneous. The microstructure shown in Fig. 1 verifies this. Effectively, aluminum-alloy islands, which can be represented as aligned oblate spheroids, lie in the x_1–x_2 rolling plane. Surrounding these islands, one finds a sea of SiC/Al highly enriched in SiC. Ledbetter and Datta [6] showed that this type of nonhomogeneity explains the peculiar elastic constants of this composite. Qualitatively, we see that such a model predicts $\alpha_3 > \alpha_1$ because the restraining effect of SiC is higher along x_1 and x_2 than along x_3.

For transversely isotropic media, Rosen and Hashin [8] gave relationships that account for thermal-expansion anisotropy by introducing anisotropic elastic constants:

$$\alpha_1 = \alpha_2 = \bar{\alpha} + \frac{\alpha_m - \alpha_p}{\dfrac{1}{B_m} - \dfrac{1}{B_p}} \left[\frac{3(1 - 2\nu_{32})}{E_{33}} - \overline{\left(\frac{1}{B}\right)} \right] \tag{12}$$

And

$$\alpha_3 = \bar{\alpha} + \frac{\alpha_m - \alpha_p}{\frac{1}{B_m} - \frac{1}{B_p}} \left[\frac{3}{2K_{12}} - \frac{3\nu_{32}(1-2\nu_{32})}{E_{33}} - \overline{\left(\frac{1}{B}\right)} \right] \qquad (13)$$

In these relationships, $\nu_{32} = 0.282$ denotes the Poisson ratio $-S_{32}/S_{33}$; $E_{33} = 1.108 \times 10^{11}\ \mathrm{N \cdot m^{-2}}$ denotes the axial Young modulus; and $K_{12} = C_{11} - C_{66} = 1.168 \times 10^{11}\ \mathrm{N \cdot m^{-2}}$ denotes the plane–strain bulk modulus for the transverse-isotropic plane. All of these elastic-constant values are from Ledbetter and Datta [6]. Results in Table I show that the Rosen–Hashin equations account reasonably well for the thermal-expansion anisotropy: too high by 13% along x_3, too high by 11% along x_1 and x_2, and too low by 4% for the α_3/α_1 anisotropy ratio. Thus, the anisotropic elastic con-

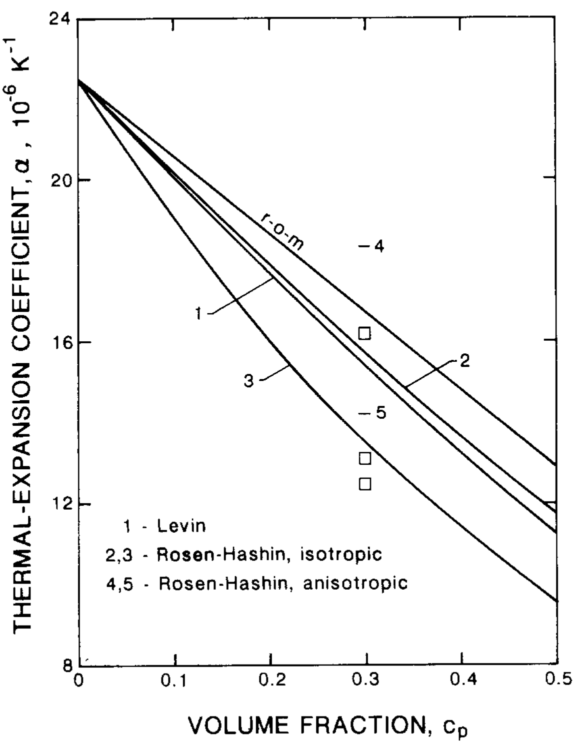

Fig. 4. For the SiC/Al case, theoretical predictions of composite thermal expansion. Open squares represent measurements. Two small bars indicate predictions of Eq. (8). r-o-m, rule of mixture.

stants explain the anisotropic thermal expansivity. Figure 4 shows our measurements together with calculations for various models for $c_p = 0$–0.5.

Finally, we remark that one expects a rough inverse relationship between α_i and E_i, the principal Young's moduli. From Ref. 6, we find that $E_1 = 125.2$, $E_2 = 124.4$, and $E_3 = 110.8$ GPa. For the three directions one finds a one-sigma spread of 7% in the $E_i \alpha_i$ product, compared with 14% in α_i and 7% in E_i. Thus, the rough inverse relationship is confirmed.

5. CONCLUSIONS

1. A powder-metallurgy wrought-plate SiC/Al particle-reinforced composite exhibits anisotropic thermal expansion: α_3 (perpendicular to plate) exceeds $\alpha_1 \simeq \alpha_2$ (plane of plate) by 26%.

2. A rule-of-mixture prediction exceeds by 20% the observed α_1–α_2–α_3 average.

3. Isotropic models predict values within 10% of the observed α_1–α_2–α_3 average.

4. The Rosen–Hashin equations explain the strong anisotropy that results from microstructural nonhomogeneity arising from processing. The explanation involves introducing the anisotropic elastic constants. Apparently no orthotropic-symmetry composite-material model now exists to explain the difference between α_1 and α_2.

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