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Temperature-dependent Young's modulus of an SiC_w/Al_2O_3 composite

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Using a computer-controlled resonant-bar apparatus at frequencies near 5 kHz, we determined the temperature-dependent (86–732 K) Young's modulus of a ceramic–ceramic composite with a 0.30 volume fraction of SiC whiskers in an Al_2O_3 matrix. Using a megahertz-frequency pulse-echo method, it was verified that the composite shows little anisotropy (variation of the elastic properties with direction). Using a scattered-plane-wave ensemble-average method, we modelled the ambient-temperature elastic constants and found good model–observation agreement. To model the behaviour of the Young's modulus with temperature, Varshni's three-parameter relationship for Einstein-oscillator monocrystals was used. Again, good model–observation agreement was found. The mechanical-loss spectrum showed no remarkable features, indicating good whisker–matrix interface properties up to 732 K.

1. Introduction
For composite materials, elastic constants provide fundamental material characterization, they enter prominently into various solid-mechanics models, and they relate many engineering properties, such as the load–deflection, the thermoelastic stress, the internal strain (residual stress), and the fracture toughness.

The present study focused on a ceramic–ceramic composite, with SiC whiskers oriented randomly in an Al_2O_3 matrix. Using a megahertz-frequency pulse-echo method, the complete ambient-temperature elastic constants were determined, including the directional dependence. Using a kilohertz-frequency resonant-bar apparatus, the 86–732 K temperature dependence of the Young's (or extension) modulus was determined.

2. Materials
From a commercial source, composite materials were obtained having been processed into plates as described by Homeny *et al.* [1]. The whiskers were α-SiC monocrystals with an average diameter of 0.6 μm and an aspect ratio ranging from 17 to 133. α-SiC possesses a hexagonal crystal structure and thus it has five independent elastic constants, which remain unknown. Elastic constants of cubic β-SiC show only a small to moderate anisotropy [2]; thus it can be assumed that α-SiC also shows only a small to moderate elastic anisotropy, and the numbers given below confirm this. The Al_2O_3 powder showed a 0.3–0.5 μm grain size. Fig. 1 shows the microstructure.

The intended composition was 25 mass % or 29.3 vol %. From measured mass densities, the volume fraction of c was calculated as 0.308. From quantitative optical microscopy, a value of $c = 0.286$ was obtained. For the present purposes, $c = 0.30$ taken as the correct value. Table I shows the measured mass density. Because it agreed within 0.5% with the theoretical values, the possible effects of voids were ignored.

3. Measurements
3.1. Megahertz-frequency pulse-echo-superposition
For brevity, only the following values from [3] are given: quartz transducers (x-cut and ac-cut), frequencies near 5 MHz, specimen thickness 5 mm. Fig. 2 shows a pulse-echo pattern.

3.2. Resonant-bar apparatus
The free–free-mode resonant flexural eigenvibrations were excited in a rectangular-cross-section bar (5 mm by 1 mm by 5 cm) using an apparatus described by Weller and Török [4]. These eigenvibrations are determined entirely by the specimen's mass density, geometry and elastic constants. From Bernoulli–Euler and Timoshenko beam theory, the Young's modulus is

$$E = 0.9642\rho(l/h)^4 f^2 F \qquad (1)$$

where ρ denotes the mass density, l is the length, h is

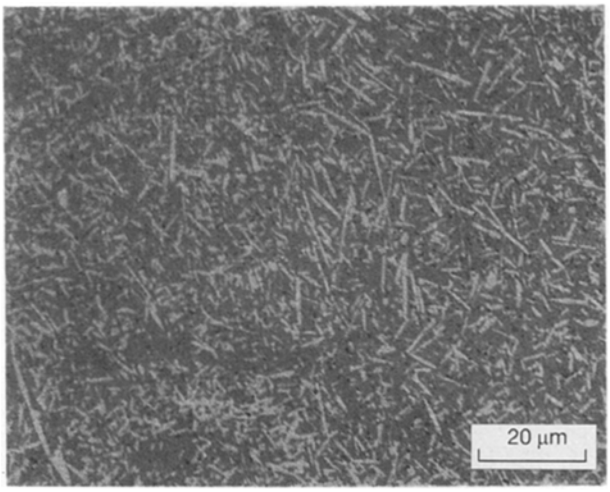

Figure 1 The microstructure of the SiC_w/Al_2O_3 composite. The fibres appear as lighter randomly oriented needles with a nearly homogeneous distribution.

TABLE I Elastic constants of the composite and its constituents

	Al_2O_3 [a]	SiC [b]	SiC/Al_2O_3	
			Measured	Calculated
ρ ($g cm^{-3}$)	3.986	3.181	3.730	3.745
G (GPa)	163.2	178.6	166.9	167.7
E (GPa)	403.3	417.8	407.6	408.1
B (GPa)	254.4	210.7	243.5	240.4
ν	0.236	0.170	0.221	0.217

[a] From [7].
[b] From [8]; modified to α-SiC(4H) by the method in [9].

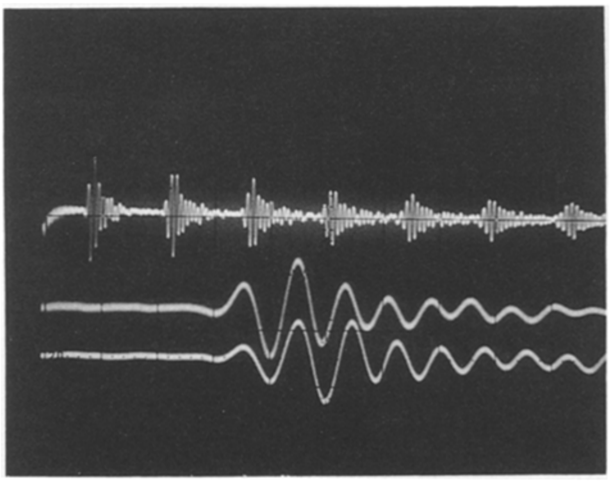

Figure 2 A pulse-echo-pattern oscilloscope display for the composite for a longitudinal wave at 10 MHz in the x_1 direction. The transit time, measured between the leading cycle of the first two echoes, is shown expanded at the bottom of the figure.

the thickness, f is the fundamental-mode eigenfrequency, and F is a correction factor that depends on the specimen shape and on the Poisson ratio. For our specimens, $F = 1.0026$.

4. Results

Table I shows the ambient-temperature-measurement results together with values for both constituents. The results in Table II show that these materials exhibit a near elastic isotropy for the variations of the sound velocity with direction. The coordinate system used had x_1 perpendicular to the plate, x_2 was an arbitrary direction in the plate, and x_3 was the third orthogonal direction. To check the composite-material elastic constants, the Young's modulus E, was measured by a kilohertz-frequency composite-oscillator resonance method [5]; it was found that $E = 408.2$ GPa, within one part in one thousand of the megahertz-frequency pulse-echo measurement.

Fig. 3 shows the temperature variation of f^2 and E. The $E(T)$ curve was normalized by requiring it to pass through 408 GPa at 300 K.

5. Discussion

5.1. Ambient-temperature modelling

To model the composite's elastic constants, a scattered-wave ensemble-average method given by Ledbetter and Datta [6] was used. That study considered SiC particles (prolate spheroids, $c/a \simeq 3.0$) in an aluminium matrix. However, the method is quite general, and it applies to any spheroidal ellipsoid in any matrix. Such ellipsoids include whiskers and fibres. Because

TABLE II The directional variation of the sound velocities

v_{ijkl}	Velocity ($cm\ \mu s^{-1}$)
v_{1111}	1.118
v_{2222}	1.118
v_{1212}	0.669
v_{2121}	0.667
v_{1313}	0.668
v_{2323}	0.672

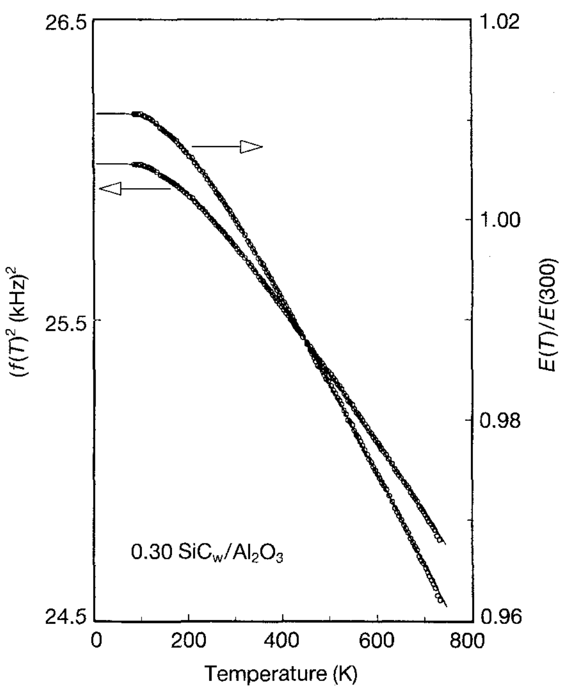

Figure 3 The temperature variation of the squared eigenfrequency and the Young's modulus. The curve represents the Varshni relationship of Equation 2. E is normalized to its value at $T = 300$ K.

the details have been given elsewhere [5] only a minimum statement is given here.

The analysis considers multiple scattering of plane waves from inclusions. Deriving the relationship for the total scattered field involves a three-step determination of three quantities:

1. the field scattered from a single inclusion;
2. the exciting field acting on a single inclusion, i (the sum of the incident field and the field arising from N scatterers); and
3. the total field arising from all of the possible i–j interactions.

As input for the calculations, a Voigt–Reuss–Hill average was used for the monocrystal Al_2O_3 elastic constants reported by Gieske and Barsch [7].

For α-SiC, the Voigt–Reuss–Hill average of the monocrystal C_{ij} reported by Arlt and Schodder [8] was used. They reported the results for α-SiC (6H), which we converted to the α-SiC (4H) case using a method described by Lyubimskii [9]. The known elastic constants of α-SiC (6H) give fair, but slightly high, predictions. Converting these to α-SiC (4H) values improves the measurement–modelling agreement. For the modelling, we chose an effective whisker aspect ratio of $c/a = 75$. The results vary only slightly with this ratio.

5.2. Temperature dependence

To model the $E(T)$ behaviour, we used the following three-parameter relationship derived by Varshni [10] for monocrystalline solids

$$E(T) = E_0 - \frac{s}{\exp(t/T) - 1} \qquad (2)$$

Here, E denotes the zero-temperature Young's modulus, s is an adjustable parameter which is physically related to the zero-point vibrations, and t is an adjustable parameter related to the effective Einstein temperature. For the $f^2(T)$ curve, we obtained the fitting parameters $f_0^2 = 26.02\ \text{kHz}^2$, $s = 1.2747$ and $t = 518.1$ K. The last parameter implies a Debye temperature of $(4/3)518 = 691$ K. For the constituent materials, the reported [11, 12] Debye temperatures are 1035 and 1116 K for Al_2O_3 and α-SiC. Thus, the $SiC–Al_2O_3$ composite shows a surprisingly soft temperature behaviour. Whether this softness reflects interphase boundaries remains uncertain.

6. Conclusions

From this study, we reached six conclusions.

1. The $0.30SiC_w/Al_2O_3$ composite shows practically isotropic elastic constants. This indicates a random whisker-orientation distribution.
2. The modelling–measurement agreement is excellent, to within about 1%. The model used a scattered-plane-wave ensemble average.
3. The essentially identical kilohertz-frequency and megahertz-frequency Young's moduli suggest that there is no appreciable dispersion.
4. Varshni's three-parameter relationship, developed for monocrystals, fits the $E(T)$ behaviour very well.
5. The low Debye temperature inferred from $E(T)$ suggests a softening that could reflect the interphase-boundary contribution to the elastic constant.
6. At kilohertz frequencies, between 86 and 732 K, the composite shows no remarkable feature in its mechanical-loss spectrum. Thus, this property does not provide a chance to study the interphase-boundary behaviour.

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