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Brief Notes

Aluminum Matrix Composite Elasticity Measured Ultrasonically

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Introduction

Many studies [1–3] have been made in the past decade to ultrasonically evaluate the elastic moduli of fiber-reinforced composites, in particular the organic matrix systems. The recent emergence of aluminum matrix composites, with greater specific strength and stiffness over a wider temperature range, has also led to ultrasonic evaluations [4–5] of their properties. We report here ultrasonic results obtained on two such composites with unidirectional fiber reinforcement: Graphite/Al (G/Al) and SiC/Al. Comparisons with theory and available mechanical property data are also made.

Experimental

Samples. Both composite systems possessed a nominal 30 volume percent unidirectional fiber-reinforcement in an aluminum matrix. The G/Al was continuous-fiber-reinforced plate 2.6mm thick, with a density of 2.44 gm/cm^3 for a 30 volume percent fiber content. The plate was fabricated [6] by diffusion bonding 1.2 mm dia precursor composite wires, previously formed by liquid metal (201 Al) infiltration of highly anisotropic Thornel 50 fiber tows.

The SiC/Al samples were taken from discontinuous-fiber-reinforced extruded rod (2024 Al matrix) 10 mm dia [7], with a density of 2.90 gm/cm^3 for a 32 volume percent fiber content. The SiC fibers were principally particulate of micrometer dimensions, with a small percentage of whiskers having an aspect ratio on the order of 30. The extrusion direction was taken to be the axis of symmetry for transverse isotropy.

Ultrasonic Technique. Ultrasonic velocity measurements of both longitudinal and shear waves were made in three principal directions in the composite samples: parallel, perpendicular, and 45° to the fiber direction. Two techniques for ultrasonic velocity measurements were used: pulse echo with a transducer—delay rod—sample arrangement, and through transmission with a second transducer attached to the previous arrangement. The through transmission technique was used on a second G/Al sample set to corroborate the pulse echo results for which a second echo was sometimes difficult to observe. The pulse echo technique utilized a sharp spike voltage excitation of the transducer to produce broadband ultrasonic pulses of about 0.5 microsec duration and a nominal center frequency of 5 MHz. Time-of-flight velocity measurements were made by pulse-echo-overlap with an oscilloscope internal time delay and digital readout. The through transmission technique utilized a tone burst excitation to produce a relatively narrowband signal at 5 MHz. With this technique, the time-of-flight measurements were made by noting the shift in time of the received signal upon sample removal. The estimated precision of the pulse echo and through transmission velocities were 1 and 1.5 percent, respectively.

Table 1 Ultrasonic wave speeds (in mm/μs) for Graphite/Al and SiC/Al

Wave Mode	G/Al^a	G/Al^b	SiC/Al^a
Longitudinal: $\mathbf{k} \parallel 3$	8.64	8.33	7.67
Longitudinal: $\mathbf{k} \perp 3$	4.04	3.89	7.37
Shear: $\mathbf{k} \parallel 3, \epsilon \perp 3$	2.78	2.84	3.92
Shear: $\mathbf{k} \perp 3, \epsilon \parallel 3$	2.78	3.01	3.96
Shear: $\mathbf{k} \perp 3, \epsilon \perp 3$	2.07	2.09	3.85
Quasi-long: $\sphericalangle(\mathbf{k}, 3) = 45°$	6.17	6.27	7.46
Quasi-shear: $\sphericalangle(\mathbf{k}, 3) = 45°$ ϵ in plane $(\mathbf{k}, 3)$	3.07	2.78	4.10
Shear: $\sphericalangle(\mathbf{k}, 3) = 45°$ $\epsilon \perp$ plane $(\mathbf{k}, 3)$	2.45	2.30	3.92

^{a} Pulse echo.
^{b} Through transmission.

By means of the stress-strain constitutive relationships for orthotropic media with transverse isotropy, the elastic coefficients C_{ij} were calculated from the material density and wave velocities [8]. The elastic engineering parameters: Young's and shear moduli, and Poisson's ratio, were in turn calculated from the C_{ij} [5].

Results and Analysis

Table 1 lists velocities obtained on the three sets of composite samples for wave modes of propagation direction $\mathbf{k}$ and polarization ϵ. Table 2 compares the elastic moduli calculated from these velocities with their respective model predictions and available mechanical property data [9]. Tensile specimens of SiC/Al yielded values of 100

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Table 2 A comparison of composite moduli (in GPa) obtained ultrasonically with mechanical measurements and model predictions

	Graphite/Al				SiC/Al	
Modulus	Ultrasonic[a]	Ultrasonic[b]	Model	Mechanical	Ultrasonic[a]	Model
E_{33}	160.	161.	166.	135–165	131.	124.
E_{11}	29.8	29.9	31.7	32	116.	117.
G_{13}	18.9	19.7	18.5	17	45.1	45.5
G_{12}	10.5	10.6	10.6	—	42.9	40.7
ν_{13}	0.44	0.28	0.34	—	0.29	0.30

[a] Pulse echo.
[b] Through transmission.

to 130 GPa for E_{33} [10]. The second subscript is the stress direction, making E_{33} and G_{13} the axial or longitudinal moduli, and E_{11} and G_{12} the transverse moduli. A judicious choice of velocities based on sample path length, waveform clarity, and a minimization of error propagation in the C_{ij} derivation allowed for the calculation of the respective sets of G/Al moduli.

Two distinct mathematical models were used to predict the moduli based on material constituent properties. The composite cylinder assemblage model by Hashin [11] was applied to G/Al for its particular relevance to that composite's peculiar transverse properties: a matrix stiffer than the fiber in the transverse direction. An interpolated self-consistent model for short-fiber composites by Halpin and Tsai [12] was applied to SiC/Al.

Discussion

A comparison of the velocities in Table 1 for the two G/Al sample sets shows agreement for a majority of the data. The larger differences could be attributed to sample differences and the effect of geometric dispersion between the two ultrasonic techniques. The ultrasonic moduli calculated from these velocities are in good agreement with both theory and mechanical property data. The agreement between experiment and theory is especially significant for its corroboration of the composite cylinder assemblage model recently elaborated on for the special case of G/Al [11]. However, Poisson's ratio, which is highly dependent on the measurement sensitive C_{13} coefficient, could not be reliably evaluated by the ultrasonic method.

Good agreement is also observed between the ultrasonic results and the semiempirical model [12] applied to SiC/Al. While full alignment of the whiskers in the extrusion direction was assumed in the model calculations, the material's high degree of elastic isotropy confirms the SiC reinforcement to be largely particulate as noted earlier.

Conclusions

The ultrasonically measured elastic moduli of continuous-fiber G/Al and discontinuous-fiber SiC/Al composites are in good agreement with mechanical property data and selected theoretical models. In particular, the data for G/Al corroborates the composite cylinder assemblage model effective for the unusual transverse boundary condition between the aluminum matrix and graphite fibers.

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Acoustoelastic Effect of Thickness Oscillations

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Application of stress to the solid material causes a slight change in the propagation velocities of elastic waves, which has been called acoustoelastic effect in general. Acoustoelasticity has been hoped to provide a new tool for the nondestructive stress measurement. For the thickness oscillations in plate, it was theoretically revealed [1] that the effect appears as (*i*) slight change in the resonance frequency and (*ii*) slow amplitude modulation of transverse (thickness-shear) mode unless polarized in the principal directions of stress. This Note offers some experimental results about the first result. Comparison with the sing-around method by the ultrasonic bulk waves will be presented about the third-order elastic constants obtained experimentally. Although the second result seems to be worth studying from the practical viewpoint, the corresponding experiment has not been available so far.

Change in Resonance Frequency

The acoustoelastic measurement of the thickness oscillations can be made by using oscillator with continuously variable frequency, frequency counter, oscilloscope, and testing machine as shown in Fig. 1. Monochromatic steady oscillation was sent out from the oscillator. One of the two PZT plates attached face to face on the specimen sides converted it into the thickness oscillation in plate. The other PZT plate transformed thus generated oscillation back into the electronic oscillation which was monitored by the oscilloscope. The pair of the PZT plates were of the same center frequency. It was nominally 10 MHz for longitudinal (L) mode and 5 MHz for transverse (T) mode.

When the frequency was scanned by the oscillator tuner, the amplitude of the thickness oscillation showed a series of distinct peaks with almost regular intervals. The frequency difference of two successive peaks equals the resonance frequency of the fundamental mode. With this value, the order of the overtones was experimentally determined.

Data were taken about the change in the resonance frequency as

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