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IEEE TRANSACTIONS ON ULTRASONICS, FERROELECTRICS, AND FREQUENCY CONTROL, VOL. 48, NO. 1, JANUARY 2001

High Frequency Properties of Passive Materials for Ultrasonic Transducers

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Abstract—**The acoustic properties of passive materials for ultrasonic transducers have been measured at room temperature in the frequency range from 25 to 65 MHz using ultrasonic spectroscopy. These materials include alumina/EPO-TEK 301 composites and tungsten/EPO-TEK 301 composites. Experimental results showed that the acoustic impedance of the composites monotonically increased with the volume fraction of the particle filler, which is in agreement with the Denavey model. The attenuation, however, peaked between 7 and 9% volume fraction of particle filler. For comparison, several other passive materials were also fabricated and measured. The results suggest that materials that possess a higher attenuation also appear to have a larger velocity dispersion.**

I. INTRODUCTION

A FACTOR limiting the performance of ultrasonic transducers is the large acoustic impedance mismatch between the piezoelectric element and the load (tissue). As a result, the acoustic pulse transmitted into the tissue displays a long ringdown that degrades the axial resolution. One method commonly used to dampen the ringdown is to attach a lossy backing material. This procedure results in a shorter pulse and reduced sensitivity. A better approach is to incorporate an optimal front matching layer, which can reduce the pulse length without sacrificing the sensitivity. Two or three matching layers can be used for such a purpose with various combinations of acoustic impedance and thickness [1]–[3]. Often a lens is incorporated in front of the matching layer(s) to collimate the ultrasound beam over a specified distance. Typically, the acoustic impedance of the lens material is similar to that of the tissue. The overall performance of a transducer depends critically on these passive materials, i.e., matching, backing, and lens materials.

Ultrasonic transducers operating at frequencies greater than 20 MHz can provide higher resolution in both the axial and lateral directions, resulting in improved diagnosis of many diseases and new medical applications [4]. Currently, the design and fabrication of high frequency transducers operating between 30 and 100 MHz remains an engineering challenge [5]. Knowledge of the high frequency properties of active and passive transducer materials is crucial at the design stage. Numerous papers were published on the characterization of active materials [6], [7]; unfortunately, experimental data on the acoustic properties of passive materials at high frequencies are scarce. This paper reports a set of such data for a number of matching, backing, and lens materials measured using an ultrasonic spectroscopic technique. Both acoustic impedance and attenuation were measured in the frequency range from 25 to 65 MHz.

II. MATERIALS AND METHODS

Ultrasonic spectroscopy has been extensively used in the characterization of solid materials [8]–[10]. By adjusting the angle of incidence, the mode conversion effect allows for the measurement of both longitudinal and shear wave properties [10]. The experimental arrangement used in this case is shown in Fig. 1. A pair of transducers with a center frequency of 50 MHz, a bandwidth of 80%, and an element diameter of 0.63 cm were used. Because the ultrasonic attenuation in water is about 6 dB/cm at 50 MHz and increases with frequency, the high frequency components of the acoustic signal decrease in amplitude as the separation distance between the transmitter and receiver increases. Therefore, the distance between the transmitter and receiver should be made as small as possible and, at the same time, allow sufficient room for the sample to rotate. In our experiments, the distance L in Fig. 1 is set to 3 cm.

A Panametrics 200-MHz computer-controlled pulser/receiver was used to generate a pulse with an energy of 1 μJ and a damping value of 50 Ω. The output waveform from the receiving transducer was sampled by a digital oscilloscope (Tektronix TDS 460A) through a 50-Ω coax cable with a length of 1 m. The sampling rate was 10 Gs/s. The total sample length for each waveform was 2500 points, and each waveform was transferred to a computer via a GPIB interface. To reduce random errors, each signal was averaged 64 times. The amplitude A_w and the phase spectra φ_w of water were calculated using the FFT from the output with the sample absent. With the sample in place, the trigger delay time was adjusted to compensate for the additional delay resulting from the sample path length. The amplitude A and the phase φ of the output signal with the sample in place were then obtained. The phase

Manuscript received July 23, 1999; accepted May 9, 2000. Financial support was provided through NIH under the Grant #P41RR11795-01A1 and ONR under Grant #N00014-96-1-1173.

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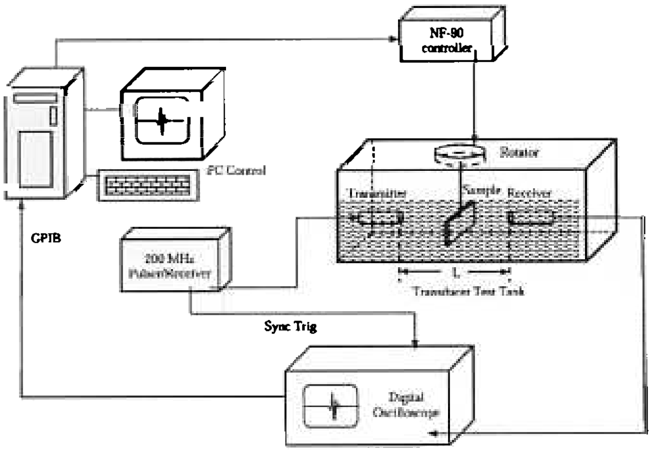

Fig. 1. Experimental arrangement.

velocity C_L and attenuation α_L of the longitudinal wave were calculated using the following relationship [10]:

$$C_L = \frac{C_w}{1+\frac{(\varphi-\varphi_w+2\pi f\tau)C_w}{2\pi f d}} \qquad (1)$$

$$\alpha_L = \alpha_w + \ln\left(\frac{T_L A_w}{A}\right)/d \,. \qquad (2)$$

Here, the attenuation of water, α_w is $0.000271{*}f^2$ (dB/mm*MHz^2) (f in MHz); C_w is the velocity of water (1480 m/s) [10]; f is frequency; τ is the trigger delay time; and d is the thickness of the sample. T_L represents the total transmission coefficient for the longitudinal wave, which is equal to the product of the two transmission coefficients of the acoustic wave from the water to the sample and from the sample to the water. When the wave is incident at an angle other than 0°, a shear wave is generated by the mode conversion effect. With the incident angle at the critical angle of the longitudinal wave, the phase velocity C_S and attenuation α_S of the shear wave were calculated using (3) and (4), respectively [10]:

$$C_S = \frac{C_w}{\sqrt{\sin^2\theta_i + \left[\frac{(\varphi-\varphi_w+2\pi f\tau)C_w}{2\pi f d}+\cos\theta_i\right]^2}} \qquad (3)$$

$$\alpha_S = \alpha_w\cos(\theta-\theta_i) + \left(\ln\frac{T_S A_w}{A}\right)\cos\theta/d \qquad (4)$$

where θ_i is the incident angle, θ is the refractive angle of shear wave, and T_S is the total transmission coefficient of the shear wave. In our experiment, θ_i was controlled by a computerized UNISLIDE rotary table (Velmex, Inc., Bloomfield, NY), and θ was calculated from Snell's law.

Optimized matching layers must have low attenuation and a well-characterized impedance. 0-3 composites of alumina (Al_2O_3) (Buehler Ltd., Lake Bluff, IL) in an epoxy matrix of EPO-TEK 301 (Epoxy Technology, Inc., Billerica, MA) meet this requirement. EPO-TEK 301 was chosen for its low viscosity, low attenuation, and long pot life. Alumina powder with a 3-μm particle size was selected to minimize the attenuation and provide a reasonable level of loading. EPO-TEK 301 was characterized first, and then increasing volume fractions of alumina particles were added to obtain impedances above 3.0 Mrayls. The desired amount of alumina was hand mixed with EPO-TEK 301 in a 40-mm diameter sample holder. The mixture was degassed in a vacuum chamber at less than 10 mtorr. The mixture was then cast between two mold released glass plates spaced 0.5 mm apart, cured at room temperature overnight, and post cured for another hour at 65°C in the oven. The specimens were then 0.5-mm thick, 25-mm in diameter, and the major surfaces were flat and parallel with a thickness variation of less than 1%. The volume fraction of alumina (V) was determined by the relationship $V = (M/\rho)/(M/\rho + M'/\rho')$, where M and M′ are the mass of alumina and EPO-TEK 301, and ρ and ρ' are the density of alumina and EPO-TEK 301, respectively. For these experiments, the volume fraction of alumina varied between 1.5 and 30%. For each volume fraction of alumina, five specimens were made to check the consistency of the properties.

Backing materials were fabricated with the acoustic impedance ranging from 2 to 10 Mrayls. For this application, a high attenuation is desired. Tungsten polymer composites are the most commonly used backing materials. Tungsten powder with a particle size less than 5 μm (Alfa Aesar, Ward Hill, MA) was selected. A set of tungsten/EPO-TEK 301 composites was prepared using the same procedure described for the Al_2O_3 powder-epoxy composites. The maximum volume fraction of fine tungsten particles (less than 5 μm) that added to the epoxy was approximately 25%. Again, five specimens were prepared to check the consistency of the properties.

III. Experimental Results

A. Matching Material

Fig. 2 shows the properties of alumina/EPO-TEK 301 composites at 30 MHz. Adding alumina powder to epoxy leads to an increase in density [Fig. 2(a)], ultrasonic velocity [Fig. 2(b)], and acoustic impedance [Fig. 2(c)]. The attenuation, however, exhibits a nonlinear variation [Fig. 2(d)]. An attenuation peak is observed between 7 and 9% volume fraction of alumina. Similar behavior had also been observed experimentally by Grewe in alumina/Spurr epoxy composites [11].

It should be noted that because the polymer was the major constituent by volume (greater than 70 volume percent), all of the composites in this part of the study were assumed to have a 0-3 connectivity, which means that each particle was surrounded by the polymer matrix [11]. Devaney and Levine [12] have proposed a model based on a self-consistent formulation of multiple-scattering theory to describe the elastic properties of such a two-phase composite. With this model, the bulk modulus K and the shear

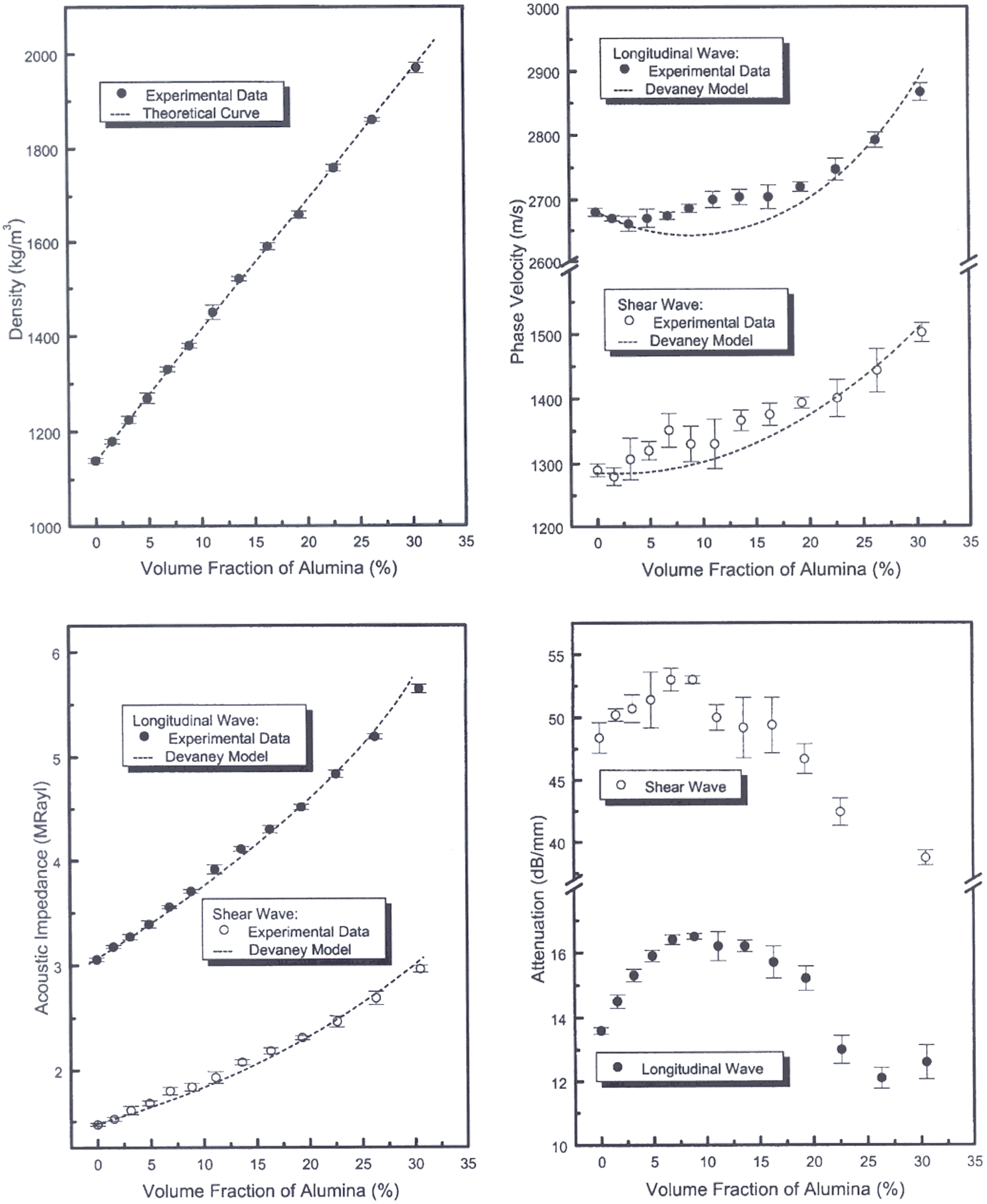

Fig. 2. Variation of the following material properties as a function of the volume fraction of alumina in EPO-TEK 301 (Epoxy Technology, Inc., Bellerica, MA) at 30 MHz: a) density, b) phase velocity, c) acoustic impedance, and d) attenuation. Error bars represent standard deviations.

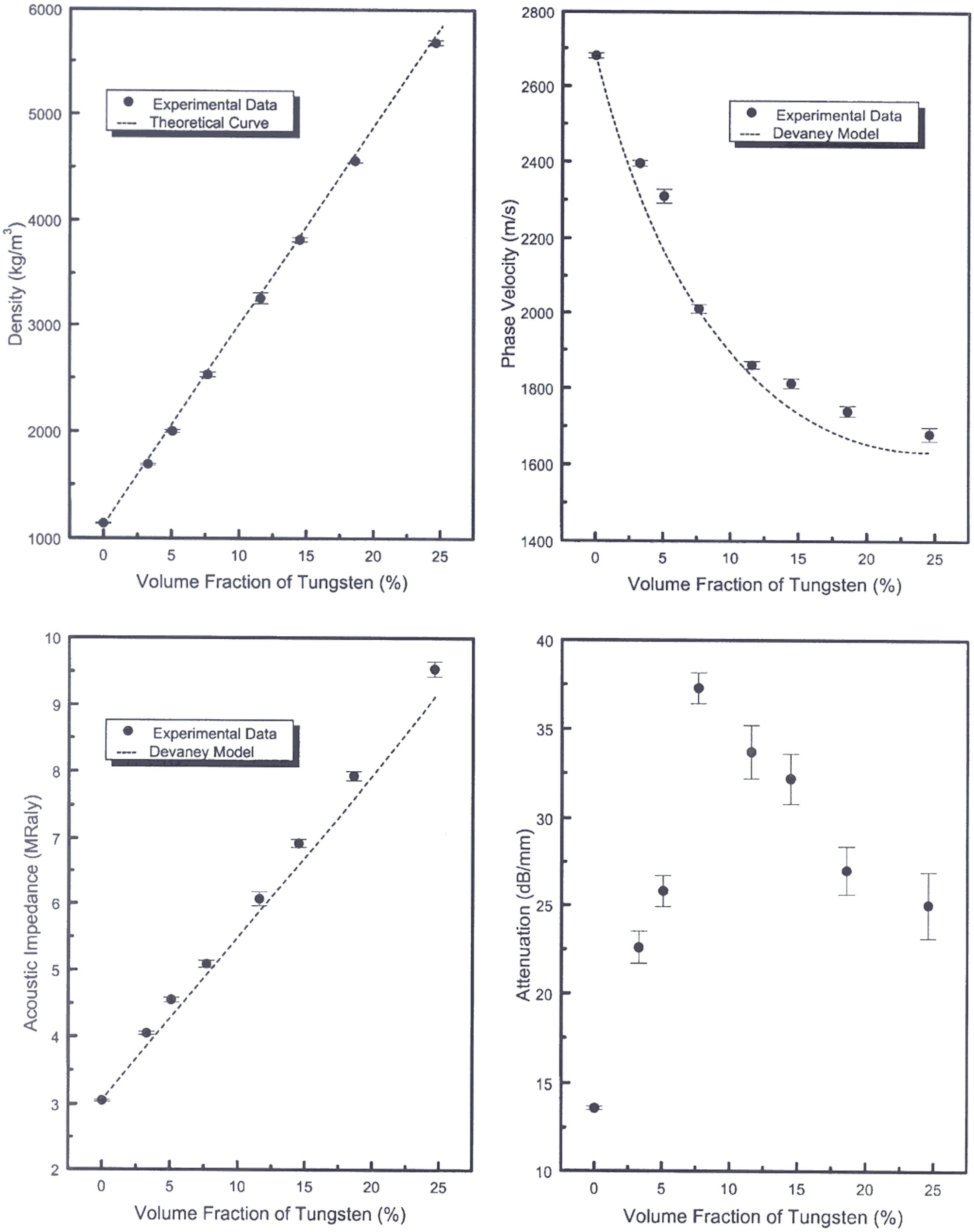

Fig. 3. Variation of the following material properties as a function of the volume fraction of tungsten in EPO-TEK 301 (Epoxy Technology, Inc., Bellerica, MA) at 30 MHz: a) density, b) phase velocity, c) acoustic impedance, and d) attenuation of longitudinal wave. Error bars represent standard deviations.

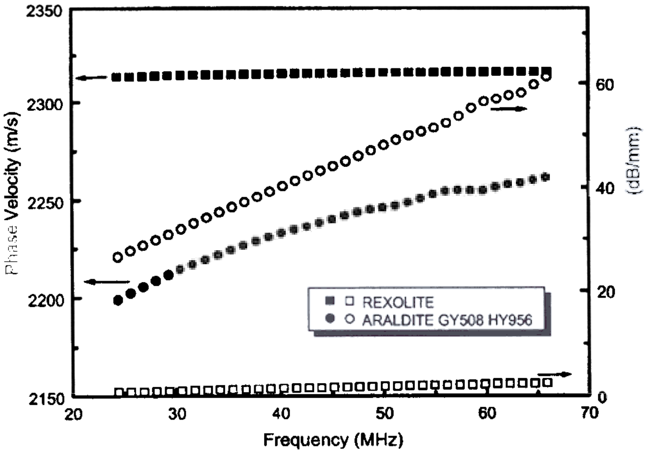

Fig. 4. The frequency dependence of phase velocity and attenuation of longitudinal wave in Rexolite and Araldite (GY508/HY956) (Curbell Plastics, Glenshaw, PA).

modulus G of the composites are given by

$$K = K_1 + V_2 \frac{(3K + 4G)(K_2 - K_1)}{3K + 4G + 3(K_2 - K_1)} \tag{5}$$

$$G = G_1 + V_2 \frac{5(3K + 4G)G(G_2 - G_1)}{(15K + 20G)G + 6(K + 2G)(G_2 - G_1)} \tag{6}$$

where K_1, G_1, K_2, and G_2 are the bulk modules and shear modulus of the matrix and particle, respectively. V_1 and V_2 are the volume fraction of the matrix and particle. The density ρ of a two-phase system is simply the volume-averaged density

$$\rho = V_1\rho_1 + V_2\rho_2 \tag{7}$$

where ρ_1, ρ_2 are the densities of the matrix and filler, respectively.

The longitudinal velocity C_L is related to the mechanical properties of the medium through

$$C_L = \sqrt{\frac{K + \frac{4}{3}G}{\rho}}\,, \tag{8}$$

and the shear velocity is given by

$$C_S = \sqrt{\frac{G}{\rho}}\,. \tag{9}$$

The density, phase velocity, and acoustic impedance of the alumina/EPO-TEK 301 composites were calculated from (5)–(9), and the results are shown in Fig. 2(a)–(c) as dashed lines. Good agreement between the model and experimental results was observed.

Several other matching materials were also investigated, and the measured properties at 30 MHz are summarized in Table I. The materials cover a range of impedance from 2 to 6 Mrayls for applications in single element, array, composite, and monolithic transducers.

B. Backing Material

Fig. 3 shows the variations of four properties as a function of the volume fraction of tungsten in tungsten/EPO-TEK 301 composites. Interesting effects were observed in this tungsten-epoxy composite system. Initially, a fairly sharp fall in ultrasonic velocity occurs with the increase of tungsten content [Fig. 3(b)]. Because the density of the composites increases linearly with the addition of tungsten [Fig. 3(a)], the net result is a monotonic increase in acoustic impedance [Fig. 3(c)]. It is very interesting to see that an attenuation peak also occurred between 7 and 9% volume fraction of tungsten [Fig. 3(d)], similar to the alumina/EPO-TEK 301 composites.

Based on the Denavey model, we have calculated the density, phase velocity, and acoustic impedance for the tungsten-loaded epoxies. The results are shown in Fig. 3(a)–(c) as dashed lines. The agreement between the model and the experimental results is satisfactory.

Table I lists the acoustic properties of several other backing materials measured at 30 MHz, including Ablebond 16-LV and E-Solder 3022. These materials consist of silver particles surrounded by an epoxy matrix. They all demonstrated high attenuation, a requirement for acoustic backings. As would be expected, the acoustic properties of these materials changed after the centrifuging process, which increased the volume fraction of the silver. The centrifuge used was a Beckman Model TJ-6 (Beckman Instruments, Inc., Palo Alto, CA). The material was centrifuged using a centripetal acceleration of 17.5 m/s^2 (corresponding to 3000 rpm at a 7" radius) for 10 min. This step separated the material into two strata; the top layer consisted of an unloaded epoxy. The sample was lapped to thickness by removing unloaded material from the top surface so that the densest portion was used for characterization.

C. Frequency Dependence of Acoustic Properties of Lens Materials

The frequency dependence of the acoustic properties of two potential lens materials was measured in the frequency range from 25 to 65 MHz. In Fig. 4, the phase velocity and attenuation of two representative materials, Rexolite and Araldite (GY508/HY956) (see Table I for manufacturer information) are plotted as a function of frequency. It was found that the attenuation of Rexolite was very low (1.1 dB/mm at 30 MHz), and its velocity dispersion was also very small. On the contrary, the attenuation of the Araldite (GY508/HY956) (35 dB/mm at 30 MHz) was very high, and its velocity also displayed a strong frequency dependence.

IV. Summary and Conclusions

In summary, the acoustic properties of several passive materials for ultrasound transducers were characterized at room temperature in the frequency range of 25 to

TABLE I
ACOUSTIC PROPERTIES OF SOME PASSIVE MATERIALS AT 30 MHz.

		Longitudinal wave			Shear wave		
	Density (*10^3 kg/m^3)	Velocity (*10^3 m/s)	Loss (dB/mm)	Impedance (Mrayls)	Velocity (*10^3 m/s)	Loss (dB/mm)	Impedance (Mrayls)
EPO-TEK 353 ND[1]	1.24				1.23		1.52
EPO-TEK 301-2[1]	1.15				1.23		1.41
2038/3404[2]	1.18				1.26		1.49
*Ablebond16-ILV[3]	2.40						
*Ablebond16-ILV[3] (2800 RPM centrifuge for 15 min)	3.66	1.02	1.0*10^2	3.73			
*E-Solder 3022[4]	2.59	2.11	40	5.46			
*E-Solder 3022[4] (3000 RPM centrifuge for 10 min)	3.20	1.85	1.1*10^2	5.92			
Araldite GY508/HY956[5]	1.11	2.21	35	2.45			
Conap EN-4/EN-7[6]	1.10	1.71	39	1.88			
Castall U-2521, Urethane, Shore D-40[7]	1.08	2.11	32	2.28	–	–	–
TPX[8]	0.822	2.17	5.8	1.78	–	–	–
Rexolite[9]	1.06	2.34	1.1	2.57	–	–	–
Celazole[9]	1.28	3.43	1.8	4.39	1.47	7.2	1.88

[1] Epoxy Technology, Inc., Bellerica, MA.
[2] Insulcast, a division of American Safety Technologies, Inc., Roseland, NJ.
[3] Ablestik, a division of the National Starch and Chemical Company, Rancho Dominguez, CA.
[4] Von Roll Isola USA, Inc., New Haven, CT.
[5] CIBA Specialty Chemicals, Performance Polymers, Inc., Brewster, NY.
[6] Conop, Inc., Olean, NY.
[7] Castall, Inc., East Weymouth, MA.
[8] Matsui Plastics, White Plains, NY.
[9] Curbell Plastics, Glenshaw, PA.
*Electrically conductive.

65 MHz using ultrasonic spectroscopy. The alumina/EPO-TEK 301 and tungsten/EPO-TEK 301 composites were fabricated with different volume fractions of particle loading. Experimental results demonstrated a monotonic increase in the acoustic impedance with increasing particle volume fraction. An attenuation peak was found to occur at approximately 9% volume fraction of particles. Several important passive materials were also fabricated and measured in the frequency from 25 to 65 MHz. The measured results showed that higher attenuation corresponds to greater velocity dispersion. These measured passive material properties can be used to design high frequency ultrasonic transducers.

ACKNOWLEDGMENTS

The authors acknowledge the help of Wenhua Jiang, Bei Jiang, Jianhua Yin, and, especially, Gene Gerber.

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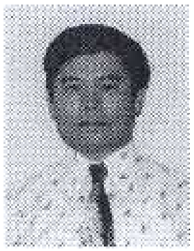

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