DETERMINATION OF THE ACOUSTIC PROPERTIES OF TUNGSTEN/EPOXY AND TUNGSTEN/POLYURETHANE COMPOSITES USING ULTRASONIC TRANSMISSION TECHNIQUE

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Abstract. *In many ultrasonic applications, broadband transducers capable of producing short pulses are required. To increase the bandwidth and, consequently, to reduce the ringing in the transducer, a highly damped backing with an acoustic impedance similar to that of the piezoelectric ceramic material is commonly used. Tungsten particles in epoxy or polyurethane matrices are the most commonly used backing materials. This work presents the measurement of the density, longitudinal velocity, attenuation and acoustic impedance as a function of the volume fraction of Tungsten in Tungsten/Epoxy and Tungsten/Polyurethane composites. The composite samples are fabricated by hand mixing the Tungsten powder with an average particle size of 12 micrometers and the resins. An important step is the choice of a resin with suitable viscosity to avoid Tungsten precipitation during the cure process and to allow an easy mixture of the components. Air bubbles into the sample are removed using a vacuum chamber. The properties are measured using a through-transmission ultrasonic technique at 1 MHz. The experimental results are in good agreement with those provided by the theoretical model for small particles.*

Keywords*: Ultrasonic transducer, acoustic properties, composite.*

1. Introduction

Ultrasonic transducers typically use as active part a piezoelectric material that has a low ultrasonic loss, that is responsible for the relatively long duration acoustic pulse when the electrical impulse is applied. This phenomenon is known as “transducer ringing” and causes degradation of the axial resolution, that is the ability to distinguish between different structures along the axis of the transducer (Grewe *et al*., 1990). To reduce the pulse duration, it is used a backing material having an acoustic impedance closely matched to that of the piezoelectric material to assure a good coupling and a very high attenuation to eliminate back reflections (Bar-Cohen, Stubbs and Hoppe, 1984).

The backings most commonly used consist of an epoxy resin with high ultrasonic absorption filled with Tungsten powder to increase the density and therefore the acoustic impedance (Sayers and Tait, 1984). Moreover, the filler increases the attenuation due to the scattering introduced by the Tungsten particles. The PZT (Lead Zirconate Titanate) that is the most used piezoelectric material has a high acoustic impedance of about 30 MRayls. Then, due to the low phase velocity and density of the epoxy, it is required high Tungsten volume concentrations to match the PZT

impedance, which is subject to physical packing limits. Moreover, high filler concentration makes reproducibility of the backing impedance difficult to obtain (Bar-Cohen, Stubbs and Hoppe, 1984).

In this work Tungsten/Epoxy and Tungsten/polyurethane composites are studied for different volume fractions. The two more important properties of ultrasonic transducer backings are the acoustic impedance and the attenuation. These properties are measured using a method presented by Wu (1996). The experimental results are compared with a analytical model (Sayers and Tait1984) that describes the acoustical properties of the composite.

2. Analytical model

A treatment of the acoustic properties of composites with two phases, *1* and *2*, are presented in the paper of Sayers and Tait (1984). It is assumed that the ultrasonic wavelength is very greater than the size of the particles. If ρ_i is the density, μ_i the shear modulus, v_{li} and v_{ti} the longitudinal and traverse ultrasonic velocities, $k_i=\omega/v_{li}$ and $K_i=\omega/v_{ti}$ the longitudinal and traverse wavenumber of medium *i*, with *i=1, 2,* and ρ, μ, v_l, v_t, $k=\omega/v_l$ and $K=\omega/v_t$ the corresponding quantities for the composite, then, the following equations relate the acoustic properties of the composite to the properties of each phase:

$$\rho=\rho_1(1-\delta)+\rho_2\delta \tag{1}$$

$$\left[3\frac{\mu_1}{\mu}\left(\frac{K_1}{k_1}\right)^2-4\left(\frac{\mu_1}{\mu}-1\right)\right]\left[3\frac{\mu_2}{\mu}\left(\frac{K_2}{k_2}\right)^2-4\left(\frac{\mu_2}{\mu}-1\right)\right]\left[5\delta\left(\frac{\mu_1}{\mu}-\frac{\mu_2}{\mu}\right)-\left(\frac{\mu_1}{\mu}-1\right)\left(2\frac{\mu_2}{\mu}+3\right)\right]$$
$$-4\left(\frac{\mu_1}{\mu}-1\right)\left(\frac{\mu_2}{\mu}-1\right)\left[3\frac{\mu_2}{\mu}\left(\frac{K_1}{k_1}\right)^2-4\left(\frac{\mu_2}{\mu}-1\right)+\delta\left(3\frac{\mu_1}{\mu}\left(\frac{K_1}{k_1}\right)^2-3\frac{\mu_2}{\mu}\left(\frac{K_2}{k_2}\right)^2+4\left(\frac{\mu_1}{\mu}-\frac{\mu_2}{\mu}\right)\right)\right]=0 \tag{2}$$

$$\left(\frac{K}{k}\right)^2=\frac{\frac{1}{3}\left[3\frac{\mu_1}{\mu}\left(\frac{K_1}{k_1}\right)^2-4\left(\frac{\mu_1}{\mu}-1\right)\right]\left[3\frac{\mu_2}{\mu}\left(\frac{K_2}{k_1}\right)^2-4\left(\frac{\mu_2}{\mu}-1\right)\right]}{\left[3\frac{\mu_2}{\mu}\left(\frac{K_2}{k_2}\right)^2-4\left(\frac{\mu_2}{\mu}-1\right)\right]+\delta\left[3\frac{\mu_1}{\mu}\left(\frac{K_1}{k_1}\right)^2-3\frac{\mu_2}{\mu}\left(\frac{K_2}{k_2}\right)^2-4\left(\frac{\mu_1}{\mu}-\frac{\mu_2}{\mu}\right)\right]} \tag{3}$$

where δ is the volume fraction of the material 2 and ω is the angular frequency of the wave. The density ρ can be calculated from Eq. (1), μ and $(K/k)^2$ can be evaluated from Eqs. (2) and (3) and the transverse velocity is related with the shear modulus by:

$$v_t=\sqrt{\frac{\mu}{\rho}} \tag{4}$$

Table 1 shows the material properties used to calculate the composite analytical behavior. Tungsten velocities were extracted from Sayers (1984) and the density from Kino (1987). Epoxy and polyurethane phase velocities were measured using the method explained in section 3, excepting polyurethane transverse velocity that its hard to measure due to the high critical angle for the water-polyurethane interface, in that case was used a transverse velocity equal to half of the longitudinal velocity.

Table 1. Properties of Tungsten, epoxy and polyurethane.

Material	v_l (m/s)	v_s (m/s)	$\rho(kg/m^3)$
Tungsten powder ($12\mu m$) 26751-1 sold by *Aldrich Chemical Company*	5233	2860	19400
Epoxy (*araldite)* sold by *Brascola Ltda* Mixture: 50:50 (weigh) Cure: 24h at room temperature	2196	1041	1087
Polyurethane Ureol 5073-1 and 6414-B sold by *Ciba* Mixture: 100:18 (weigh) Cure: 14h at 40°C	1459	-	1066

3. Experimental procedures

A discrete frequency method (Wang *el al*, 2001) is used to measure the acoustical properties. This method uses a pulse burst with enough time duration so that the central frequency becomes well defined, but enough short to avoid degradation of the axial resolution. The method uses two equal transducers coaxially placed, one as the emitter and the other as the receiver. The resonance frequency of the transducers is equal to the central frequency of interest. A sample of thickness d is placed between the transducers. Comparing the time of flight in the case with sample and without sample, the phase velocity can be determined. This method measures the group velocity in the central frequency, because many materials present low dispersion at frequencies less than 10 MHz. Then, the phase velocity is approximately equal to the group velocity (Wu, 1996). By adjusting the angle of incidence, the mode conversion allows measuring both shear and longitudinal wave properties. The attenuation is determined by comparing the amplitudes of the signals measured in the case with and without sample. The acoustic impedance is obtained by multiplying the density and the phase velocity, the density is calculated by dividing the weight and the volume of the samples. Equation (5) and (6) are used to calculate, respectively, the longitudinal phase velocity and attenuation of the sample:

$$c_l = \frac{c_W}{1 + \frac{\Delta t\, c_W}{d}} \quad , \tag{5}$$

$$\alpha_l = \alpha_W + \ln\left(\frac{T\, A_W}{A_S}\right) / d \, , \tag{6}$$

where c_w is the velocity of sound in water, Δt is the time delay between the received signals with and without sample, d is the sample thickness, A_S and A_W are the amplitudes of the received signals with and without sample, respectively, and T is the total transmission coefficient for the longitudinal wave, which is equal to the product of the two transmission coefficients of the wave from water to the sample and from the sample to water (Wu, 1996). Transverse phase velocity is calculated by:

$$c_t = \frac{c_W}{\sqrt{\sin^2\theta_i + \left[\frac{\Delta t\, c_W}{d} + \cos\theta_i\right]^2}} \quad \text{, for } \theta_i > \theta_c \tag{7}$$

where θ_i is the angle of incidence and θ_c the critical angle of the water-sample interface.

Figure 1 shows the experimental setup used for the ultrasonic characterization of the samples: two transducers with 1MHz of central frequency and diameter of 19mm, a pulser/receiver *Panametrics 5072PR,* and a 500MHz digital oscilloscope *Hewllet-Packard Infimun* communicated via GPIB interface with a PC.

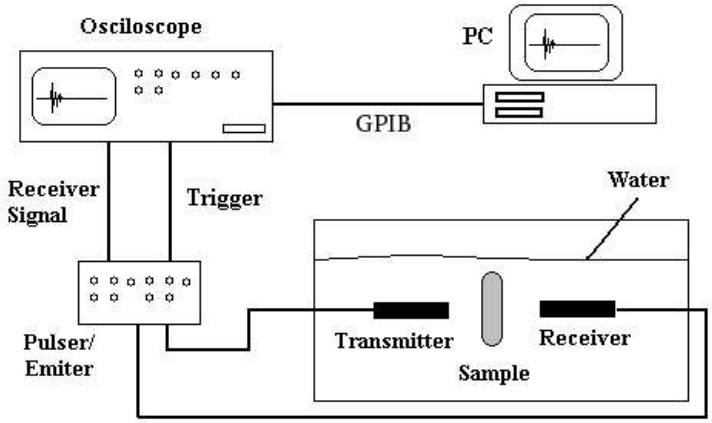

Figure 1. Experimental setup.

For the preparation of the composites the following steps were required: The components of the mixture were weighted with precision of 0.01g, and were hand mixed; the mixture was placed in a vacuum chamber for at least 15 minutes to take off internal air bubbles, and it was poured in a cylindrical mold; and the resin was cured at room temperature. The mixture proportions and the time of cure were presented in table 1. A suitable resin viscosity is important, principally at low volume fractions, because the high density of the Tungsten causes precipitation of the particles during the cure process, and the homogeneity is important for a better sample characterization. The maximum volume fraction of Tungsten obtained by this method was 29.5% for the Tungsten/Epoxy samples and 40% for the Tungsten/Polyurethane samples.

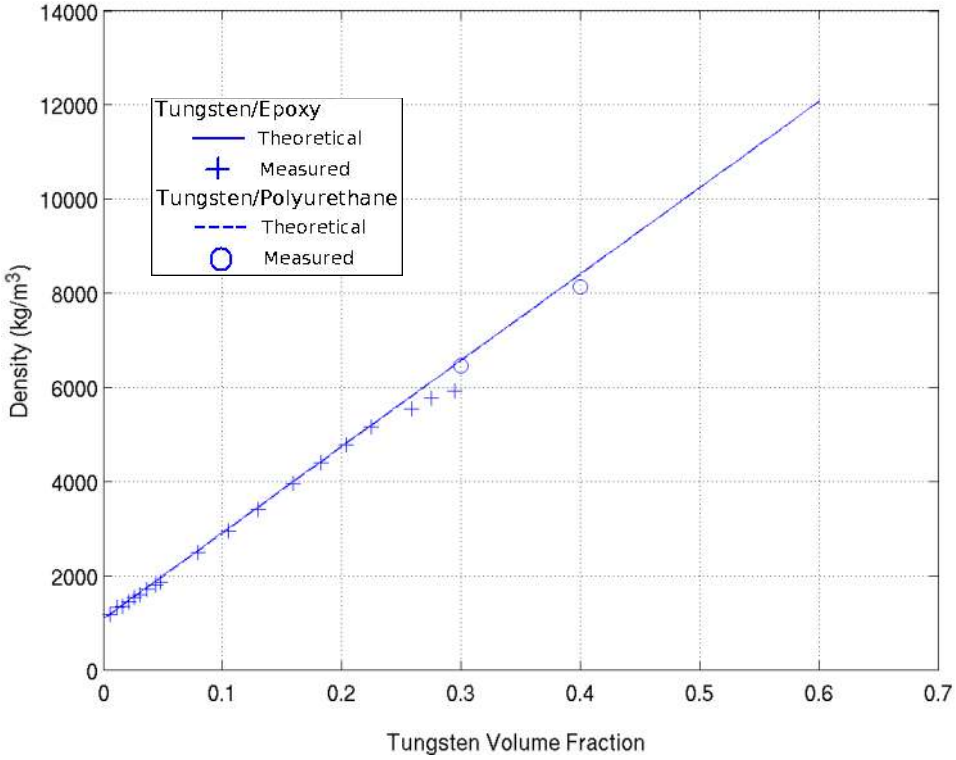

Figure 2. Theoretical and experimental composite densities.

4. Results

In Fig. 2, the theoretical densities (Eq. 1) of the Tungsten/Epoxy and Tungsten/Polyurethane composite sare plotted as a function of the Tungsten volume fraction, showing good agreement with the experimental results. As can be seen in the figure, the composite density increments linearly with the Tungsten volume fraction, the theoretical densities are overlapped due to similar resins densities.

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Figure 3 shows the theoretical and experimental longitudinal phase velocities of the composites. Initially, the addition of Tungsten to resin at low concentrations leads to a drop in the ultrasonic velocity reaching a minimum value for approximately 25%, later, the velocity begins to increase reaching again the pure resin ultrasonic velocity for concentrations of about 50%. This only occurs at low frequency and results from the high ultrasonic scattering by heavy inclusions. When the radius of the Tungsten particles is comparable to the ultrasonic wavelength, wave scattering becomes important and the zero frequency analytical model are not valid. A theoretical analysis of the frequency dependence of acoustical properties can be found in the Sayers and Tait's paper (1984).

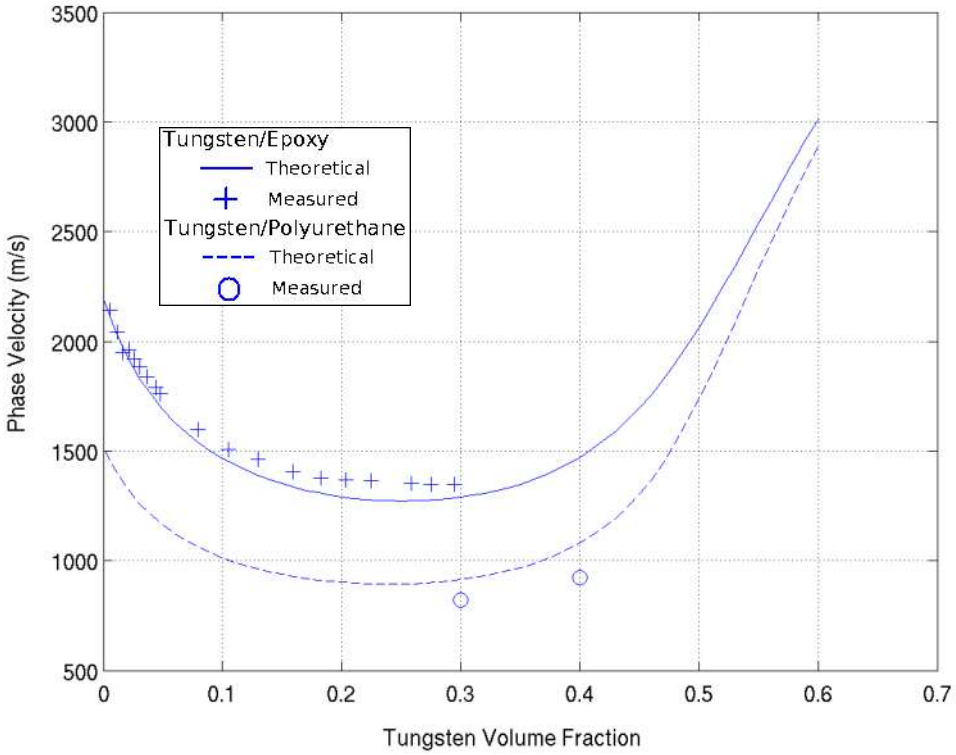

Figure3. Theoretical and experimental composite phase velocities.

Figure 4 shows the comparison between the theoretical and experimental acoustic impedances. The maximum measured values of impedance were 8MRayls for Tungsten/Epoxy composites, and 7.5MRayls for Tungsten/Polyurethane composites with volume fractions of 29.5% and 40%, respectively. The acoustic impedance of the composite rises slowly at small volume fraction, The impedance that matches that one of the PZT was obtained at concentration between 56% and 60% and at these volume fractions the transition from low to high impedance takes place over a narrow range of volume fraction.

The measured attenuation is shown in Fig. 5, it is clearly seen an increment with the volume fraction. An important attenuation increment occurs principally at the highest filler concentrations that could be caused by additional scattering introduced by air bubbles. The bubbles remain in the sample after the vacuum treatment due to the very high viscosity of the mixture.

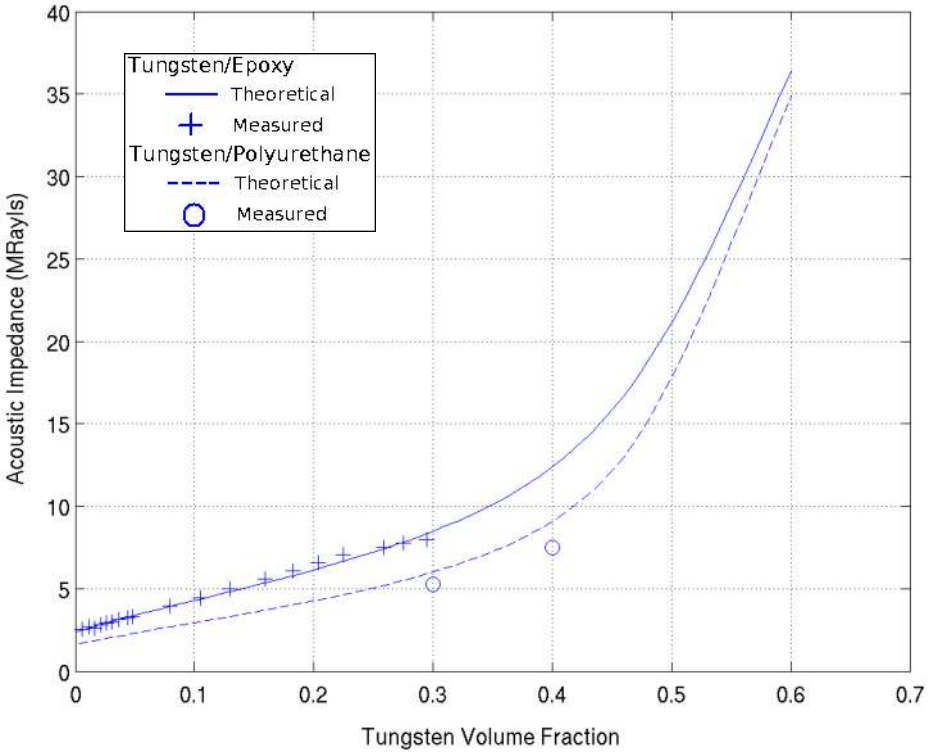

Figure 4. Theoretical and experimental acoustic impedance.

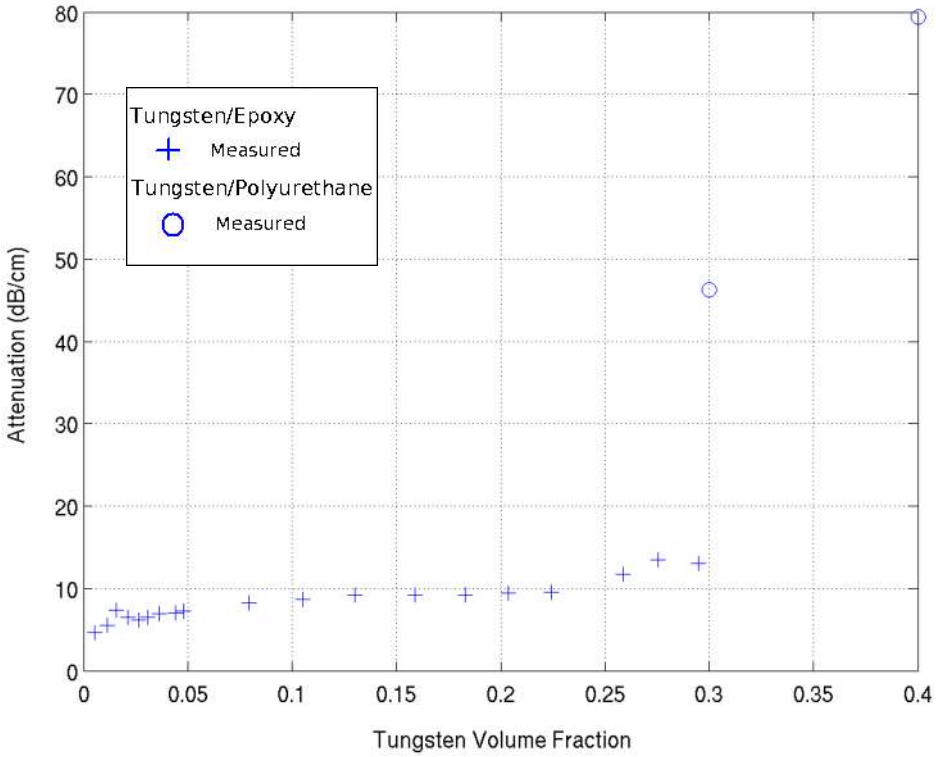

Figure 5. Experimental attenuation.

5. Conclusions

The theoretical modeling of the backing properties showed a good agreement with that measured in the Tungsten/Epoxy composites. However, in the case of the epoxy/polyurethane composites there was not good agreement due to the approximated transverse velocity used in the calculations, moreover, as these composites are very lossy materials, it is difficult to measure accurately the acoustic properties.

It is necessary to develop a better fabrication process to obtain greater Tungsten concentrations and therefore an acoustic impedance close to that of PZT ceramics.

The Tungsten/Polyurethane composites are an interesting backing material due to its very high attenuation that make possible thin backing layers.

6. Acknowledgments

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7. References

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