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Experimental Determination of Ultrasonic Wave Velocities in Plastics as Functions of Temperature. II. Effect of Lamination Angle for Layered Materials

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Synopsis

Ultrasonic longitudinal wave velocities in layered materials were measured as a function of the lamination angle at several temperatures. It was found that the longitudinal wave velocity versus lamination angle curve maintains the same shape (for a given material) for temperatures between 25 and 125°C. Furthermore, it was found that the wave velocity versus lamination angle curve can be predicted to within 2% by a theoretical equation involving only the lamination angle, θ (taken as the angle between the grain of the sample and the direction of sound propagation); c (0°), the measured wave velocity at an angle of 0°; and c (90°) the measured wave velocity at an angle of 90°. Finally, it was found that the longitudinal wave velocity of certain materials varies as much as 25% between lamination angles of 0° and 90°, while other materials show less variation, and some none at all.

Introduction

It is often necessary to evaluate the dynamic response of materials to high-pressure, short-duration loadings. Of primary concern in understanding the propagation of shocks is such information as the high-pressure equation of state which allows one to determine the shape and amplitude of shock waves as they are altered in progressing through various materials. An understanding and determination of the velocity of sound is an important factor which is necessary as an input in determining the Grüneisen ratio as it applies to the equation of state formalism normally utilized.

This work, in particular, describes the determination of ultrasonic longitudinal-wave velocities through nose cone materials at several temperatures as a function of lamination angles for three typical nose-cone materials. The lamination angle is defined as the angle between the plane of the layers and the direction of incidence of the ultrasonic signal and can best be explained by reference to Figure 1. As shown in the figure, the interwoven layers are extremely nonuniform (exaggerated here) so that it is difficult to define an exact lamination angle θ. However, the procedure followed in this investigation was to determine an average angle of incidence by averaging the fluctuations of the layers.

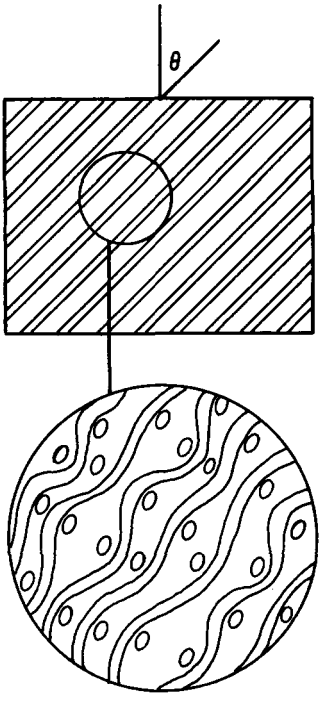

Fig. 1. Typical sample showing lamination angle θ and typical nonuniformities of the individual layers.

The present study is a continuation of the research effort to describe the ultrasonic properties of selected common plastics and nose-cone materials.[1]

Experimental Method

In brief, a time mark generator (Hickok Model 1817) is utilized to simultaneously trigger the sweep of a cathode ray oscilloscope (Tektronix Model 555) and a pulsed oscillator (Arenberg Model PG-605C). The pulsed oscillator produces a sinusoidal signal several cycles long with a frequency of 3.0 Mc./sec. which is displayed on the oscilloscope, and simultaneously applied to a lead zirconate–lead titanate crystal on the sample. The crystal generates an ultrasonic signal in the sample, and an identical PZT crystal receives the delayed signal after transmission through the sample.[2] The time lag between the arrival of these two signals is measured by use of the time-delay mechanism of the oscilloscope, which is calibrated with the use of time marks from the time-mark generator.

The velocity is obtained by mounting the samples between two aluminum buffer rods in a bonding clamp described elsewhere[3] and measuring the transit times of the combination with and without the sample inserted between the buffers. The wave velocity in the sample is then calculated as

$$c_{\text{sample}} = \text{Thickness of sample}/(\Delta t_{\text{total}} - \Delta t_{\text{buffers only}}) \quad (1)$$

One advantage of this method over those previously employed is that only one sample is needed to obtain the wave velocity through a material. Measuring velocities with such a single-sample technique eliminates the complications involved in preparing different samples of the same angular orientation. A disadvantage of this method is that there are not the same number or types of interfaces present when making the two measurements. The error thus introduced, however, has been found to be less than 1% for samples 20 mm. or greater in thickness. The standard deviation for the entire system is less than 2%.

Results

The materials studied have longitudinal wave velocities which show a large, moderate, and small dependence on the lamination angle; these are, respectively, phenolic fiber glass (PFG), phenolic carbon (PC), and tape-wound phenolic nylon (TWPN). Wave velocities in these three materials were studied as a function of lamination angle at several temperatures between 25°C. and 125°C. These data are available elsewhere in numerical form.[4] The majority of measurements of wave velocity of *PFG* (*density 1.91 g./cc.*) versus lamination angle were made at 30°C. Measurements at angles of 1°, 23°, 44°, and 89° were also made at temperatures of 50 and 93°C. to show the consistent shape of the velocity versus lamination angle curve as a function of temperature over this range (Fig. 2). Wave velocity measurements were not made above 95°C. because the material emitted water vapor. It was thought that this emission could cause changes in the mechanical properties of the material and thus affect wave velocity measurements.

The change in wave velocity as a function of lamination angle in PC (*density 1.48 g./cc.*) (Fig. 3) is less than the change observed in PFG.

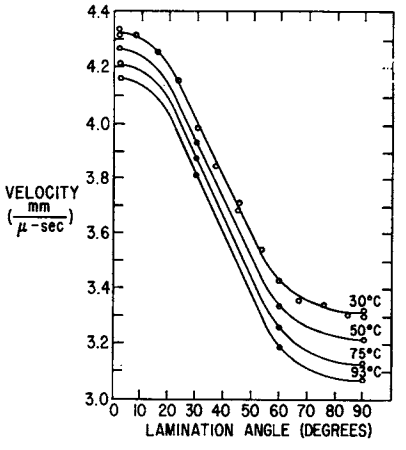

Fig. 2. Phenolic fiber glass wave velocity vs. lamination angle at various temperatures

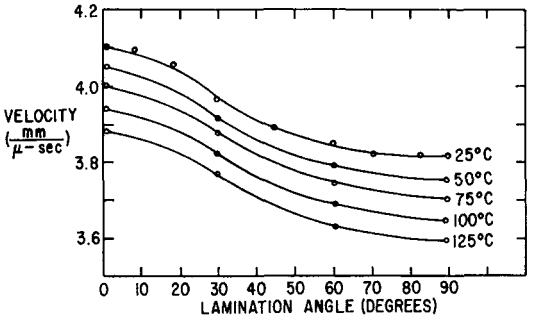

Fig. 3. Phenolic carbon wave velocity vs. lamination angle at various temperatures.

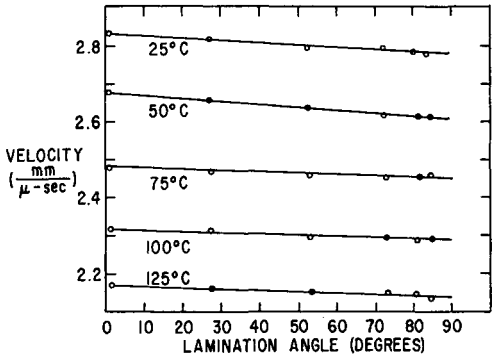

Fig. 4. Tape-wound phenolic nylon wave velocity vs. lamination angle at various temperatures.

For this reason there is more uncertainty in drawing a unique curve to fit the data points. The chosen curve, however, appears to fit all data points better than any other simple curve.

In TWPN (*density 1.21 g./cc.*) there is almost no dependence of wave velocity on the lamination angle (Fig. 4). For this reason, a straight line is used to fit the data points in Figure 4. However, a curve with the same shape as the PFG and the PC curves, only with less vertical variation, also fits the TWPN data.

Analysis

The similar shapes of the PFG, the PC, and the TWPN wave velocity versus lamination angle curves led to an attempt to predict these curves theoretically. Horio and Onogi[5] have derived an expression from general elasticity considerations, giving the elastic modulus as a function of lamination angle in ideal layered materials. Campbell[6] extended this derivation to the prediction of velocity in layered media and found that the velocity as a function of lamination angle should be given as

$$c^2(\theta) = \frac{c^2(0°)\, c^2(90°)}{c^2(90°) \cos^2\theta + c^2(0°) \sin^2\theta} \tag{2}$$

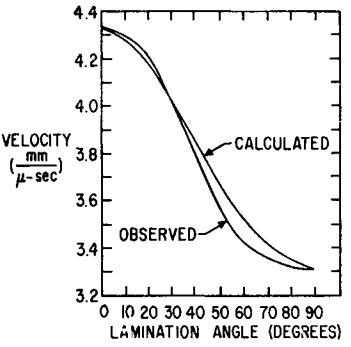

Fig. 5. Wave velocity for phenolic fiber glass at 30°C. showing the relation between the observed values and those calculated by using eq. (2).

where θ is the lamination angle, $c(\theta)$ is the wave velocity for an arbitrary angle of incidence θ, $c(0°)$ is the wave velocity for parallel incidence, and $c(90°)$ is the wave velocity for normal incidence. With a knowledge of the wave velocity at 0° and 90°, eq. (2) fits the present experimental data to within 2%. The calculated curve and the observed curve for PFG are shown for comparison in Figure 5. Considering that these nose-cone materials are very irregular in layer thickness and orientation, the fit to Campbell's expression is quite good.

It should be noted that the wavelengths of the sound waves in these materials are larger than the layer spacing at 3.0 Mc./sec. The thickness of a complete layer is 0.22 mm. for PFG, 0.33 mm. for PC, and 0.43 mm. for TWPN, where a complete layer is a layer of the main material and a layer of phenolic binder. The wavelength at 3.0 Mc./sec. and at normal incidence is 1.1, 1.25, and 0.9 mm. for each material, respectively.

Application

A rather important application of ultrasonic velocities is in the determination of certain parameters occurring in the equation of state of solid materials under shock-loaded conditions. The equation of state of shocked materials can be given by the Hugoniot equation of state obtained from several Hugoniot curves. A Hugoniot curve is the locus of pressure, volume, and internal energy points obtained from a series of shocks applied to a material initially in a specified state.[7] The relationship between the pressure and density thus obtained can be expressed as[8,9]

$$P = A\mu + B\mu^2 + C\mu^3 + (\Gamma\rho E/\rho_0) \tag{3}$$

where μ is the compressibility, $\mu = (\rho/\rho_0)^{-1}$, A, B, and C are constants, E is internal energy, Γ is the Grüneisen ratio, $\Gamma = (1/\rho)\ (\partial P/\partial E)_v$, and ρ is the density.

The constant A can be expressed as

$$A = (\partial P/\partial \mu)_0 = \rho_0\ (c_L^2 - 4/3c_T^2) \tag{4}$$

in the Maclaurin expansion, where c_L and c_T are longitudinal and transverse wave velocities, respectively. Similarly, the Grüneisen ratio can be thermodynamically related to the bulk modulus and consequently to the ultrasonic sound velocities

$$\Gamma = (\beta/C_P)\ (c_L{}^2 - 4/3c_T{}^2) \tag{5}$$

where β is the volume coefficient of thermal expansion and C_P is the specific heat at constant pressure. This relationship, derived for isotropic materials, is found to give Grüneisen coefficients which agree closely with those obtained by other methods. For anisotropic materials, such as finely layered media, reasonable results can now be obtained using the velocities obtained for any angle of incidence. A more thorough theoretical investigation is being conducted to relate the angular dependence of velocity to any deviation of the Grüneisen coefficient.

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References

1. Arnold, N. D., and A. H. Guenther, *J. Appl. Polymer Sci.*, **10,** 731 (1966).
2. Nolle, A. W., and P. W. Sieck, *J. Appl. Phys.*, **23,** 888 (1952).
3. Sullivan, P. F., *J. Acoust. Soc. Am.*, **34,** 1879 (1962).
4. Dorr, A. J., Master's Thesis, Air Force Institute of Technology, Wright-Patterson AFB, Ohio (1965).
5. Horio, M., and S. Onogi, *J. Appl. Phys.*, **22,** 971 (1951).
6. Campbell, J. G., *Austral. J. Appl. Sci.*, **12,** 356 (1961).
7. Bradley, R. S., *High Pressure Physics and Chemistry*, Vol. 2, Academic Press, New York, 1963.
8. Guenther, A. H., *Symposium on Dynamic Behavior of Materials*, Special Technical Publication No. 336, Am. Soc. for Testing and Materials (1962).
9. Slater, J. C., *Introduction to Chemical Physics*, McGraw-Hill, New York, 1963.

Résumé

Les vitesses de propagation d'une onde longitudinale ultrasonique dans des matériaux stratifiés ont été mesurées en fonction de l'angle de laminage à de nombreuses températures. On a trouvé que la vitesse de propagation longitudinale de l'onde en fonction de cet angle garde la même allure (pour un même matériau) à des températures variant de 25 à 125°C. En outre, on a trouvé que la vitesse de l'onde en fonction de cet angle peut être prédit endéans 2% par une équation théorique qui comporte uniquement l'angle de laminage (pris comme angle entre le fil de l'échantillon et la direction de propagation du son); c (0°), la vitesse de l'onde mesurée pour un angle de 0° et c (90°) la vitesse de l'onde mesurée pour un angle de 90°. Finalement, on a trouvé que la vitesse de propagation de l'onde longitudinale d'un certain matériau varie jusqu'à 25% entre des angles de 0 à 90°, alors que pour d'autres matériaux la variation est inférieure et pour certains entièrement nulle.

Zusammenfassung

Die Geschwindigkeit longitudinaler Ultraschallwellen in Schichtmaterialien wurde als Funktion des Laminieurungswinkels bei mehreren Temperaturen gemessen. Es zeigte

sich, dass die Kurve der longitudinalen Wellengeschwindigkeit gegen den Laminieurungswinkel bei einem gegebenen Material für Temperaturen zwischen 25°C und 125°C dieselbe Gestalt beibehält. Weiters wurde gefunden, dass die Kurve der Wellengeschwindigkeit gegen den Laminierungswinkel innerhalb 2% durch eine theoretische Gleichung vorhergesagt werden kann, welche nur den Laminierungswinkel θ (gemessen als Winkel zwischen dem Probenkorn und der Richtung der Schallfortpflanzung); c (0°), die gemessene Wellengeschwindigkeit bei einem Winkel von 0° und c(90°), die gemessene Wellengeschwindigkeit bei einem Winkel von 90° enthält. Schliesslich wurde gefunden, dass die longitudinale Wellengeschwindigkeit gewisser Stoffe sich zwischen Laminierungswinkeln von 0° und 90° um bis zu 25% ändert, während andere Stoffe eine geringere Änderung und einige überhaupt keine Änderung zeigen.

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