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PHOTOACOUSTIC MEASUREMENTS OF THE THERMAL DIFFUSIVITY OF SOLIDS IN THE PRESENCE OF A DRUM EFFECT

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The photoacoustic measurements of the thermal diffusivity of the thick plates of metals are discussed when the drum effect is not quenched. The dominant machanism responsible for the photoacoustic signal was determined. Depending on the configuration arrangement, the ratio of the thermal signal to the thermoelastic bending one was determined. The thermal diffusivity was obtained from both the frequency dependence of the rear amplitude and rear phase characteristics. The influence of the thermoelastic bending on both rear and front frequency characteristics is discussed. The way of calculation of the thermal diffusivity in the case of the results showing strong thermoelastic bending effect is discussed.

1. Introduction

The thermal diffusivity α is defined as the ratio of the thermal conductivity λ, the density ϱ and the thermal capacity c as:

$$\alpha = \frac{\lambda}{\varrho c}. \tag{1.1}$$

It is the measure of the rate of diffusion of heat in a material [1]. There are several methods described in the literature concerning the measurement of this parameter [2–7]. The thermal diffusivity can be calculated from the slope of the I_F/I_R as a function of the frequency of modulation of the exciting beam of light, where I_F and I_R are the amplitudes of the photoacoustic front and rear signals. The same parameter can be drawn from the "phase-lag" method [2]. In this case the phase lag between the rear and front signals gives the information about $l \cdot a_s$ where l is the thickness of the measured sample and a_s is given by the formula:

$$a_s = \sqrt{\frac{\pi f}{\alpha}}. \tag{1.2}$$

For the given frequency of modulation f, the α parameter can be simply determined. This method is independent of the frequency of excitation but it is sensitive, just like the former one, to the so-called "drum" effect. When this method is used for measurements, one must be sure that the "drum" effect is almost entirely quenched.

It is known that the photoacoustic signal measured at the rear side of the sample p_r is given by the formula [3]:

$$p_r \cong \frac{1}{\sigma \cdot \sigma_g} \cdot \frac{1}{\sinh(l \cdot \sigma)}, \tag{1.3}$$

p_r is the complex value of the periodical part of the overpressure in the photoacoustic cell (PA). The PA signal measured at the front of the sample is given by p_f which is given by:

$$p_f \cong \frac{1}{\sigma \cdot \sigma_g} \cdot \frac{\cosh(l \cdot \sigma)}{\sinh(l \cdot \sigma)}, \tag{1.4}$$

where l is the thickness of the sample, $\sigma = (1 + j) \cdot a_s$, where $a_s = 1/\mu_s$ (μ_s is the thermal diffusion length of the sample at a given frequency of modulation), σ_g is given by the relation $\sigma_g = (1 + j) \cdot a_g$ for air.

The presence of the temperature gradient causes additional contributions to the photoacoustic signal, caused by the expansion of the sample parallel to the beam direction and can create two effects: drum effect and piston effect. The piston effect can be neglected thanks to the construction of the PA cell. The value of the α parameter is important, among others, in the case of modelling of the thermal behaviour of electronic structures in the case of controlling the quality of production of electronic elements [8].

2. Experiment

All experiments were carried out using a photoacoustic cell that allowed to change the contribution of a drum effect in the total photoacoustic signal of the measured samples of different dimensions and shapes; the convenient fitting of the samples that allowed to exchange them quickly.

A schematic diagram of the photoacoustic cell is shown in Fig. 1.

A schematic diagram of the measuring arrangement is shown in Fig. 2.

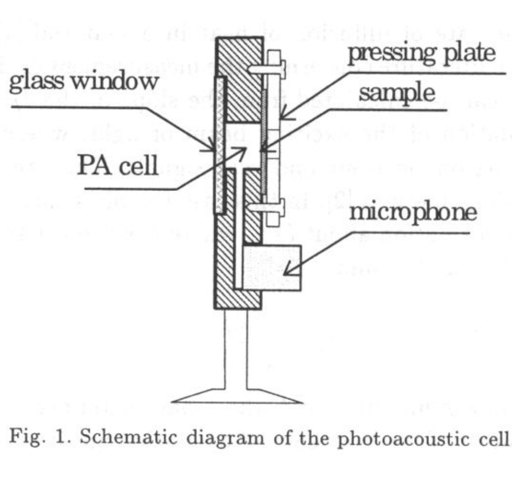

Fig. 1. Schematic diagram of the photoacoustic cell.

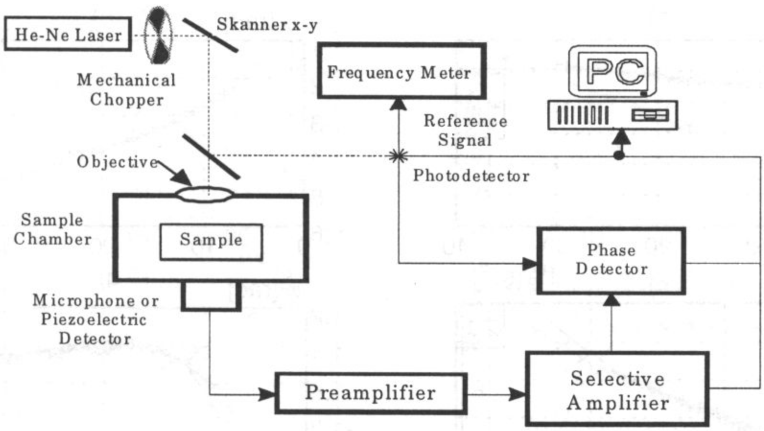

Fig. 2. Schematic diagram of the measuring arrangement.

For excitation of a temperature wave, the 640 nm laser beam of the HeNe laser LGM-222 of 50 mW output power was used. After chopping the beam is divided by the beam splitter. One beam is directed to the photodetector giving the reference signal to the phase detector that was a two channel Tektronix oscilloscope of the 2252 type. The main part of the laser beam is directed straight to the front side or the rear side of the sample. As a pressure detector, a condenser microphone of 10 mm diameter, mounted on one of the sides of the PA cell, was used. As indicated in the earlier articles, the samples needed a special shape, for example disks of 8 mm diameter were used. In our case the sample can be of any shape. It was obtained by a pressing plate with a whole for rear excitation. The samples studied were aluminium plates of the 500 μm thickness.

All the measured samples were optically opaque and the PA signal was strong enough, so that a special blacking of the surfaces was unnecessary.

3. Results and discussion

The results of the measurements for the Al plates are shown in Figs. 3 a, b, c, d.

The figures represent the results of measurements when the expected "drum" effect, caused by the thermoelastic bending of the samples, is maximum. Figure 4 a, b, c, d presents the measurements of the same samples when the pressing plate was used for quenching of the "drum" effect.

The ratio of R/R_c was 1, where R_c is the radius of the PA cell and R is the support radius of the sample. From the theoretical considerations in paper [3], one can state that the expected behaviour of the 4a curve should be as follows:

$$I_R = A \cdot \frac{1}{f} \cdot \exp\left(-c \cdot \sqrt{f}\right), \qquad \text{where} \quad c = l \cdot \sqrt{\frac{\pi}{\alpha}}. \tag{3.1}$$

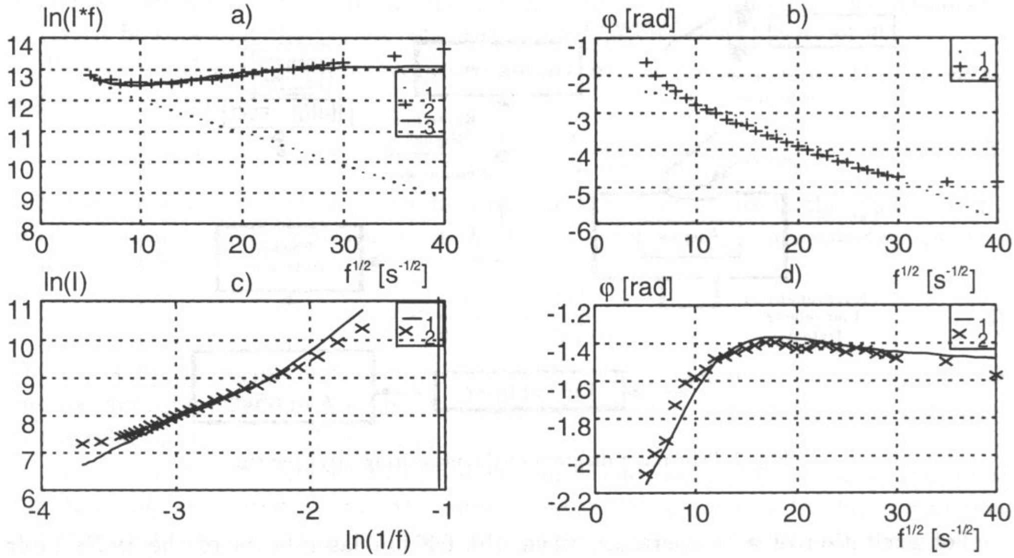

Fig. 3. Plots of the amplitudes and phases of the measured signals. Drum effect not quenched. a) $\ln(I \cdot f)$ versus $\sqrt{f}$ where I is the amplitude of the rear PA signal, the dotted line represents the results from Fig. 4 a (drumless case), b) phase shift of the signal in relation to the reference one versus $\sqrt{f}$, c) $\ln(I)$ versus $\ln(1/f)$ for the front signal, d) the phase shift signal in relation to the ref. signal versus $\sqrt{f}$.

Thus the slope of the curve, defined as

$$c = \frac{d(\ln(I_R \cdot f))}{d(\sqrt{f})}, \tag{3.2}$$

gives the thermal diffusivity of the sample in the measured case as

$$\alpha = \frac{\pi \cdot l^2}{c^2} = 0.67 \frac{\mathrm{cm}^2}{\mathrm{s}}. \tag{3.3}$$

This approximation is valid only for higher frequencies for which the phase of the front signal reaches the value of $\pi/2$. From Fig. 4 d it can be seen that $\sqrt{f} \geq 12.5\,[\mathrm{s}^{-1/2}]$. In such a case the measured object can be considerd to be thermally thick. In the light of the results, curve 4 d is important only at a proper choice of the range of frequencies for which this approximation is valid. For the same range of frequencies, the phase shift of the rear signal (Fig. 4 b) should be of the form $\varphi(\mathrm{rad}) = \mathrm{c} \cdot \sqrt{\mathrm{f}}$ with the same value of the c parameter.

$$c = \frac{d\varphi(\mathrm{rad})}{\mathrm{d}\sqrt{\mathrm{f}}} = \frac{d(\ln(I_R \cdot f))}{d(\sqrt{f})}. \tag{3.4}$$

From the slope of the curve 4 b we obtain the same value of c and consequently, the same value of $\alpha = 0.67\,\mathrm{cm}^2/\mathrm{s}$. From the above mentioned considerations, the equality of the slope coefficients obtained from the amplitude and phase dependences proves

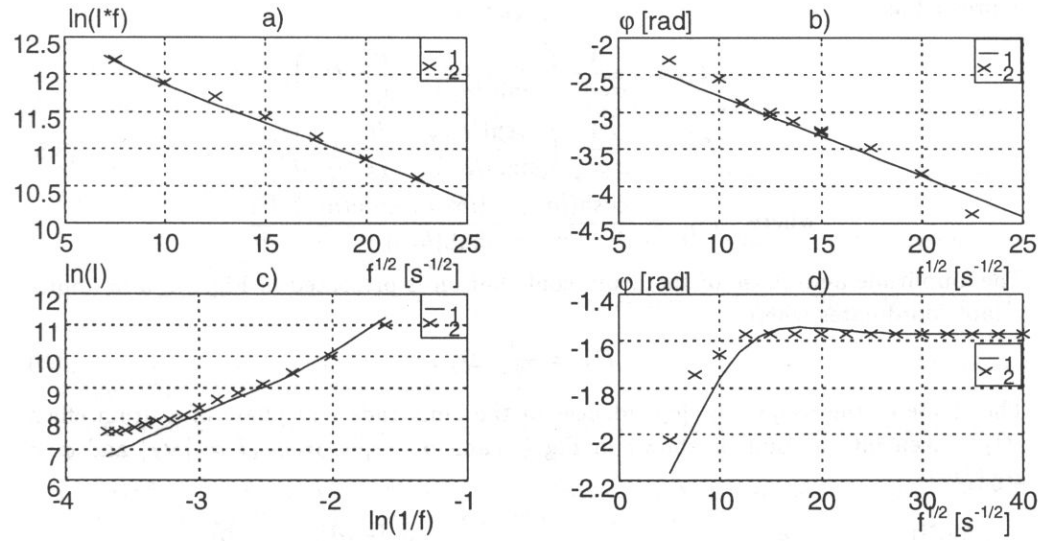

Fig. 4. Plots of the amplitudes and phases of the measured signals. Drum effect strongly quenched. a) $\ln(I \cdot f)$ versus $\sqrt{f}$ where I is the amplitude of the rear PA signal, b) phase shift of the signal in relation to the reference one versus $\sqrt{f}$, c) the phase shift signal in relation to the ref. signal versus $\sqrt{f}$.

that the "drum" effect can be neglected since it is almost entirely quenched by proper fastening in the PA cell.

The situation changes considerably in the case when the contribution of the drum effect can not be neglected as presented in Fig. 3.

The slope coefficients of the curves in Fig. 3 a and Fig. 3 b are considerably different. At the same time, these curves indicates that the sensivity of the parameters to the drum effect are considerably different. It was found that the amplitude characteristics are much more sensitive to it than the phase characteristics measured in the case of rear signal. Because the amplitude of the front signal is much greater than the rear signal but the contribution of the drum effect measured at the same level of excitation is the same in both cases, it follows that the front characterestrics presented in Fig. 4 c, d are much less sensitive to it.

Figure 3 a presents the three characteristics. Curve 1 shows the result for the drumless case for $\alpha = 0.67\,\mathrm{cm}^2/\mathrm{s}$, crosses represent the experimental values, and curve 2 shows the results of computations when the "drum effects" is taken into account. Taking into account the theoretical frequency dependence of the drum effect at some fitting parameters, good correlation between the experimental and calculated results were obtained. If the total PA signal can be presented in the form $\mathrm{PA} = A(\mathrm{PA}_T + B \cdot D_T)$, where PA_T is the thermal contribution to the measured signal and D_T is the drum contribution to the signal, then the B parameter is a measure of the ratio of drum to thermal contributions to the signal being measured. In this case the value $B = 2.5$ was determined. When the contribution of the drum effect can not be neglected then the total PA signal can be expressed as:

$$\begin{aligned} P_r &= \frac{A}{\sigma_S\sigma_g}\left(\frac{1}{\sinh(l\sigma_S)} + \frac{B}{\sigma_S}\cdot D_T'\right), \\ P_F &= \frac{A}{\sigma_S\sigma_g}\left(\frac{\cosh(l\sigma_S)}{\sinh(l\sigma_S)} - \frac{B}{\sigma_S}\cdot D_T'\right), \\ \text{where}\quad D_T' &= \frac{\cosh(l\sigma_S) - (l\sigma_S/2)\sinh(l\sigma_S) - 1}{\sinh(l\sigma_S)}. \end{aligned} \tag{3.5}$$

The amplitude and phase of the drum contribution is presented in Fig. 5 a, b in appropriate coordinates where:

$$D_T = \frac{1}{\sigma_s^2\sigma_g} D_T'. \tag{3.6}$$

The shape of the frequency dependences of the amplitude and phase of a drum effect (D_T) taken into account is shown in Fig. 5 a and b, respectively ($I = |D_T|$ and $\varphi = \arg(D_T)$).

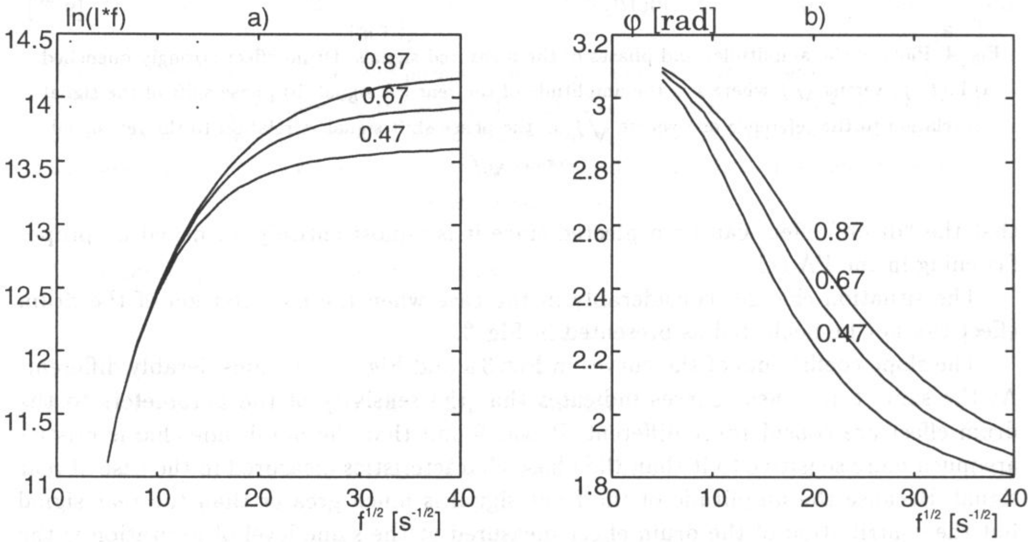

Fig.6. a) Amplitude and b) phase dependences of the drum effect versus $\sqrt{f}$ for diffusivities in cm^2/s for the aluminium sample of a diffusivity of 0.67 and thickness of 500 µm according to Eq. (3.6).

4. Conclusions

The results of the measurements of the thermal diffusivity of thick opaque objects are presented. The influence of the "drum effect" on different thermal wave characteristics was shown and discussed. It was shown that it is possible to calculate the proper value of α even from the results of experiments made on objects with strong drum effects. It was proved that the very simple method of reducing the drum effect applied in the PA cell is sufficient for almost entire quenching of the thermoelastic bending.

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