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INVESTIGATION OF STRESS WAVES IN GLASS TEXTOLITE AND FLUOROPLASTIC ARISING WITH RAPID HEATING BY RADIATION

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1. As a result of rapid heating of a condensed medium up to a level corresponding to a concentration of absorbed radiation energy much less than the heat of vaporization, stress waves are excited in the medium [1-3]. Recording these waves gives information concerning the physical properties of the irradiated substance.

Let the concentration distribution of absorbed energy as a function of the coordinate follow an exponential law $\varepsilon(x) = \varepsilon_0 e^{-\mu x}$, where μ is the linear absorption coefficient and ϵ is the concentration of absorbed energy. The propagation of stress waves in the acoustical approximation for one-dimensional deformation of semiinfinite liquid media or for one-dimensional deformation of a linear elastic half-space with instantaneous heating is described, in dimensionless variables, by the wave equation

$$\partial^2 S/\partial\xi^2 = \partial^2 S/\partial\tau^2.$$

The solution of this equation with the initial and boundary conditions

$$S(\xi, 0) = e^{-\xi},\ S(0, \tau) = 0$$

is given by the expression

$$S = h(\tau)e^{-\xi}ch\tau - h(\tau - \xi)ch(\tau - \xi), \tag{1.1}$$

where $h(\tau)$ and $h(\tau - \xi)$ are unit Heaviside functions; $\tau = \mu c_0 t$ is the dimensionless time; c_0 is the speed of sound; $\xi = \mu x$ is a dimensionless coordinate; $S = \sigma_x/\mu\gamma_\Gamma E_0(1-\alpha)$ is the dimensionless stress; γ_Γ is the Grüneisen coefficient; α is the coefficient of reflection of radiation; E_0 is the energy density of the incident radiation; σ_x is the stress in the direction of propagation of the wave $(\varepsilon_0 = \mu E_0(1-\alpha))$. The first term on the right side of Eq. (1.1) describes the compression wave. It follows from (1.1) that along the characteristic $\tau = \xi$, the stress σ_x changes sign in a discontinuous manner from positive (compression) to negative (tension). Both positive as well as negative stresses with maximum amplitude are realized along this same characteristic. According to (1.1), the maximum compression stress with instantaneous heating varies with distance as

$$S^+_{0\max} = e^{-\xi}ch\tau\,|_{\tau=\xi} = \frac{1+e^{-2\xi}}{2},$$

i.e., it rapidly decreases with ξ, approaching its limiting value $\lim S^+_{0\max} = 1/2$ for $\xi \to \infty$.

The finite value of the heating time leads to a decrease in the maximum amplitude of both phases of the stress wave. The transition from compression to expansion in this case occurs smoothly in a zone with finite dimensions.

The maximum compression stresses can be represented in the form

$$S^+_{\max} = S^+_{0\max} f(\tau_0) = \frac{1+e^{-2\xi}}{2} f(\tau_0), \tag{1.2}$$

where the function $f(\tau_0) \leqslant 1$ takes into account the finiteness of the heating time; $\tau_0 = \mu c_0 t_0$ is the dimensionless heating time; t_0 is the characteristic heating time taken as equal to the characteristic duration of the radiation pulse.

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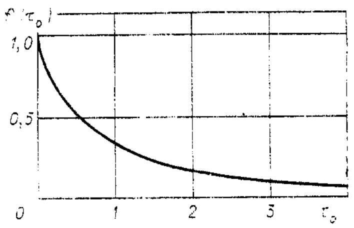

Fig. 1

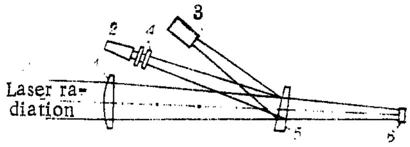

Fig. 2

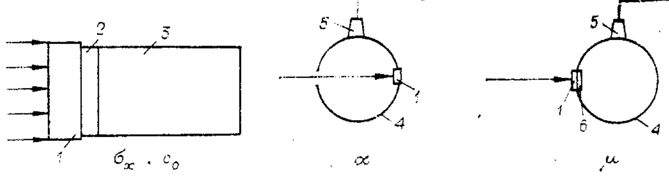

Fig. 3

Let the heating be accomplished by absorption of laser radiation energy. The value of the function $f(\tau_0)$ depends on the temporal dependence of the radiation intensity. Figure 1 shows the computed values of $f(\tau_0)$ for the radiation intensity function

$$\varepsilon(\tau_0) = \text{const}\left(e^{-\tau/\tau_0} - e^{-2\tau/\tau_0}\right),$$

characteristic for a single laser radiation pulse [2]. The strong influence of the radiation time on the maximum amplitude of the compression wave follows from the form of the function $f(\tau_0)$ in Fig. 1 and expression (1.2). The fact that S^+_{max} decreases with increasing τ_0 was observed experimentally in [4].

In dimensional form, formula (1.2) has the form

$$\sigma^+_{x\max} = \gamma_\Gamma \mu E_0 (1-\alpha)\left(\frac{1+e^{-2\xi}}{2}\right) f(\mu, c_0, t_0). \tag{1.3}$$

Therefore, according to (1.3), by measuring $\sigma^+_{x\max}$, μ, E_0, α, t_0 for known c_0, it is possible to compute the Grüneisen coefficient γ_Γ, which is an important parameter in the equation of state of a condensed medium

$$\gamma_\Gamma = \frac{2\sigma^+_{x\max}}{\mu E_0 (1-\alpha)(1+e^{-2\xi}) f(\mu, c_0, t_0)}. \tag{1.4}$$

Expression (1.4) is simplified in certain cases: heating that is close to instantaneous,

$$\gamma_\Gamma \simeq \frac{2\sigma^+_{x\max}}{\mu E_0 (1-\alpha)(1+e^{-2\xi})}; \tag{1.5}$$

large values of ξ

$$\gamma_\Gamma \simeq \frac{2\sigma^+_{x\max}}{\mu E_0 (1-\alpha) f(\mu, c_0, t_0)}. \tag{1.6}$$

2. In the experiments described in what follows, the properties of glass textolite and polytetrafluoroethylene (FT-4) were investigated. Glass textolite, which has a density $\rho_0 \approx 1.5$ g/cm^3, consisted of a layered composite material with a silicon fiber framework filled with an epoxy compound. Specimens, cut out of a sheet of commercial FT-4 fluoroplastic, had a density of $\rho_0 = 2.19$ g/cm^3. The quantities necessary, according to (1.4) or (1.5) and (1.6), to calculate the values of the Grüneisen coefficient were measured experimentally. In this work, we used an optical neodymium glass laser with a characteristic pulse duration of $t_0 = (70-100)10^{-9}$ sec. The block diagram of the experimental setup is shown in Fig. 2. In all the experiments, the diameter of the specimens was 20 mm and was equal to the diameter of the light spot. The laser radiation was focused by a lens 1 onto the experimental block 6. With the help of a beam splitting wedge 5, a small fraction of the radiation energy ($\approx 8\%$) was diverted to a coaxial photodetector 2 through a light filter 4 in order to record the temporal dependence of the radiation intensity, i.e., in order to find the quantity t_0, as well as onto a IKT-1M calorimeter 3 in order to measure the overall quantity of radiation energy E_0. E_0 was measured in a separate test with an accuracy $\approx \pm 20\%$. The values of t_0 and E_0 were determined in each test.

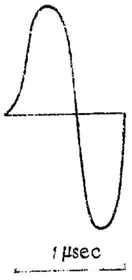

Fig. 4

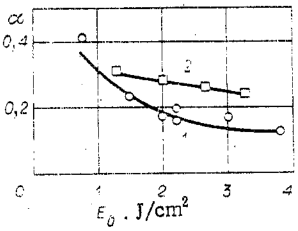

Fig. 5

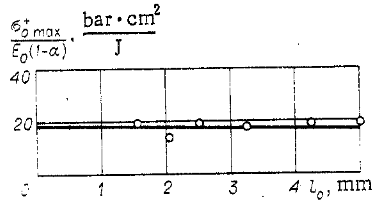

Fig. 6

Diagrams of the experimental blocks for measuring σ_x, α, μ, and c_0 are shown in Fig. 3. The stress wave in the specimen being investigated 1 was detected by a quartz sensor 2 with a diameter of 20 mm and a thickness of 4 mm with a matched rod 3 consisting of D-16 aluminum alloy having a length ≈ 25 mm. A typical oscillographic trace of the signal from the sensor is shown in Fig. 4. The shape of the signal from the pressure sensor indicates the fact that a stress wave consisting of a compression phase followed by an expansion phase propagates in the glass textolite. A similar stress wave was recorded in [5] for a composite material made of quartz strands and phenolic resin. In calculating the stress in the quartz σ_{qu} the value of the piezoelectric sensitivity factor K was taken as equal to 2.08×10^{-8} C/kbar. The relation between the recorded stress σ_{qu} in quartz and the true stress in the substance being investigated was taken in the acoustical approximation as $\sigma_x = \frac{\sigma_{qu}}{2}\left(1 + \frac{z}{z_{qu}}\right)$. The magnitude of the acoustic impedance $z = \rho_0 c_0$ was computed from the values of the sound velocity determined in the present work. For quartz, we used $c_0 = 5.7$ km/sec and $\rho_0 = 2.2$ g/cm³ [6].

The amount of radiation energy reflected from a specimen E_{ref} was measured with the help of an integrating sphere 4 and a coaxial FÉK-14 photodetector 5. The specimen was placed on the inner, with respect to the radiation, surface of the sphere. In order to measure the quantity of radiation energy passing through a specimen with given thickness l_0, E_{tr}, an integrating sphere, and a coaxial FÉK-14 photodetector were used. The specimen was placed in this case on the external, with respect to the radiation, surface of the sphere. In order to achieve the best scattering of radiation inside the sphere, an etched plate 6 was placed between the specimen and the cavity of the sphere. The system was calibrated beforehand in special tests with the help of a IKT-1M calorimeter by determining the dependence of the measured signal amplitude on the amount of radiation energy input to the cavity of the sphere. The reflection coefficient $\alpha = E_{ref}/E_{inc}$ and the coefficient of linear absorption $\mu = \frac{1}{l_0}\ln\frac{E_0(1-\alpha)}{E_{tr}}$ were computed from the results of the measurements. The dependence of the reflection coefficient α on the energy density E_0 incident on the specimen is shown in Fig. 5 (curve 1 for glass textolite and curve 2 for FT-4 fluoroplastic). The quantities E_{ref}, E_{inc}, and E_{tr} were measured in a single experiment with an accuracy of $\approx \pm 20\%$. The scheme for measuring the speed of sound (longitudinal velocity for propagation of small disturbances) is similar to the scheme for measuring stresses. For a given sample thickness, the time interval between the maximum radiation intensity (first beam) and the maximum stress amplitude (second beam), which was received during the time of propagation of the disturbances, was measured on a two-beam oscillograph. In the experiments with FT-4, a thin screen consisting of a material with a high value of μ was placed on the irradiated surface of the specimen. From the time interval for propagation of disturbances, in this case, the time of propagation of the signal along the screen was computed.

The results of the analysis of the experiments on determining μ and c_0 are displayed in Table 1. Each value of μ and c_0 was obtained in a series of 3-6 runs. In the range of values of E_0 indicated, μ and c_0 did not depend on E_0. The value $c_0 = 1.45 \pm 0.03$ km/sec determined for FT-4 agrees well with the values available in the literature ($c_0 = 1.5$ km/sec [7]). For glass textolite the time factor is $\tau_0 \approx \mu c_0 t_0 \approx 0.2$ and for FT-4 $\tau_0 \approx 0.03$. Thus, heating is rapid in glass textolite, and in FT-4 it is practically instantaneous.

Figure 6 shows the dependence of $\sigma^+_{0\max}/E_0(1-\alpha)$ on the distance l_0, traversed by the compression wave. The quantity $\sigma^+_{0\max}$ was obtained by taking into account the finiteness of the radiation time and the magnitude of ξ according to the formula [see (1.3)]

$$\sigma^+_{0\max} = \sigma^+_{\max}/[f(\tau_0)(1 + e^{-2\xi})].$$

As follows from Fig. 6, the maximum amplitude of the compression wave is weakly damped, which, apparently, is related to processes. The weak damping of compression waves in a composite material was also obtained in [5]. By extrapolating the value of $\left(\frac{\sigma^+_{0\max}}{(1-\alpha)E_0}\right)_{l_0=0}$ to $l_0 = 0$, we compute the value of the Grüneisen coefficient γ_r from the relation

TABLE 1

Material	E_0, J/cm^2	μ, 1/cm	c_0, km/sec
Glass textolite	1,9—2,6	9,4±0,4	2,44±0,03
FT-4	0,5—2	2,1±0,1	1,45±0,03

$$\gamma_\Gamma = \frac{2\sigma^+_{0\,\max}}{(1-\alpha)\,E_0\mu}\bigg|_{l_0=0}.$$

For glass textolite, we obtain the average value γ_Γ = 0.38. For FT-4, measurements were carried out only for a single thickness, l_0 = 4.5 mm. In this case, the quantity $\sigma^+_{0\max}/(1-\alpha)\,E_0$ equals 9 bar/(J/cm²). According to formula (1.5), the average value is γ_Γ = 0.86. For the FT-4 fluoroplastic, the determined value of γ_Γ agrees well with the value γ_Γ = 0.83, found from experiments with shock waves [8]. We note that for glass textolite, in view of the presence of porosity, the value of γ_Γ is an effective value $\gamma_{\Gamma\,\mathrm{eff}}$, which may not coincide with γ_Γ for continuous glass textolite, but gives the relation between the concentration of absorbed energy and the magnitude of the stresses arising with rapid heating. In this case, it is assumed that the linear absorption coefficients for different components are nearly equal.

For paraffin and for a composite material based on quartz strands and phenolic resin, the value of γ_Γ, obtained from the magnitude of the maximum amplitude of the compression wave, was determined in [9, 5], respectively. The error in the values of γ_Γ found did not exceed 15%.

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