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TEMPERATURE–FREQUENCY DEPENDENCE OF MECHANICAL LOSSES UNDER PERIODIC DEFORMATION OF LAMINAR GLASS-CARBON PLASTICS

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UDC 534.28+532.135

Experimental results [1-3] indicate that under periodic deformation the temperature–frequency locations of the relaxation maximums of the tangent of the mechanical loss angle $\tan\delta$ of a laminar composite and the material of its matrix do not agree. The reasons and regularities for such a shift of the $\tan\delta$ maximums remain unexplained within the framework of these papers. Meanwhile it is shown theoretically that the insertion of an elastic filler in a polymer material as well as the passage from shear over to longitudinal or bending vibrations in unfilled polymers and composites will distort the relaxation spectrum and change the effective relaxation time [4].

Regularities in the temperature–frequency location and the magnitude of the loss tangent maximum and the real part of the Young's modulus in laminar composites are examined below. The mixture rules proposed in [5, 6] were used here. The formulas in [6] are approximate and convenient for utilization for a large number of constituents in the composite. Moreover, they permit easy evaluation of the stress concentration coefficients in the composite material [7]. As is mentioned in [8], such approaches that take account of the actual mode of interaction between the composite constituents will permit obtaining results that are in satisfactory agreement with test data and are consequently adequate for technical applications.

1. Let a composite, which is transversally isotropic on the average, consist of a viscoelastic matrix and an elastic filler. The stochastic inhomogeneity of the composite is not taken into account. The energy dissipation mechanism is related only to the inelastic behavior of the matrix [9]. There is no relaxation of the bulk modulus K in a viscoelastic composite. Shear relaxation is described by the Yu. N. Rabotnov kernel, i.e., in the operator representation the shear modulus of the viscoelastic component is written as follows [10]:

$$\hat{G} = G_\infty[1 - \chi\hat{\partial}(x)], \tag{1.1}$$

where $\hat{\partial}(x)$ is the Yu. N. Rabotnov resolvent operator while the rheological parameters x, χ are expressed in terms of the unrelaxed G_∞ and relaxed G_0 values of the shear modulus and the effective relaxation time τ_ε:

$$x = -\tau_\varepsilon^{-\gamma}, \quad \chi = (G_\infty - G_0)/G_\infty\tau_\varepsilon^\gamma \quad (0 < \gamma \leqslant 1), \tag{1.2}$$

where γ is the kernel singularity parameter.

The expression for the Young's modulus operator of the viscoelastic constituent has the form [4]

$$\begin{gathered}\hat{E} = E_\infty\left[1 - \chi_E\hat{\partial}(x_E)\right],\\ x_E = -\tau_E^{-\gamma} = x + G_\infty\chi/(3K + G_\infty), \quad E_\infty = 9KG_\infty/(3K + G_\infty),\\ \chi_E = \eta\chi, \; 1/\eta = 1 + G_\infty/3K.\end{gathered} \tag{1.3}$$

Kuibyshev. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 6, pp. 139-144, November-December, 1984. Original article submitted October 14, 1983.

0021-8944/84/2506-0931$08.50

We direct the coordinate axis X_3 perpendicularly to the layers. For the mixture rule [6], the operator values of the nonzero matrix components of the effective elastic moduli $\hat{C}_{mn}$ will have the form

$$\hat{C}_{11} = v_1\hat{\varkappa}_1 + v_2\varkappa_2 = C_{11}^\infty\left[1 - \chi_{11}\hat{\ni}(x)\right],$$
$$\hat{C}_{12} = v_1\hat{\lambda}_1 + v_2\lambda_2 = C_{12}^\infty\left[1 + \chi_{12}\hat{\ni}(x)\right],$$
$$\hat{C}_{13} = \left(\frac{v_1}{\hat{E}_1} + \frac{v_2}{E_2}\right)^{-1}\left[\frac{v_1\hat{\nu}_1}{(1+\hat{\nu}_1)(1-2\hat{\nu}_1)} + \frac{v_2\nu_2}{(1+\nu_2)(1-2\nu_2)}\right] \simeq$$
$$\simeq \left(\frac{v_1}{\hat{E}_1} + \frac{v_2}{E_2}\right)^{-1}\left(v_1\frac{\hat{\nu}_1}{1-\hat{\nu}_1} + v_2\frac{\nu_2}{1-\nu_2}\right) = C_{13}^\infty\left[1 - \chi_{13}^{(1)}\hat{\ni}(x_1) + \chi_{13}^{(2)}\hat{\ni}(x_2)\right], \tag{1.4}$$
$$\hat{C}_{33} = \left(\frac{v_1}{\hat{E}_1} + \frac{v_2}{E_2}\right)^{-2}\left[\frac{v_1}{\hat{E}_1}\frac{1-\hat{\nu}_1}{(1+\hat{\nu}_1)(1-2\hat{\nu}_1)} + \frac{v_2}{E_2}\frac{1-\nu_2}{(1+\nu_2)(1-2\nu_2)}\right] \simeq$$
$$\simeq \frac{\hat{E}_1E_2}{v_1E_2 + v_2\hat{E}_1} = C_{33}^\infty\left[1 - \chi_{33}\hat{\ni}(x_1)\right],$$
$$\hat{C}_{44} = \frac{\hat{G}_1G_2}{v_1G_2 + v_2\hat{G}_1} = C_{44}^\infty\left[1 - \chi_{44}\hat{\ni}(x_3)\right],$$

where

$$C_{11}^\infty = v_1\varkappa_1^\infty + v_2\varkappa_2,\quad C_{12}^\infty = v_1\lambda_1^\infty + v_2\lambda_2,$$
$$C_{33}^\infty = \frac{E_1^\infty E_2}{v_1E_2 + v_2E_1^\infty},\quad C_{13}^\infty = \left(v_1\frac{\nu_1^\infty}{1-\nu_1^\infty} + v_2\frac{\nu_2}{1-\nu_2}\right)C_{33}^\infty, \tag{1.5}$$
$$C_{44}^\infty = G_1^\infty G_2/(v_1G_2 + v_2G_1^\infty),$$

in which

$$\varkappa = \lambda + 2G,\quad \lambda = K - 2G/3,$$
$$x_1 = x + \chi - \chi_1,\quad x_2 = x - \chi_2 - \chi_3,\quad x_3 = x + \chi_4,$$
$$\chi_1 = \frac{v_1E_2\eta\chi}{M_E^\infty},\quad \chi_2 = \frac{2G_1^\infty\chi}{3K_1 - 2G_1^\infty},\quad \chi_3 = \frac{18K_1G_1^\infty\chi}{(3K_1 - 2G_1^\infty)(3K_1 - 4G_1^\infty)},$$
$$\chi_4 = v_2G_1^\infty\chi/M_G^\infty,\quad M_Q = v_1Q_2 + v_2Q_1,\quad Q = E, G, \tag{1.6}$$
$$C_{11}^\infty\chi_{11} = 4v_1G_1^\infty\chi/3,\quad C_{12}^\infty\chi_{12} = C_{11}^\infty\chi_{11}/2,\quad \chi_{33} = \chi_1,\quad \chi_{44} = v_1C_{44}^\infty\chi/G_1^\infty,$$
$$\chi_{13}^{(1)} = \chi_1 + \frac{v_1\chi_1\chi_3}{\left(v_1\frac{\nu_1^\infty}{1-\nu_1^\infty} + v_2\frac{\nu_2}{1-\nu_2}\right)(\chi - \chi_1 + \chi_2 - \chi_3)},$$
$$\chi_{13}^{(2)} = \frac{v_1\chi_3}{v_1\frac{\nu_1^\infty}{1-\nu_1^\infty} + v_2\frac{\nu_2}{1-\nu_2}}\left(1 + \frac{\chi_1}{\chi - \chi_1 + \chi_2 - \chi_3}\right).$$

Here v_i, E_i, ν_i are the relative bulk content, the Young's modulus, and the Poisson ratio of the i-th phase which is inelastic for i = 1 and elastic for i = 2 (the expression for the Poisson ratio operator of the viscoelastic constituent is presented in [4]), $\hat{\varkappa}_1$ and $\hat{\lambda}_1$ are operators whose form can be obtained by substituting the operator value of the shear modulus of the viscoelastic phase (1.1) into (1.6).

Let us compare the expressions (1.4)-(1.6) with known expressions [11] that have been derived for averaging [5]. It is seen from (1.4)-(1.6) that each of the coefficients $\hat{C}_{mn}$, with the exception of $\hat{C}_{13}$, is determined by one operator, while $\hat{C}_{13}$ is expressed in terms of the sum of two operators. Meanwhile, as is shown in [11], the coefficients $\hat{C}_{11}$ and $\hat{C}_{12}$ are characterized by the superposition of two operators upon averaging according to [5], and the coefficients $\hat{C}_{13}$, $\hat{C}_{33}$, $\hat{C}_{44}$ by one operator, where the coefficient $\hat{C}_{44}$ is determined for the mixing [6] exactly as in [5].

Attention is turned in (1.4) to the fact that for the laminar texture under consideration

$$C_{12} \geqslant C_{12}^\infty \tag{1.7}$$

for any values of the parameters of the composite constituents, while the inequality

$$C_{13} \geqslant C_{13}^{\infty} \tag{1.8}$$

is satisfied in the case $\chi_{13}^{(1)}\ni(x_1) \leqslant \chi_{13}^{(2)}\ni(x_2)$.

Let us note that from the results of [11] the inequality (1.8) follows for any values of the parameters of the composite constituents, while the inequality (1.7) follows under the condition

$$\ni(x) \geqslant \frac{1}{3}\left[\frac{3v_2(K_1-K_2)+\varkappa_2}{M_{\varkappa}^{\infty}}\right]^2 \ni\left(x+\frac{4v_2 G_1^{\infty}\chi}{3M_{\varkappa}^{\infty}}\right).$$

It is interesting to obtain the presence of effects described by the inequalities (1.7) and (1.8), by which the stress relaxation functions that are the kernels of the operators $\hat{C}_{12}$ and $\hat{C}_{13}$ can grow, from experiment. For the presence of these effects, it is important to obtain conditions for their validity.

When bulk relaxation of the viscoelastic constitutent also holds in addition to shear relaxation, while the Poisson ratio of this constituent is a constant, the expressions for the elasticity coefficients of a two-constitutent composite during mixing [6] take the form

$$\begin{gathered}\hat{C}_{11}=C_{11}^{\infty}\left[1-\chi_{11}'\ni(x)\right],\quad \hat{C}_{12}=C_{12}^{\infty}\left[1-\chi_{12}'\ni(x)\right],\\ \hat{C}_{33}=C_{33}^{\infty}\left[1-\chi_{33}'\ni(x_1')\right],\quad \hat{C}_{13}=C_{13}^{\infty}\left[1-\chi_{13}'\ni(x_1')\right],\\ \hat{C}_{44}=C_{44}^{\infty}\left[1-\chi_{44}'\ni(x_2')\right].\end{gathered} \tag{1.9}$$

Here

$$\begin{gathered}x_1'=x+\frac{v_2E_1^{\infty}\chi}{M_E^{\infty}},\quad x_2'=x+\frac{v_2G_1^{\infty}\chi}{M_G^{\infty}},\\ C_{11}^{\infty}\chi_{11}'=v_1\varkappa_1^{\infty}\chi,\quad C_{12}^{\infty}\chi_{12}'=v_1\lambda_1^{\infty}\chi,\quad C_{33}^{\infty}\chi_{33}'=v_1E_2\chi,\\ C_{13}^{\infty}\chi_{13}'=C_{33}^{\infty}\chi_{33}'\left(v_1\frac{\nu_1}{1-\nu_1}+v_2\frac{\nu_2}{1-\nu_2}\right),\quad C_{44}^{\infty}\chi_{44}'=v_1G_2\chi,\end{gathered}$$

C_{mn}^{∞} are determined by (1.5).

It follows from (1.9) that in the case of constancy of the Poisson ratio, each of the coefficients $\hat{C}_{mn}$ is characterized by one operator. Moreover, in contrast to (1.7) and (1.8) the following inequality is valid

$$C_{ij} \leqslant C_{ij}^{\infty}.$$

It is useful to have expressions for the technical elastic moduli. The Young's modulus of a composite in the plane of the layers is expressed in terms of the coefficients C_{ij} as follows:

$$E_{\parallel}=(C_{11}-C_{12})\frac{C_{33}(C_{11}+C_{12})-2C_{33}^2}{C_{33}C_{11}-C_{13}^2}. \tag{1.10}$$

Substituting the unrelaxed values of the elasticity matrix coefficient [6] into (1.10), we obtain for the case of a two-constituent composite

$$\begin{gathered}E_{\parallel}=v_1E_1+v_2E_2+\Delta_1+\Delta_2,\\ \Delta_1=\frac{v_1v_2(\nu_1-\nu_2)^2E_1E_2}{v_1E_1+v_2E_2},\quad \Delta_2=\frac{v_1v_2(E_1\nu_1-E_2\nu_2)^2}{v_1E_2+v_2E_1}.\end{gathered} \tag{1.11}$$

To the accuracy of the terms in the denominator of Δ_1 which contains squares of the Poisson ratios of the constituents, the expression (1.11) differs only in the last term from the expression [4] obtained for averaging [5].

In order to analyze the magnitude and temperature–frequency location of the mechanical loss peak for tension–compression vibrations in the plane of the layers, we examine the operator structure of the Young's modulus (1.11). For simplicity, we first consider the Poisson ratio of the viscoelastic constituent a constant. In place of the Young's modulus E_1 we substitute its operator value (1.3) into (1.11), and reducing the function of the operators to standard form, we obtain

$$\hat{E}_{\parallel}=E_{\parallel}^{\infty}\left[1-\chi_E^{(1)}\ni(x_E^{(1)})-\chi_E^{(2)}\ni(x_E^{(2)})+\chi_E^{(3)}\ni(x_E^{(3)})\right], \tag{1.12}$$

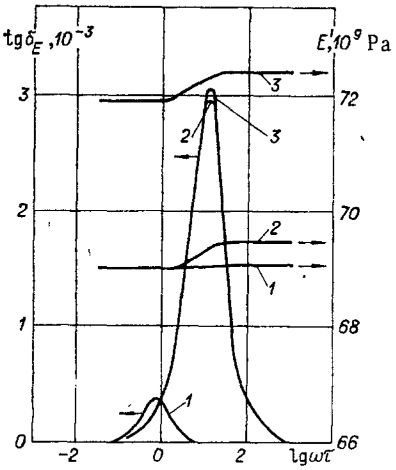

Fig. 1

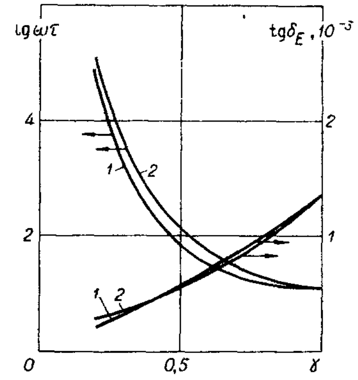

Fig. 2

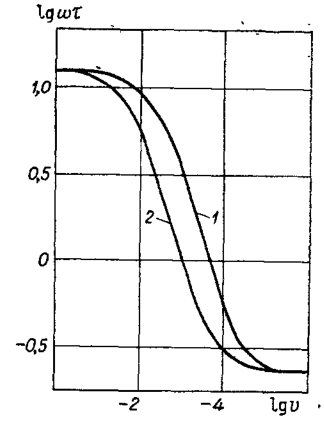

Fig. 3

where $E_{\parallel}^{\infty}$ is determined by the equality (1.11) with the substitution $E_1 \to E_1^{\infty}$, while

$$x_E^{(1)} = x_E, \quad x_E^{(2)} = x_E + \frac{v_1 E_1^{\infty} \chi_E}{E_{\infty}^{*}}, \quad x_E^{(3)} = x_E + \frac{v_2 E_1^{\infty} \chi_E}{M_E^{\infty}}, \quad E_{\infty}^{*} = v_1 E_1^{\infty} + v_2 E_2,$$

$$E_{\parallel}^{\infty} \chi_E^{(1)} = v_1 \left(1 + \nu_1^2\right) E_1^{\infty} \chi_E, \quad E_{\parallel}^{\infty} \chi_E^{(2)} = \frac{v_1 v_2^2 (\nu_1 - \nu_2)^2 E_1^{\infty} E_2^2 \chi_E}{(E_{\infty}^{*})^2},$$

$$E_{\parallel}^{\infty} \chi_E^{(3)} = \frac{v_1 (v_1 \nu_1 + v_2 \nu_2)^2 E_1^{\infty} E_2^2 \chi_E}{(M_E^{\infty})^2}.$$

The correction Δ_2 in the expression for the elastic modulus (1.11) specifies the appearance of a term with the effective relaxation time $x_E^{(3)}$ in the operator relationship (1.12). It follows from the comparison of the expressions for $x_E^{(2)}$ and $x_E^{(3)}$ that in the important practical case when the content of the constituents in the composite is approximately identical, the relaxation times $x_E^{(2)}$ and $x_E^{(3)}$ differ insignificantly. Therefore, the mixings [5, 6] in the example being considered of tension—compression vibrations in the plane of the composite result in expressions with approximately identical relaxation time spectra. It hence follows that the temperature—frequency location of the maximums of the tangent of the mechanical loss angle will be practically identical for both mixing cases under consideration.

A more exact approximation of the operator expression for the Young's modulus (1.11) is the relationship obtained with relaxation of the Poisson ratio ν_1 taken into account. It turns out that if the relaxation of ν_1 is taken into account in the terms containing the product $\nu_1 E_1$ in the numerators of the corrections Δ_1 and Δ_2, then the operator structure of (1.12) will not change. The effective relaxation times $x_E^{(1)}$, $x_E^{(2)}$, and $x_E^{(3)}$ remain the same. Only the relaxation intensities $\chi_E^{(1)}$, $\chi_E^{(2)}$, and $\chi_E^{(3)}$ change negligibly.

We also note the fact of relaxation time spectrum broadening for tension—compression vibrations in the plane of the composite layers as compared with the spectrum of the homogeneous viscoelastic constitutent because of the appearance of additional distributions with the effective relaxation times $x_E^{(2)}$ and $x_E^{(3)}$. Since the magnitude of the parameter γ can be a measure of the spread in the relaxation spectrum [12], it then follows that the value of the effective singularity parameter of a laminar composite should be less than the corresponding value of the singularity parameter for the viscoelastic matrix.

2. We illustrate the regularities obtained by numerical computations of the frequency-dependent elastic and damping characteristics of laminar glass- and carbon-plastics (the relative bulk content of resin is v_1, of glass fabric v_2, of carbon fabric v_3) in the area of matrix passage from the glassy to the highly elastic state. We evaluate the dissipative and elastic characteristics as a function of the dimensionless quantity $\omega\tau$, which is the product of the cyclic frequency ω by $\tau = (\tau_\varepsilon \tau_\sigma)^{1/2}$, the geometric mean of the relaxation time τ_ε and the retardation τ_σ [13]. It is possible to go over to the temperature dependences of the loss tangent and the dynamic Young's modulus by taking into account the relation of the relaxation time τ_ε to the temperature T. It is customary to describe this relation by the Arrhenius formula

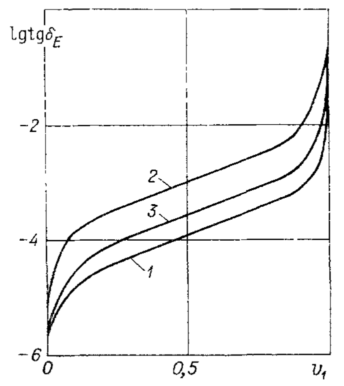

Fig. 4

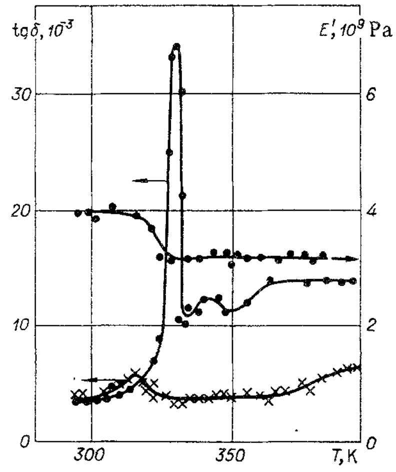

Fig. 5

$$\tau_\varepsilon = \tau_0 \exp(H/RT), \tag{2.1}$$

where τ_0 is the characteristic time, H is the activation energy of the relaxation process, and R is the universal gas constant.

We give the viscoelastic properties of the epoxy resin in terms of the complex shear moduli [14] corresponding to the Rabotnov and Rzhanitsyn relaxation functions. We take for the epoxy resin $G_1^\infty = 4\cdot10^8$ Pa, $G_1^0 = 3\cdot10^6$ Pa [15], $\nu_1 = 0.35$, for the glass fabric $E_2 = 7\cdot10^{10}$ Pa, $\nu_2 = 0.22$, and the carbon fabric $E_3 = 3\cdot10^{11}$ Pa, $\nu_3 = 0.20$ [16]. Constructing the vector diagram of the complex shear modulus of the epoxy resin by means of data from [15], we obtain the numerical value of the singularity parameter $\gamma = 0.3$. We neglect relaxation of the bulk modulus.

Presented in Fig. 1 are graphs of the dynamic Young's modulus E' and the loss tangent for periodic deformation of the specimen in the plane of the layers $\tan\delta_E$ as a function of the quantity $\log\omega\tau$. The specimen is a carbon plastic with resin content $v_1 = 0.77$. The computation was performed by Voight averaging when the deformations are considered equal at all points of the composite, and also according to the mixture rules [5, 6] (curves 1-3, respectively). It is assumed that the properties of the epoxy resin are described by an exponential kernel.

It is seen from Fig. 1 that both models [5, 6] that take account of the dependence of the coupling of the composite elements on the kind of stress state yield the very same location for the maximum of $\tan\delta_E$ on the frequency (temperature) axis. The magnitudes of the loss tangent and the dynamic modulus differ by not more than 4%. The maximal value of $\tan\delta_E$ in the case of Voight averaging is approximately 7 times less than for mixing [5, 6].

As the magnitude of the parameter γ changes, the maximum of $\tan\delta_E$ shifts towards higher frequencies along the $\log\omega\tau$ axis, or as follows from (2.1), towards low temperatures. In Fig. 2 this shift is seen as well in an example of a glass-carbon plastic of the following composition: $v_1 = 0.45$, $v_2 = 0.32$, $v_3 = 0.23$. Curves 1 and 2 correspond to giving the viscoelastic properties of the composite matrix by Rabotnov and Rzhanitsyn relaxation kernels. Presented in this same graph are dependences of the magnitude of the loss maximum on the matrix parameter γ.

The effect of the shift in the loss tangent maximum as the magnitude of the parameter γ changes can be used to monitor changes in the matrix structure during exploitation of articles from composites since the singularity parameter γ is structure-sensitive and depends essentially on the material treatment and exploitation conditions [12].

Let us note that for a Rabotnov kernel describing the shear relaxation of a homogeneous material, the temperature—frequency location of the loss maximum during shear strains and any values of the singularity parameter γ corresponds to the condition $\omega\tau = 1$, which follows from the expression [17]

$$\omega\tau_\varepsilon = (G_0/G_\infty)^{1/2\gamma}, \tag{2.2}$$

since $(\tau_\varepsilon/\tau_\sigma)^\gamma = G_0/G_\infty$ [12].

As regards the condition of the loss maximum in a homogeneous material during tension—compression vibrations, it is easily written down by noting that the operator expression

(1.3) can be obtained from (1.1) and (1.2) by the replacements $\tau_\varepsilon \to \tau_E$, $G_0 \to E_0$, $G_\infty \to E_\infty$. Making this substitution in the equality (2.2), we find the condition for maximum $\tan \delta_E$: $\omega\tau = (G_0E_\infty/G_\infty E_0)^{1/2}\gamma$.

The almost jumplike shift in the location of the maximum $\tan \delta_E$ along the frequency (temperature) axis upon the addition of a negligible quantity (just several percent) of elastic filler to the viscoelastic matrix (Fig. 3, where the curves 1 and 2 correspond to a carbon-plastic and a glass-plastic) is of special interest. The computation was performed by the mixture rules [6]. The matrix properties were given by an exponential kernel.

The dependence of the maximal loss value in the carbon-plastic on the bulk epoxy resin content is represented in Fig. 4. Curve 1 corresponds to a Voight shift. The rheological properties of the composite matrix are given in terms of the exponential relaxation kernel. The remaining curves correspond to a shift according to [6]. Curves 2 and 3 correspond to giving the matrix properties in terms of an exponential and a Rabotnov kernel. It is seen from the graph that $\log \tan \delta_m$ is proportional to v_1 in the range of variation from 0.2 to 0.8 for the relative bulk epoxy resin concentration.

It is interesting to note that the domain of an abrupt diminution in the magnitude of the loss tangent maximum (see Fig. 4) upon the addition of just several percent of carbon fabric corresponds to an abrupt shift in the location of this maximum on the frequency (temperature) axis in Fig. 3. The dependences represented in Fig. 4 are in agreement with the experimental results [18].

3. The effect of a shift in the location of the maximum tangent of the composite mechanical loss angle along the frequency (temperature) axis as compared with the location of the corresponding maximum of the matrix was detected experimentally in ÉDT-10 epoxy resin specimens and in glass-plastics with it as base. The glass-plastic was a 14-layer quasi-isotropic composite, i.e., the stacking of each glass fabric layer was at a 60° angle to the preceding layer, and contained 30% resin and 70% glass fabric. Specimens of 160 × 16 × 4 mm were fabricated from glass-plastic slabs. The epoxy resin specimens were 150 × 11 × 10 mm in size.

The temperature dependences of the loss tangent and the elastic modulus (Fig. 5) were measured on an "Elastomat" apparatus by the method of a resonance rod with bending vibrations at an 800-Hz frequency in an amplitude-independent domain. The passage from the glassy to the highly elastic state was investigated. The points on the graph correspond to the resin measurement data, and the crosses to the composite. The shift in the composite maximum $\tan \delta_E$ as compared with the maximum in the resin was 14°K. The Young's modulus of the glass plastic was practically unchanged in the whole temperature range investigated and was $4 \cdot 10^{10}$ Pa. The Poisson ratio of the epoxy resin, measured at room temperature, was 0.37.

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DYNAMIC PHOTOELASTIC PROPERTIES OF AN EPOXY RESIN ABOVE THE ELASTIC LIMIT

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UDC 539.30

Epoxy resins are widely used as optically sensitive stress transducers for both static and dynamic loading methods. Their photoelastic properties have been well studied in the range of elastic deformation down to loading times on the order of 10^{-5} sec [1, 2]. However, there is almost no experimental data in the literature for compression above the elastic limit due to the brittle fracture of glassy polymers. In the present study, we were successful in measuring the photoelastic effect in a broader range of pressures by loading the material with compression pulses of about 10^{-7} sec duration.

1. Experimental Unit and Measurement Method. The compression pulses were created by a laser operated in the modulated Q-factor regime. The duration of the laser pulse was 30 nsec at half-height. The output energy was 0.65 J and the diameter of the focal spot was about 1 mm. Focusing was done on a specimen of ED-6, the surface of which was covered by a 50-μm-thick copper foil. A film of distilled water about 1 mm thick was placed on the foil to obtain sufficiently high pressures. The amplitude of the pressure pulses in the polymer here was on the order of 1 GPa, with a duration of about 10^{-7} sec. Figure 1 shows a profile of the pressure pulse (time scale of grid 50 nsec) obtained with a thin (100 μm) quartz transducer. The profile is extended somewhat compared to the radiation pulse, a fact connected with the multiple reflections and interference of the pressure pulse in the foil due to the substantial difference in the acoustic impedances of the copper and epoxy resin.

We used a standard method [1] to observe the dynamic photoelastic effect. We used a variant in which the transmitting radiation passed through a specimen placed between an analyzer

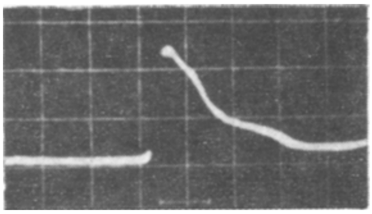

Fig. 1

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 6, pp. 145-148, November-December, 1984. Original article submitted September 22, 1983.

0021-8944/84/2506-0937$08.50