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ON THE VIBROCREEP OF POLYMER MATERIALS

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The constitutive equations existing in the mechanics of deformable solids, in the case of loading with the superposition of small vibrations, give deformation characteristics that differ little from analogous parameters for processes occurring without disturbances. At the same time, for a number of materials, under certain conditions, a sharp change in the deformation characteristics is observed in the presence of variable components of small amplitude. Thus, studies are known of the creep of metals ([1,2]), elastomers ([3]), and concrete ([4]), in which the creep curves obtained when small oscillations are superposed on the main load run substantially above the creep curves obtained for a static load corresponding to the maximum variable force. There have been attempts to explain the phenomenon of vibrocreep from the standpoint of molecular-kinetic ([3]) and phenomenological ([5]) theory.

In the present work, a mechanism of vibrocreep associated with heating of the material under the action of vibrational loading is discussed. Experimental data are presented; comparison of these data with the theory developed shows that this mechanism does indeed occur for some polymer materials.

Fig. 1. *a*—the effect of vibrations according to G. L. Slonimskii and P. I. Alekseev ([3]); *b*—the effect of vibrations caused by thermal phenomena. 1—creep curve (elastic aftereffect) of a polymer material in the absence of vibrations; 2—creep curve (elastic aftereffect) after application of the vibrational component. The moment of application of the vibrations is indicated by an arrow.

The vibrocreep process observed in our experiments in caprolite proceeded differently than in the experiments of G. L. Slonimskii and P. I. Alekseev ([3]) (see Fig. 1). When the vibrational component was applied, according to the data of ([3]), the material behaved as if, at the moment marked by the arrow (Fig. 1*a*), the specimen had been additionally loaded. In our experiments, after vibrations were applied in addition to the acting static load, at first the material creeps in

Figure 2

Figure 1: Figure 2

exactly the same way as in the absence of vibrations, and only after some time (the induction period) does the creep rate $\dot{\varepsilon}$ begin to increase slowly. After the process reaches the straight-line segment 2 (Fig. 1*b*), the value of $\dot{\varepsilon}$ sometimes exceeds by 2-3 orders of magnitude the value of $\dot{\varepsilon}$ before the application of vibrations. The temperature of the material then rises considerably.

Vibrocreep tests were carried out on a special apparatus constructed in the Department of Plasticity of the Scientific Research Institute of Mechanics of Moscow State University named after M. V. Lomonosov. Figure 2 presents the results of creep tests of caprolite specimens under a constant static load $\sigma = 3$ kg/mm^2 (calculated on the undeformed cross section) at temperatures 20, 40, 60, and 80°. The specimens were made in the form of rods 6 mm in diameter and with a working length of 60 mm. Figure 3 presents the re-

results of tests of the same caprolite specimens when, together with a static load $\sigma = 3$ kg/mm^2 (40% of the short-term strength), a dynamic load was applied. The frequency of the dynamic load was 200 Hz, and the amplitude was 0.06 kg/mm^2, i.e., 2% of the applied static load. The room temperature and the initial temperature of the specimens tested under vibration conditions was 20°. When static and dynamic loads were applied simultaneously, the temperature of the specimens (Fig. 3) changed as shown by curves 3. The temperature was measured in the middle of the working part of the specimen surface with copper —constantan thermocouples made from wires 0.03 mm in diameter. The differences in the heating rate of specimens 1 and 2 were due mainly to differences in their thermal insulation. Thermal insulation was used to equalize the temperature field both over the cross section and along the length of the specimen. In the absence of insulation, the nonuniformity of the temperature distribution along the radius would have been considerably greater.

Fig. 2. Creep curves of caprolite under a static load ($\sigma = 3$ kg/mm^2).
$1, 2$—$T = 20°$; $3, 4$—$T = 40°$; $5, 6$—$T = 60°$; $7, 8$—$T = 80°$

Comparison of the results presented in Figs. 2 and 3 does not answer the question of whether the effect of vibrations on the creep rate of polymers is due only to heating of the material and the corresponding reduction in its mechanical characteristics, or whether another mechanism, independent of temperature, is operating here. Indeed, the data presented in Fig. 2 were obtained at a temperature T that remained unchanged over the course of the test, whereas in the experiments shown in Fig. 3, T changed continuously. To judge whether there exists or does not exist a proper vibrocreep effect independent of temperature, experiments of two types could have been carried out. First, one could, for example, perform an experiment with vibration while providing heat removal from the specimen so that its temperature remained constant. A comparison of creep

Fig. 3. Vibrocreep curves of caprolite. 1 —experiment; 2 —calculation by formula (2); 3 —change in specimen temperature

Figure 2: Fig. 3. Vibrocreep curves of caprolite. 1 —experiment; 2 —calculation by formula (2); 3 —change in specimen temperature

curves (with the static load being constant in both cases) with and without vibration would make it possible to judge the influence of the proper vibration effect and of the specimen temperature. Experiments of this kind were carried out by A. M. Lokoshchenko and S. A. Shesterikov on duralumin specimens, in which a vibrocreep effect was observed that was not associated with a change in temperature in the specimen. Second, one could carry out an experiment with a constant static load in which the temperature of the specimen would change with time in the same way as in the corresponding experiment with vibration (the static load is also assumed equal in these experiments). On polymer specimens, conducting experiments of both the first and the second types presents certain difficulties.

Following works ([6],[7]), we shall proceed from kinetic concepts of deformation and write the expression for the rate of creep deformation in the form

$$d\varepsilon_c/dt = F(\varepsilon_c, \sigma)\exp\{-[U-\gamma\sigma]/\mathcal{R}T\}, \tag{1}$$

where ε_c is the creep deformation, U is the activation energy, σ is the stress, T is the temperature, $\mathcal{R}$ is the universal gas constant, γ is a material constant, and t is time. This expression assumes an Arrhenius dependence

···dependence of the strain rate on temperature, a linear dependence of the activation energy on stress, and also a certain dependence of the creep rate on the parameters of the current state, i.e., on the accumulated strain and stress, determined by the function $F(\varepsilon_c, \sigma)$. In the general case, when $\sigma = \text{const}$ and T depends on time, the integral of equation (1) can be written in the form

$$\varepsilon_c = \Psi\left\{\int_0^t \exp\left[-(U-\gamma\sigma)/RT\right]\,dt, \sigma\right\}. \tag{2}$$

A relation of the form (2), from the point of view of the phenomenological theory of creep, representing a variant of the theory of hardening, was apparently first indicated in work (8). On the basis of this relation one can quite simply determine the function Ψ, as well as the parameters U and γ, from experimental data relating to isothermal creep under the action of a constant stress.

Fig. 3. Vibrocreep curves of caprolite. 1 —experiment; 2 —calculation by formula (2); 3 —change in specimen temperature.

The question of the change in temperature caused by vibrations in the absence of the principal load was first considered in work (9), under the assumption that the temperature gradient inside the specimen is small and that the main thermal resistance is concentrated at the wall of the specimen. To determine the temperature taking into account its variation over the cross section, we note that the intensity of heat release per unit volume is equal to (10, 11) $\omega\sigma_0^2 I''/2$. Here σ_0 is the amplitude of the vibrational component of the load, ω is the frequency, and I'' is the so-called loss compliance, for which, as analysis of experimental data shows, one may adopt the approximate expression

$$I'' = \frac{K}{\omega^n} \exp[\beta(T - T_0)], \tag{3}$$

where K, n, β are constants, and T_0 is the reference temperature, which may be taken as the ambient temperature.

Writing the heat-balance equation for a cylindrical specimen, neglecting the change of temperature along the axis, we obtain

$$\rho c \frac{\partial T}{\partial t} = \lambda \frac{1}{r} \frac{\partial}{\partial r} r \frac{\partial T}{\partial r} + \frac{K}{2} \sigma_0^2 \omega^{1-n} \exp[\beta(T - T_0)], \tag{4}$$

where ρ is the density, c the heat capacity, λ the thermal conductivity of the material, and r the current radius measured from the axis of the cylinder. Calculation of the change of temperature with radius and in time reduces to solving equation (4)

under natural initial and boundary conditions. After the temperature distribution has been found, it should be averaged over the radius and substituted into relation (2).

The investigation of the boundary-value problem to which the determination of the temperature reduces is analogous to the investigation of the problem of a stationary thermal explosion, first considered by D. A. Frank-Kamenetskii (([12]; see also ([13,14])). This problem, as is known, has a certain nontrivial feature, which also has an interesting interpretation in vibrational heating. It turns out that stationary temperature distributions are impossible when the specimen radius R is greater than

$$R^* = [2\lambda\delta_0\omega^{n-1}/\beta K \sigma_0^2]^{1/2},$$

(the dimensionless parameter δ_0 is determined by the intensity of heat exchange at the wall of the specimen; $\delta_0 = 2$, if the temperature changes continuously in passing from the medium to the specimen). Under such conditions the temperature of the specimen will rise more and more until thermal destruction or some other processes of chemical degradation of the polymers begin. For $R < R^*$ two stationary solutions are possible (see, for example, (^{13})), one of which (corresponding to a higher heating) is unstable; the latter circumstance was rigorously demonstrated in (^{15}). At $R = R^*$ the two solutions merge into one.

Figure 3 presents calculated points 2, constructed from formula (2), where the temperature T was not calculated but was taken from experimental data. These points deviate only slightly from the experimental curves 1 obtained under the action of vibrational loads. Hence one may conclude that the increase in the creep rate of caprolite observed in these experiments under the influence of dynamic loads is due mainly to the influence of changes in the properties of the material as the temperature rises as a result of heat generation during vibrations.

In determining the activation energy U, it was found that the latter depends on temperature. This result does not contradict data known from the literature (see, for example, (^{16})) on the change of the activation energy of relaxation processes with change in T. In the calculations, a certain "effective activation energy" was used, determined from creep curves in a definite temperature range.

At the end of the vibrational-creep experiments, the formation of a neck was observed, analogous to the "cold-flow" neck described by Carothers and Hill, Miklovich, V. A. Kargin and T. I. Sogolova, and Yu. S. Lazurkin (^{17}). Since the theories proposed in the present paper do not claim to describe the processes also occurring in the neck, there is no reason to suppose that the calculated and experimental creep curves 1 and 2 in Fig. 3 will agree also at large deformations, when the neck has already formed. The sharp deviation of the calculated curve from the experimental one for specimen 2 at large deformations apparently confirms this. A theory of the propagation of a neck in polymeric materials was proposed earlier by one of the authors (^{18}).

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