DYNAMIC PROPERTIES OF SOME POLYMER MATERIALS IN LOADING AND UNLOADING

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A series of quasi-static tests have been carried out on kapron fiber, vinyl plastic, and fluoroplastic specimens with small cross sections. Stress-strain diagrams have been obtained at strain rates from $1 \times 10^{-3}$ to $1 \times 10^3$ sec$^{-1}$. In the experiments the strain rate changed sign, which corresponded to loading and unloading. In each regime the strain rate remained constant. The experimental data are analyzed using the model of a standard linear viscoelastic solid.

The loading of certain polymer fibers at constant strain rate was investigated in [1]. The stress-strain diagrams of several polymers were obtained in [2, 3] for loading and unloading, but the experimental method did not ensure a constant strain rate.

![Fig. 1. Schematic of dynamic apparatus.](image-url)

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In the experiments we used kapron (nylon 6) fiber test pieces 60–250 mm long and 0.8 mm in diameter and vinyl plastic and fluoroplastic test pieces 150–250 mm long with uniform rectangular cross sections measuring 1.9 x 2.6 and 2.1 x 3.6 mm$^2$, respectively. The nicked ends of the test pieces were held by a grip in steel jaws. This excluded the possibility of investigating the phenomenon of fracture, which necessarily occurred in the grips.

The strains were calculated from the change in the distance between the grips, which introduced an additional error. However, as a photographic check revealed, the difference between the strains measured in this way and the strain determined over some gauge length between two marks on the test piece proved to be insignificant. This was because the ratio of test piece length to the characteristic transverse dimension was not less than 40.

Tests at strain rates of the order of $10^2$ sec$^{-1}$ were conducted on a 10-ton tensile testing machine with an auxiliary dynamometer capable of registering loads up to 20–30 kgf. The elastic element of the dynamometer was a beam with a strain gauge bonded to it. The strain gauge readings were recorded across a DU-8 amplifier on an MPO-2 loop oscillograph. To initiate unloading the machine was put into reverse as soon as a given maximum strain was reached.

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![Fig. 2. Conventional stress-strain diagrams for kapron at different constant strain rates.](image-url)

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Obviously, in this case the strain rates in the forward and reverse directions were the same.

For loading at strain rates of the order of $10^2$ sec$^{-1}$ we designed a dynamic testing apparatus (Fig. 1) similar to that used in [1]. The top of the specimen was attached to a piezoelectric transducer, which, in turn, was fastened to the end of a steel rod 5 m long. The bottom of the specimen was connected to a rigid steel beam measuring 20 x 30 x 120 mm mounted horizontally and capable of rotation about a horizontal axis. The dynamic load was applied by means of a falling 5.5-kg weight moving along guide rods. The strain rate was varied by varying both the velocity of the weight and the length of the specimen.

The minimum strain rate was fixed by the requirement that the deformation energy be at least one order smaller than the energy of the moving beam, which ensured a constant strain rate, while the maximum value was determined by the possibility of a quasi-static approach to the analysis of the test data.

The transducer consisted of two barium titanate elements, bonded to the end of the steel rod with an epoxy adhesive. The tensile strength of the joint was not less than 150 kgf/cm$^2$. The transducer signal was fed to a type ENO-1 electronic oscillograph. The transducer was calibrated in the static mode. During the experiments the velocity of the end was measured by means of high-speed motion-picture photography with an SKS-1M camera.

In order to permit unloading experiments the dynamic apparatus was equipped with a steel stop. In its downward motion the beam struck the steel stop and, rebounding from it, reversed its direction. The rebound velocity, and hence the unloading strain rate, was less than the loading rate by a factor of 3, as was also established by means of high-speed motion-picture photography. The distance $\Delta l$ (see Fig. 1) between the beam and the stop determined the maximum strain.

The conventional dynamic $\sigma$ vs. $\varepsilon$ diagrams of kapron, vinyl plastic, and fluoroplastic in the loading phase are shown in Figs. 2, 3, and 4, respectively. The results show that a five-order change in strain rate leads to an appreciable increase in the stresses, while having little effect on the general configuration of the curves. It is interesting to note the different behavior...
of the initial tangent modulus for the materials investigated. In the case of kapron there is a systematic and considerable increase in the angle of inclination of the tangent to the initial section of the curves, which cannot be said about fluoroplastic, whose initial tangent modulus did not change. For vinyl plastic the initial tangent modulus changes significantly only for a considerable increase in strain rate.

Unloading tests were performed on kapron fiber and vinyl plastic test pieces. We were unable to test fluoroplastic at high rates, since in the strain interval of interest (above 2%) the slope of the $\sigma$ vs. $\varepsilon$ diagram and hence the wave propagation velocity was so small that it would have been incorrect to analyze the test results without taking wave propagation into account.

For each material the tests were conducted at two strain rates differing by five orders. The results for kapron fiber and vinyl plastic are presented in Figs. 5 and 6, respectively. The "residual" strains, i.e., the strains obtained when the stresses in the test piece vanish, depend only slightly on the strain rate. The same can be said of the general configuration of the unloading curves.

In analyzing the data for vinyl plastic we used the standard linear solid model in the form

$$\sigma + T\dot{\varepsilon} = E\varepsilon + E_1T\dot{\varepsilon},$$

where $T$ is the relaxation time, $E$ the delayed, and $E_1$ the instantaneous elastic modulus.

We note in passing that the standard linear solid model can also be written in the equivalent form of the Boltzmann heredity law with exponential kernel

$$\sigma = E\varepsilon + (E_1 - E) \int_0^t e^{-t/T} \varepsilon_0(t) dt.$$

The coefficients $E$, $E_1$, and $T$ were selected so that at $\dot{\varepsilon} = +70$ sec$^{-1}$ correspondence with the experimental data was obtained on the interval $0 \leq \varepsilon \leq 2\%$. In this case it was found that $E = 2.00 \cdot 10^4$ kgf/cm$^2$, $E_1 = 5.85 \cdot 10^4$ kgf/cm$^2$, $T = 2.40 \cdot 10^{-4}$ sec.

Using the above equations we calculated the unloading curves for $\varepsilon = 2\%$ and $\varepsilon = 2.5\%$; in Fig. 7 these are represented by dashed lines. The solid lines correspond to the initial experimental data. Clearly, for the experimental values of $\varepsilon$ and $\dot{\varepsilon}$ the calculated curve corresponds closely to the experimental data on the initial unloading interval and, moreover, on the whole, satisfactorily describes the unloading process for vinyl plastic.