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Experimental Study of the Dependence of the Rate of High-Elastic Rupture on the Rate of Deformation of a Specimen

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When a polymer is deformed in the high-elastic state, energy is expended on deformation and on the simultaneously occurring process of rupture. The latter, in turn, can be divided into the formation of elementary "rupture foci" and their growth.

In the present study an attempt was made to investigate the regularities of the growth of ruptures in connection with the influence of various factors: the magnitude of the defect, the rate of deformation, the deforming stress, and the specific cohesive energy of the vulcanizate. For this purpose, specimens of unfilled vulcanizates of nitrile rubbers SKN-18, SKN-26, and SKN-40, with the same degree of transverse cross-linking, were used. The specimens had the form of rectangles 50 mm wide, with cuts transverse to the axis of deformation of lengths 5; 2.5; and 1.0 mm. In addition, specimens without cuts were used. The tests were carried out on an RMM-60 tensile-testing machine at deformation rates of 100; 200; 500; and 1000 mm/min. The dependences of the rate of rupture growth on various factors were studied by means of high-speed cinematography. The objects were filmed at speeds from 800 to 4000 frames per second*. When the film taken in this way is projected at a speed of 16 frames/sec, it is possible to observe the process under study slowed down by a factor of 10–500. In addition, with the aid of a special deciphering device, the image of the tearing specimen was subjected to various measurements. In order to record the time during which particular changes occurred in the frames taken, a neon lamp MN-7 was used; when supplied with alternating current of frequency 50 Hz, it gives 100 flashes per second. The light from this lamp passed through a system of optical devices to the edge of the film and exposed it at definite equal intervals of time. Figure 1 shows some frames of the initial and final stages of rupture. In the initial stage of deformation, the dimensions of the specimen were measured every 20–50 frames. From the moment of increase of the cut l (from the moment of the onset of rupture growth), measurements were made every 2–5 frames; and in the case of a nonuniform increase in the rupture rate, measurements were made successively on each frame. In all, about 300 high-speed motion-picture films were processed, which made it possible to reveal some fairly clear regularities.

Figure 1

Figure 1: Figure 1

Figure 2

Figure 2: Figure 2

All experimental data presented below were obtained at a temperature of $+40°$. As experience showed, temperature also has a very substantial effect on the kinetics of rupture growth.

Determination of the dependence of the rate of rupture propagation $(\Delta l/\Delta t) = v'$ on time t showed that the area bounded by the curve $\Delta l/\Delta t$—t, for all

* The high-speed motion pictures were taken under the supervision of I. V. Kurskii, to whom the authors express their gratitude. V. Kovriga took part in carrying out the experiment.

of the vulcanizates studied, regardless of the rate of deformation of the specimens, retained a constant value. This is to a certain extent an estimate of the accuracy of the experiment, since $\int_0^\tau v' \cdot dt = l$, where τ is the time from the start of deformation to rupture of the specimen. Figure 2 shows typical results obtained by the above-described processing of high-speed motion-picture films.

Fig. 1. Individual frames of rupture of a vulcanizate at a temperature of $40°$: a —onset of rupture; b and v—final stage of rupture

The rate of growth of the rupture under a given deformation regime remains immeasurably small for almost the entire duration of the test; it then begins to increase rapidly and discontinuously. If a line is drawn at the tip of the notch in the direction of rupture, it is easy to find that, in unfilled vulcanizates of nitrile rubbers, at the initial stage of deformation an additional stretching takes place at the tip of the notch, and consequently an additional orientation of the material also occurs. This additional orientation, detected from the thickening of the scribed line at the tip of the notch, becomes smaller as the rate of growth of deformation increases and as the rupture increases. The size of the notch substantially changes the kinetics of rupture growth. As the relative length of the notch l/L increases (where L is the width of the specimen), the time τ from the start of deformation of the specimen to the moment of its rupture decreases, as is clearly shown by the data presented in Fig. 2.

Fig. 2. Dependence of the rate of rupture growth on the size of the notch for vulcanizates based on SKN-26. Deformation rate 1000 mm/min. 1—preliminary notch of the specimen 5 mm; 2—2.5 mm; 3—1 mm

Figure 3 shows some of the results of determining the kinetics of crack growth at different deformation rates. In all the cases investigated, a decrease in τ was observed with increasing deformation rate. In addition, it is not difficult to note a general tendency for the maximum value of v' to increase with increasing deformation rate v_1 (Fig. 3). In the course of crack growth the crack velocity changes continuously. However, in principle one can select such a deformation regime in which the crack would occur at a constant velocity, traversing the same path l in an equal time interval τ. In this sense it is convenient, for a quantitative characterization, to introduce the concept of the mean-integral (or average) crack velocity v. An increase in the deformation rate of the specimens, other conditions being equal, is accompanied by an increase in the average value of the crack velocity

$$v = \int_0^\tau v'\,dt/\tau = S/\tau$$

(Fig. 3), where S is the area bounded by the curve $v' = f(t)$ and the t-axis. When the results obtained are plotted in logarithmic coordinates, a linear dependence is obtained (Fig. 4).

Fig. 3. Dependence of the crack-growth velocity of specimen SKN-40 on the deformation rate. Filming speed 1000 frames/sec. Temperature 40°. Notch width 5 mm. Deformation rate: 1—100 mm/min; 2—200 mm/min; 3—1000 mm/min

Fig. 4. Dependence of the logarithm of the mean-integral crack-growth velocity v on the deformation rate v_1: 1—SKN-40 vulcanizate; 2—SKN-18

Thus, within the range of rates investigated, the quantities v and v_1 are related by

$$v = Av_1^n, \quad (1)$$

where A and n are constants. Naturally, a more general dependence is one that takes account of crack growth at $v_1 = 0$, i.e.:

$$v = Av_1^n + f(\sigma), \quad (2)$$

where σ is the stress. However, as follows from the data presented, the second term has no appreciable effect on the value of v under the conditions of the present experiment. Comparison of the results obtained on vulcanizates differing only in the polarity of the rubbers makes it possible to conclude that an increase in the polarity of the rubbers, other conditions being equal, is accompanied by a decrease in the average crack velocity.

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Note: Figure translations are in progress. See original paper for figures.