through (2) by the theoretical strength of the material. However, one should bear in mind that the theoretical strength is then raised as the pressure increases, and for material with α satisfying (4) the amplitude of the precursor is determined by the intersection point of the pressure dependence of the theoretical strength with the dependence (1), if such a point exists in general. Another factor limiting the amplitude of the precursor is heating and melting of the material in a strong compression wave [8]. The contemporary state of the experimental data does not permit judging whether or not the situation (4) can be realized in some specified material or other having well-expressed plastic properties. The formulation of special experiments on a number of materials having suspiciously high values of α is necessary for the solution of this problem.

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DYNAMIC FRACTURING OF GLASS RODS

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UDC 539.4

Many literature sources remark that the tensile strength of rigid bodies upon dynamic loading differs from the strength under static conditions. For example, we encounter in [1] the values 2.1 and 1.4 kbar (10^3 kg/cm^2), respectively, for glass, and the dynamic value is found as a result of numerical interference of the incident measured and reflected pulses.

One can explain the discrepancy in the values of the limit in different ways, e.g., as follows. Static loading is characteristically slow in comparison with the propagation velocity of sound waves c_0 and the change in the stress state. In this case the entire rod proves to be loaded, and its strength is determined by the strength of the weakest link σ_0. In the case of dynamic action one should not discuss the entire sample but only the part of it which is entrapped, e.g., by the tension phase of a wave $\lambda = c_0T$, where T is the duration of the tension phase. It is completely natural to expect that in this part, which shifts around the sample, "its own" weakest link for λ with characteristic $\sigma_0^* \geqslant \sigma_0$ may not turn out to be the weakest link with strength σ_0 but the strongest. As λ decreases (an increase in the rate of increase), the probability of the appearance in λ of a link with strength σ_0 decreases. This may lead to an increase in the strength.

The dependence of the limiting values on loading (increase in the loading rate, decrease in the action time; e.g., see [2]) has been discussed earlier; cases are noted of the fracture of a material not in the section where active tension is increasing but where it is decreasing [2], as has been the possibility of fracture of a material not upon the first but upon the

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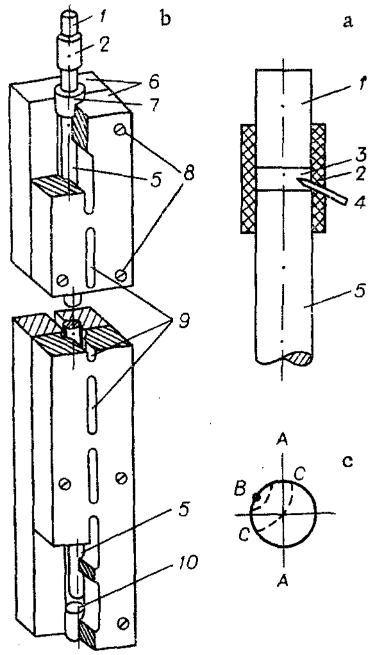

Fig. 1

second, etc., reflection of one and the same pulse [4]. However, one should keep the following ideas in mind when discussing this question.

1. Fracture of a material at a "point" and of a "sample" as a whole are different concepts [5, 6]. The first situation reflects the properties of the material, and the second one reflects the properties of the sample construction, which naturally may be changed depending on the experimental conditions. Therefore, it is understood in particular why several reflections are sometimes necessary for the fracture of a "sample," whereas the material may be fractured at a number of points already in the first stage of tension even for comparatively small stresses.

2. It is very important to have accurate data on the stress—strain state of the medium at the point of fracture. One can prove that arbitrariness in the predetermination of incomplete experimental data (signal shape, amplitude and nature of the damping, and so forth) offers the possibility in connection with the interpretation of one and the same experiment of calculating values of the strength limit which differ by a factor of several times depending upon the assumptions [7].

Definite possibilities have been exhibited in this respect in experiments on objects made out of glass, e.g., rods. The organization and results of such an experiment are discussed in this paper. A photoelastic pattern is specified here [8, 9] which permits assessing the stress state of a material, and simultaneously with this the instant of fracturing [3].

The experiments are conducted on glass rods with a diameter $d = 4.4$-4.75 mm and a length $L = 500$-1400 mm. The velocity of the longitudinal wave measured by the method of dynamic photoelasticity under conditions of photorecording [9] is equal to $c_0 = 5.16 \cdot 10^3$ m/sec. The density of the glass is $\rho = 2.2$ g/cm^3. The optical constant with respect to stress $\sigma_0^{1.0} = 310$ MPa (kg/cm^2) is determined with a freely suspended cylindrical rod ($d = 4.8$ mm, $L = 300$ mm) at a distance $l = 250$ mm from the end loaded by a pulsed load. Simultaneous recording of a movie of the interference bands $m(t)$ and the longitudinal shifts $u(t)$ was carried out with $15\times$ magnification in a photorecorder system by the procedure of [3]. A polarization-optical apparatus based on an SFR-1 camera [9, 10] was used. Light with a wavelength $\lambda_1 = 644$ nm was used for the photography in all the experiments, including the calibration experiments.

Pulsed loading was accomplished by the detonation of explosive charges (lead azide) with a weight of 5-10 mg on the end faces. The charge equipment (Fig. 1a) consists of a steel packing cylinder 1 and a limiting polychlorvinyl tube 2. Ignition of the charge 3 was done with the help of a needle electrode 4. Changing the position of the needle and the charge size permits varying the shape and size of the explosive effect.

TABLE 1

Expt. No.	Charge wt., mg	Rod length, mm	Distance of mark from loaded end of rod, mm	Rod diam., mm	Distance from free end (mm) and nature of fracture zones
1(8)	5	500	490	4,5	2—5(II), 5(IV), 5—8(II), 28—33(III), 109(IV), 120—124(V), 314(IV)
2(14)	10	500	490	4,5	0—10(I), 12(IV), 33—36(III), 82—86(V), 106(IV), 179—182(III), 204—209(V), 269, 313(IV), 341(VI), 383—388(IV), 429—435, 440—445, 452—463, 463—470(III), 473—485(V)
3(17)	10	783	700	4,75	0—15(I), 41—48(III), 72—74, 90—95, 155—159, 335, 372(IV), 374—378, 425, 429—440, 696—700(V), 710(VI), 724—728, 745—750(V), 759—774(VII).
4(19)	10	1080	1000	4,5	0—20(I), 20—29, 35—44, 65—72(III)
5(24)	10	1386	1250	4,6	0—18(I), 18—24(III), 54(IV), 60(III), 63. 67, 101, 106, 112, 136, 161, 209, 226, 238, 258, 302(IV), 306(III), 342, 390, 407, 436, 453, 462. 496(IV), 526(V), 594—597(I), 637—639, 647(III). 712—715(I), 758, 794, 910, 935, 957(IV), 966—974(I), 996(III)
6(25)	10	1350	—	4,65	0—18(I), 18, 20(IV), 22—30(III), 32. 64, 73, 106, 233(IV), 268—273(III), 298(IV), 312, 342(III), 391, 432, 442, 446(IV), 523—525(III), 560, 614, 620, 622(IV), 692—698(III), 791(IV)
7(27)	10	1245	1000	4,6	0—15(I), 15—21(III), 60, 147, 148, 154, 254, 305(IV), 371—377(III), 409, 422, 531(IV). 540(III), 590(IV), 634(VI), 640, 681, 687, 704, 706, 723(IV), 768—772(III), 910, 912(IV)

In order to prevent the fractured particles from flying apart, the glass rod 5 is mounted in a specially developed split casing 6 (Fig. 1b). The rod freely hangs in the casing supported only by a rubber bushing 7. The casing is secured by connecting screws 8. Inspection windows 9 are left for recording the photoelastic pattern. The gap between the free end of the rod and the rubber stop 10 is equal to 1 mm. The proposed construction of the casing permits maintaining the mutual position of the fractured parts of the rod. After the experiment it is necessary to place the casing on its back side, remove the front side, and carry out the analysis and measurement of the fracture fragments.

The cross section of the glass rod is also shown in Fig. 1c, where the line A—A is the observation plane, B is a possible initial fracture point, and C—C is one of the positions of the fracture front.

A total of 82 experiments were performed by the procedure described, and the results obtained in seven of them are discussed in this paper. The conditions under which they were conducted and the geometrical characteristics are presented in Table 1, where the numbering of the experiments is given in the first column in order of the discussions and in parentheses in the order in which they were performed; furthermore, the charge weight, length and diameter of the rod, and the position of the point (mark) of the film recording (in millimeters) are shown, and the position from the free end (in millimeters — Arabic numbers) and the nature of the fracture (Roman numerals in parentheses) are also noted. The Roman numerals denote: I — intensive fracture, II — zone of fine cracks which do not disrupt the integrity of the rod, III — branching of cracks from one point located approximately in the middle of the corresponding fracture zone, IV — one crack across the rod (such a crack most often is designated as a cleaving), V — a single inclined crack, VI — cracks situated in a crisscross pattern, and VII — a zone of logitudinal cracks.

A kinogram of the loading process and its interpretation at the fracture point at the instant noted by a cross on the diagram is shown in Fig. 2 (m is the number of bands). One can see the front of the loading wave (A—A) with the succeeding alternate tension and compression phases and the front of the wave reflected from the free end of the rod (B—B), in whose interior a series of cracks arises; the presence of a series indicates possible branching. The diagram shows that the loading process is close to one-dimensional, although it is not. The ratio of the length of the fundamental compression phase to the travel time of the wave across the rod (~0.9 μsec) is within the limits of 5-7. The complicated nature of the loading diagram (multiple succession of tension—compression phases, comparatively

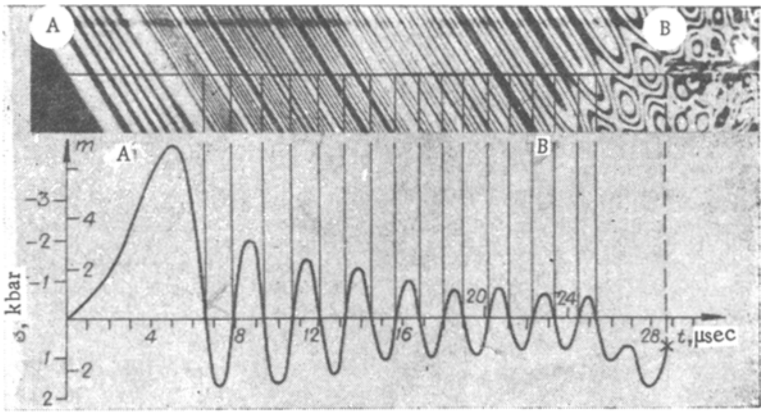

Fig. 2

TABLE 2

Expt. No.	8	14							17	19	24	25	27
kbar	2,6 (2,95)	4,9 —	5,85 —	5,2 —	6,1 —	5,85 —	4,5 —	2,95 (3,05)	1,65 (2,65)	0,65 (2,3)	1,5 (2,0)	1,5 (2,0)	0,65 (2,0)

large amplitudes of these phases) is an indicator of the non-one-dimensional nature. As a result of such nonunidimensionality, it is possible for fracturing of the rod to occur even upon the passage of the incident pulse (in its tension phases), and an exceedingly rich set of fracture patterns diverse in nature occurs (see Table 1).

The loading diagrams presented in Fig. 3 are very characteristic in this sense. If in experiment 19 tension phases in the incident wave proved to be insufficient for fracture and it occurred behind the front of the wave reflected from the free end (Fig. 2), then fracture in experiments 17, 24, 25, and 27 (Fig. 3a), whose instant of onset is noted by crosses on the diagrams, could occur in the tension phases of the incident wave. The onset of fracturing, which has not yet entered the region of visibility, is noted on the curve of experiment 17 by a point on the first tension phase, and the instant of the appearance of a crack in the visibility region is noted by a cross on the second phase.

The diagrams at seven adjacent points in experiment 14 located respectively at a distance from the free end of the rod as given are shown as dashed lines (Fig. 3b): curve 1) 3.4 mm, 2) 4.7 mm, 3) 6.0 mm, 4) 6.4 mm, 5) 7.9 mm, 6) 9.7 mm, and 7) 11.9 mm. At all these points fracture occurs at the instants of time indicated by the crosses. This experiment is similar to traditional cleaving, in contrast to the preceding ones. The case (experiment 8) shown in Fig. 3c is most similar of all to the traditional cleaving experiment. Here the diagram in the incident wave is given by curve 1, and curve 2 corresponds to variation of the longitudinal stress at the fracture point (the cross denotes the instant of fracturing) at a distance of 3.7 mm from the free end.

Figure 4 demonstrates a number of interesting elements of the kinograms of the experiments under discussion here. Multiple fracturing in experiment 14 is shown in Fig. 4a. The compression phase I with a ridge of maximum values A_1—A_1 is visible; fracturing starts in the tension phase II and has the form of an extensive black region — a continuous zone of crushing. This zone starts from a series of single cracks (the "tongues" on the left side of the black region); all seven cracks arose independently of each other at closely spaced times. The visible crack on the kinogram of experiment 17 (Fig. 4b) arose at the instant D_1. However, perturbation of the incident pulse of the wave E—E shows that there is already an initial fracture at the instant D_0 in the investigated cross section (the plane of the crack and its continuation, which is shown by a dashed line to the intersection with the perturbation wave E—E). The fracturing occurred in this case at the instant D_0 at the point B (Fig. 1c), which is not located in the observation plane A—A. This instant proved possible to establish from the perturbation wave E—E which accompanied the developing perturbation. At the instant D_1 the fracture front C—C (crack) intersects the observation beam and becomes

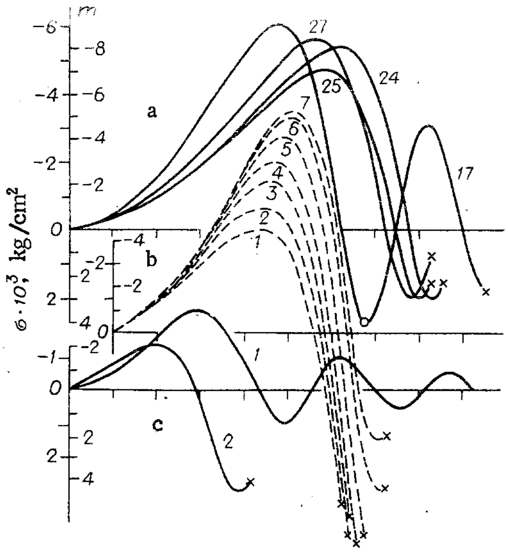

Fig. 3

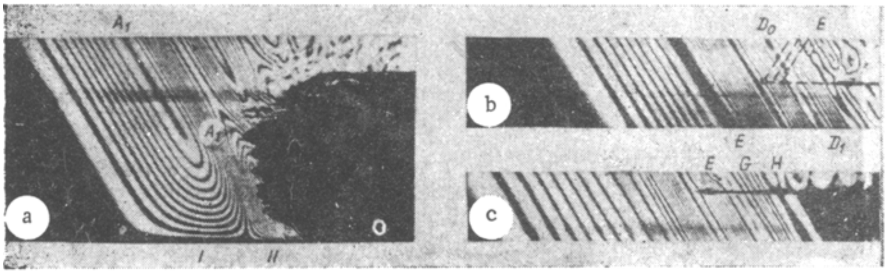

Fig. 4

visible. These peculiarities found the following reflection on the corresponding diagram in Fig. 3a: open circle — start of fracturing; asterisk — visible crack. At first, a small opening of a crack at the instant F is observed in experiment 27 (Fig. 4c); then its subsequent narrowing is the phase of the next compression at the instants G, and finally its new reopening at the instant H and further development. All of this shows that the onset of fracturing — the incipient defect at point B (see Fig. 1c) — turned out to be close to the observation plane A—A.

The strength properties of the material are usually determined from the data of Fig. 3 and data similar to those. Such a selection of values for the critical stress σ_0 is presented in Table 2, where the numbers in parentheses show the maximum tensile stress which the material withstood at the point under investigation without fracturing.

It is interesting to note two facts: the absence of a unique value which one could adopt (from these data) as the tensile strength limit under dynamic conditions; and the fact that on many curves the instant of fracture is noted on the section of the decline of active tension, and the "critical" value is sometimes several times less than the maximum tension.

One can explain this circumstance in various ways. One should note in the first place that the data obtained require some correcting: a) a correction for nonunidimensionality gives a small reduction of the amplitudes, although it reduces the scatter hardly at all; b) one can most likely expect a more significant improvement in this sense upon refinement of the instant of fracture. The place of onset of fracturing can be situated at an arbitrary distance from the observation beam A—A (Fig. 1c); this distance lies within the limits l_1 = (0–0.5)d. If one takes for the rate of propagation of the crack its maximum possible value c_{cr} = 0.38 c_0 [11], then there appears a sufficiently extensive possibility of refining the instant of fracturing to $\Delta\tau \approx$ 0–1.2 μsec.

Returning to the experiments presented above, we see that one can estimate the place and instant of fracturing (the open circle in Fig. 3a and the instant of time D_0 in Fig. 4b) rather accurately in experiment 17; the fracture site in experiment 25 is very close to the observation line. This fact gives numbers for the strength limit of the order of σ_0 = 2.0-

2.6 kbar, which are similar to those indicated in [1]. One should thereby note that glass withstands rather large tensile stresses (up to 6 kbar) not only within the medium but also on the boundaries (along the ray direction), and consequently we are dealing with a material whose strength is arbitrary and is determined by defects located on the surface (a case of fracturing from an internal defect occurred in one of the 82 experiments). It is necessary for an accurate determination of the strength characteristics of a material to have even more accurate data on the stress state at the fracture point.

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CONSTRUCTION OF THE TIME DEPENDENCE OF THE RELAXATION OF TANGENTIAL STRESSES ON THE STATE PARAMETERS OF A MEDIUM

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A change in the stress state of real rigid bodies can occur not only as a result of movement of the medium but also in the absence of any macroscopic displacements of the medium at all and inflow or outflow of heat from its elements. It was proposed by Maxwell to characterize this process as a decrease of the tangential stresses, and the concept of their relaxation time has been introduced. These ideas underwent further development in [1-3], in the first of which a representation of the relaxation time τ of the tangential stresses is discussed from the molecular-kinetic viewpoint, and in the other models are formulated and analyzed of media having a nonlinear dependence of τ on the temperature and stresses. Unfortunately, methods are presently lacking for direct experimental determination of the relaxation time in the case of intensive dynamic loads. In order to determine τ, it is necessary to use indirect experimental data, including at the same time different models of a deformable rigid body. An interpolation formula of the dependence for some metals derived on the basis of information existing in the literature about the dependence of the dynamic yield point σ_T and the tensile strength limit on the deformation rate $\dot{\varepsilon}$ has been given in [4] and then refined in [5]. A dependence of the relaxation time of the tangential stresses on their strength σ, the values of the shear (plastic) strain, and the temperature T is constructed in this paper on the basis of dislocation concepts concerning the mechanism of the relaxation process with the inclusion of a model of a viscoelastic body [3] and experimental data similar to that used in [4, 5].

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