

BREAKDOWN IN TRANSPARENT DIELECTRICS CAUSED BY INTENSE LASER RADIATION

B. M. ASHKINADZE, V. I. VLADIMIROV, V. A. LIKHACHEV, S. M. RYVKIN, V. M. SALMANOV, and I. D. YAROSHETSKIĭ

A. F. Ioffe Physico-technical Institute, Academy of Sciences, U.S.S.R.

Submitted to JETP editor November 30, 1965

J. Exptl. Theoret. Phys. (U.S.S.R.) 50, 1187-1201 (May, 1966)

The breakdown of a number of transparent dielectrics caused by an intense laser radiation was investigated. The nature of the breakdown due to ordinary and giant pulses is described and the size of the destroyed region is investigated as a function of energy, location of the focus, focal length of the lens, and temperature. It is shown that the breakdown mechanism based on coherent hypersonic phonons, generated in the course of a stimulated Mandel'shtam-Brillouin process, is the least contradictory.

INTRODUCTION

THE recent appearance of intense sources of coherent electromagnetic radiation in the optical range affords an opportunity to launch large-scale research on the interaction of such radiation with matter. Of considerable interest here is the study of breakdown processes of solids caused by intense laser radiation and, in particular, the breakdown in transparent dielectrics. Whereas the basic difficulty in the problem of opaque solid breakdown resides in the understanding of the kinetics of the act of breakdown itself, the light absorption mechanism being self-evident, in the case of transparent substances, the very mechanism of light absorption and the transformation of the absorbed electromagnetic energy into the breakdown energy, as well as the subsequent development of the breakdown process, are prime objects of interest.

The breakdown in transparent dielectrics caused by laser radiation was already observed before.^[1-6]

In particular, breakdown caused by a giant pulse at the point of emergence of the light beam from glass has been described in^[1], and evidence of breakdown at the focal point of the laser beam has been confirmed in^[6]. Unfortunately, there is no general agreement as to the particular mechanism responsible for the breakdown. In view of this, it would be appropriate to attempt a more detailed investigation of the breakdown processes in transparent dielectrics subjected to intense laser radiation. Such, then, is the purpose of the present work.

1. EXPERIMENTAL PROCEDURE

Ruby and neodymium lasers, generating photons with energies of 1.79 and 1.17 eV respectively, were used as radiation sources in this work. Both types of lasers were used in order to clarify the effect of polarization and photon energy upon the nature of the breakdown. As it developed, however, the qualitative character of the breakdown was the same for polarized radiation (ruby) and for unpolarized radiation (neodymium). Consequently, all the experiments were later carried out with the neodymium laser, which could operate in the ordinary-pulse and giant-pulse modes. The neodymium rods were 12×120 mm. In the ordinary-pulse mode, the energy reached 20 J for a total pulse length of about 5×10^{-4} sec and pulse rise time of 1×10^{-4} sec. In the giant-pulse mode, the pulse energy reached 2 J and the pulse was triangular in shape, having an approximate half-power width of $(2-3) \times 10^{-8}$ sec.

The energy incident upon the specimen could be controlled, when necessary, within wide limits by means of specially calibrated neutral filters. The pulse energy was measured with a vacuum calorimeter, and the pulse itself was recorded by a rapid-acting photodiode and displayed on the screen of the S1-29 long-persistence oscilloscope (ordinary pulse), or the pulse was photographed off the screen of the ISO-1 oscilloscope (giant pulse). In the case of an ordinary pulse, the Fabry-Perot resonator had plane-parallel plates coated with multilayer dielectrics whose reflection coefficients were 99.5 and 60% respectively.

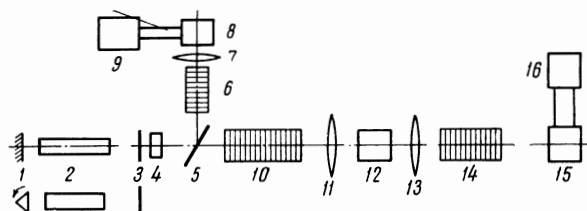


FIG. 1. Diagram of the experiment. 1 – Totally reflecting mirror, or rotating prism; 2 – ruby or neodymium rod; 3 – partially reflecting mirror or plane-parallel plate; 4 – light filter to cut off pump lamp; 5 – plane-parallel plate; 6, 10, 14 – neutral filters; 12 – specimen under investigation; 7, 11, 13 – lenses; 8, 15 – photodiodes; 9, 16 – oscilloscopes.

In the case of a giant pulse, a rotating prism (24,000 rpm) and uncoated plane-parallel plates were used. The diagram of the experiment is given in Fig. 1.

Three different groups of materials were selected as the objects of the experiments:

1. alkali-halide single crystals: LiF, NaCl, CsI, KBr, KI, and others;
2. polymers: polymethyl methacrylate (Plexiglas), polystyrene;
3. glasses: K3 silicate glass, fused quartz.

The specimens were parallelepipeds with polished faces and dimensions varying from 0.1 to 25 cm in length and from 1 to 25 cm² in cross-section. The character of the breakdown was observed under a microscope, and the size of the breakdown region was measured with a horizontal comparator.

2. EXPERIMENTAL RESULTS

Transmittance Curves

The effect of incident beam intensity upon the magnitude and time dependence of light transmitted by the specimen was investigated in order to obtain information on the kinetics of breakdown development. Figure 2a shows a typical transmittance curve for polymethyl methacrylate for the case of an ordinary pulse. It can be seen that light

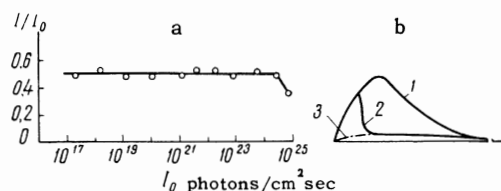


FIG. 2. a – Relative transmittance of light as a function of incident light intensity; b – oscilloscopic traces illustrating the kinetics of the breakdown process: 1 – transmitted light pulse at below-critical energies; 2 – same at above-critical energies; 3 – same at repeated irradiation.

transmittance practically does not change within a fairly wide range of incident light intensities. A certain value of intensity, critical for a given substance, causes a sharp drop in transmittance; the drop coincides with an avalanche-like breakdown of the substance. Analogous relationships were observed in all other substances under investigation.

Figure 2b shows oscilloscopic traces, normalized to a standard dimension, which indicate that the breakdown causes an almost complete screening of the light beam and that it can develop within a pulse length. In the case of the second pulse of light, the intensity of the transmitted pulse will naturally correspond to the transmittance of the destroyed substance (curve 3 in Fig. 2b). This is additional evidence that the intensity drop in the trace of Fig. 2b is attributable to the breakdown development.

Investigation of the onset of the breakdown (marked by the drop in the oscilloscopic trace) showed that increasing intensity of incident light, I_0 (if $I_0 > I_{cr}$), shortens the time interval preceding the onset of the breakdown.

Character of Breakdown

First of all, one should note the essential difference in the nature of the breakdown in the cases of ordinary and giant pulses. Ordinary pulse in polymethyl methacrylate and polystyrene produces plane cracks running approximately at an angle of 45° to the axis of the laser beam and distributed at random with respect to the rotation of the crack plane about this axis. Beam energies considerably higher than the threshold result in a large number of cracks, of the order of several dozen; the cracks are separated by regions of intact material over several mm long (especially with long-focus lenses). It can be seen in Fig. 3a that most of the cracks are small, of the order of 1 mm or even less; however, there are also large cracks with diameters of 1 cm, i.e., of the same order as the diameter of the laser beam. Secondary breakdown (Fig. 3b), caused by the reflection of the laser beam from individual cracks, has frequently been observed. The axis of the secondary breakdown forms an angle of 90° with that of the main laser beam. The overwhelming majority of large cracks are intersected by the light beam axis near their ends, rather than in the center of the crack.

When the ordinary pulse was focused in glass, within the specimen or near its forward face, no breakdown was observed even in the case of maximum energies used (20 J). On the other hand, the beam focused on the rear face produced splitting

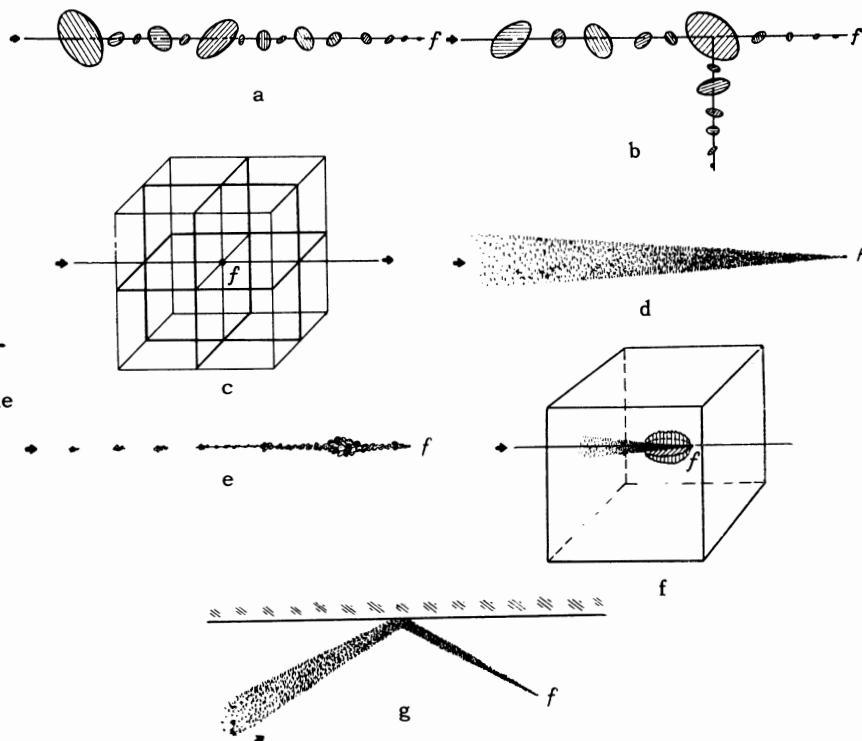


FIG. 3. Various kinds of breakdown (schematic). Arrow indicates the direction of the light beam; f — position of the focus. a — Breakdown due to ordinary pulse in polymethyl methacrylate and polystyrene; b — same, breakdown due to beam reflected from a crack; c — breakdown due to ordinary pulse in alkali-halide crystals ($E \approx 2E_{cr}$); d — breakdown due to a giant pulse in polymethyl methacrylate, polystyrene, and CsI single crystals; e — same for glass; f — same for alkali-halide crystals; g — same for total internal reflection in polymethyl methacrylate.

similar to that described in [3], but much larger, tending towards total destruction of the specimen.

In the alkali-halide crystals LiF, NaCl, KBr, and KI, an ordinary pulse focused on the surface or within the crystal produced cracks in the cleavage plane. At the same time, energies only twice as high as the threshold caused cracks large enough to destroy completely small (2 cm) crystals (Fig. 3c). Splitting occurred in one, two, or all three cleavage planes. In large crystals, the cracks failed to emerge to the surface regardless of the pulse energy (20 J). In the case of high energies, several cracks were formed in cleavage planes perpendicular to the beam.

It should be noted that the threshold energy required to initiate the breakdown is correlated with the elastic properties of crystals and the width of the forbidden gap. Of interest is the breakdown nature in CsI and AgCl crystals, which have the narrowest forbidden gap. When focused on the surface, the laser beam burns a hole in the crystal (as it does in metallic materials); however, when it is focused within the crystal, the laser causes a random breakdown, although limited to the dimensions of the beam.

Breakdown in polymethyl methacrylate and polystyrene caused by a focused giant pulse has its own special features. The breakdown region has the shape of a strongly elongated cone consisting of very fine (about 0.1–0.5 mm) cracks whose density smoothly increases towards the focal point,

reaches a maximum somewhere in its vicinity, and again decreases, turning to zero at the focal point itself. At the point of maximum density, the number of cracks is usually so large as to present an aspect of total destruction. Unlike the flat cracks caused by the ordinary pulse, the region damaged by the giant pulse consists of local irregularities resembling “stars” with random orientation. Minute flat cracks are sometimes also observed, similar to the cracks encountered in the case of an ordinary pulse. On the whole the picture resembles the tail of a comet (see Fig. 3d).

Giant pulse breakdown in K-3 glass has a sharply defined filamentary character, the filaments being markedly thickened in the focal region (Fig. 3e). The position of the breakdown filaments apparently corresponds to the maxima (with respect to the cross-section) of laser beam intensities. The cracks show no regular orientation away from the focus and are separated by large regions of undamaged material. Near the focus, the cracks as a rule form rosettes of planes intersecting along the beam axis. When high energies per pulse (2 J) and lenses of short focal length ($f \lesssim 30$ mm) are used, the nature of destruction changes both in glass and in polymethyl methacrylate. The cracks then form a large rosette due apparently to a point explosion within the specimen. (The nature of breakdown in glass of different composition may be different.)

In alkali-halide crystals (LiF, NaCl), the break-

down due to a giant pulse directed along [100] runs along all cleavage planes (100) (similarly to the case of large crystals exposed to an ordinary high-energy pulse). Cracks running in planes (100) perpendicular to the beam axis [100] form a cone converging at the focus, while planes (010) and (001) contain only two cracks of quite large dimensions which start near the focal point and intersect on the beam axis (see Fig. 3f). Investigation shows that the large cracks consist of fine, parallel, and very closely spaced microcracks.

In CsI crystals, the giant pulse causes a total destruction (within the limits of the light cone) similar to that in polymethyl methacrylate (Fig. 3d).

Figure 4 shows a photograph of breakdown in polymethyl methacrylate due to an ordinary pulse.



FIG. 4. Photograph of a breakdown in polymethyl methacrylate due to an ordinary pulse.

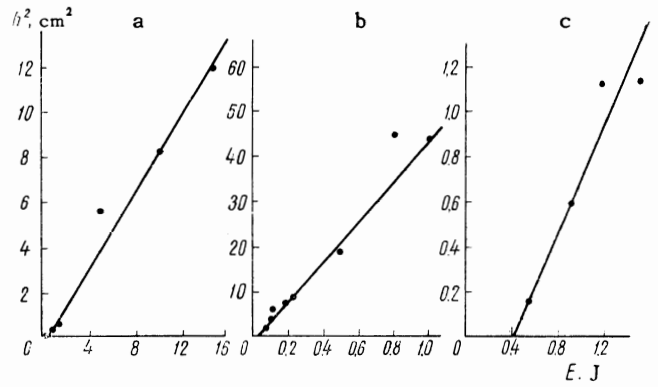


FIG. 5. Square of breakdown region size h , as a function of pulse energy E . Focal length of lens, $f = 6.1$ cm. a – ordinary pulse in polymethyl methacrylate; b – giant pulse in polymethyl methacrylate; c – giant pulse in glass.

spect to the specimen upon the length and nature of the breakdown region. Figure 6 (curve 1) shows the result for polymethyl methacrylate (the case of the ordinary pulse). It is a non-monotonic relationship: there is a maximum when the focal point is located some distance in front of the front face of the specimen, and a minimum close to zero when the beam is focused on the front face. The length of the breakdown region then rises linearly as the focal point moves into the interior of the specimen, reaches saturation, and, finally, gradually decreases to zero as the focal point is brought to the rear face. It should be noted that no breakdown has ever been observed beyond the focus when the focal point is within the specimen. The breakdown diagram (Fig. 7a) shows this condition with particular clarity.

No analogous curves were plotted for glass and crystals because of the reasons stated above.

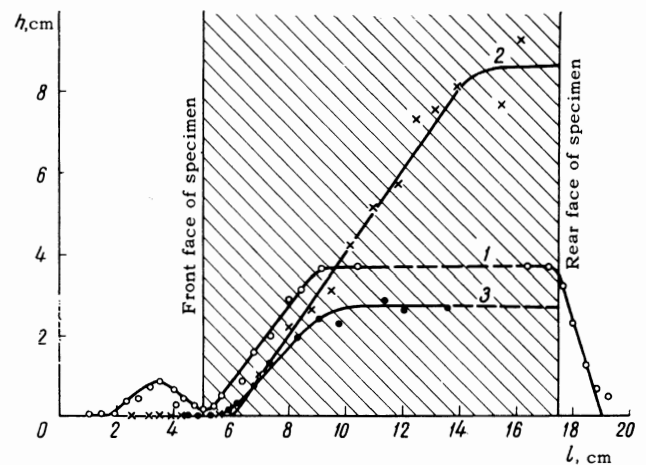


FIG. 6. Breakdown size h , as a function of focus location. Lens with $f = 6.1$ cm. 1 – Ordinary 10.8-J pulse in polymethyl methacrylate; 2 – giant 1-J pulse in polymethyl methacrylate; 3 – giant 1-J pulse in glass.

The Effect of Pulse Energy

The dependence of breakdown upon pulse energy is quite appreciable. Figure 5a shows the effect of the energy E of an ordinary pulse on the length h of the breakdown region in polymethyl methacrylate. The relationship obtained has the form, $h^2 \sim E - E_{cr}$, where E_{cr} represents the critical energy required to start the formation of first cracks at the focus. Attempts to obtain analogous curves for glass and alkali-halide crystals encountered difficulties, since no breakdown was observed within the glass exposed to an ordinary pulse, while alkali-halide crystals split off completely along the cleavage planes even when the energies barely exceeded the critical value.

In the case of the giant pulse, the dependence of the breakdown length squared upon pulse energy in polymethyl methacrylate (Fig. 5b) and glass (Fig. 5c) is analogous to the above: $h^2 \sim E - E_{cr}$. It seems significant that the breakdown threshold is approximately 10 times higher in glass than in polymethyl methacrylate; this number is equal to the ratio of their moduli of elasticity.

Effect of Focus Location

The next series of experiments investigated the effect of the position of the lens focus with re-

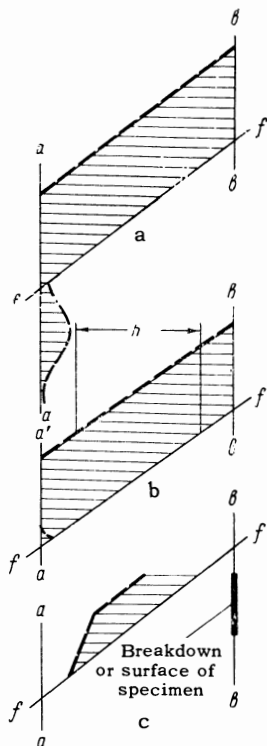


FIG. 7. Diagram of breakdown. Cross-hatched breakdown region due to successive breakdowns caused as the focus was moved along the line ff' . The cross-hatching lines show dimension and location relative to ff' of the breakdown region for each breakdown. a – ordinary pulse in polymethyl methacrylate; b – giant pulse in polymethyl methacrylate; c – giant pulse in glass.

Figure 6 (curves 2 and 3) shows the effect of the focal position on the nature and size of damage caused by a giant pulse in polymethyl methacrylate and in glass. It is clear that curves 2 and 3 are precisely analogous to curve 1 in Fig. 6, except for the fact that no damage occurs when the focal point is located ahead of the front face; this is due to the absorption of beam energy by plasma from an air breakdown near the focal point. Particularly significant is the effect of the air breakdown upon damage in glass, as shown by curve 3 in Fig. 6 (because of the considerable volume strength of glass). The start of damage occurs in this case only after the focal point has been moved to a considerable depth into the specimen. Saturation in breakdown size is obtained when the distance from the focal point and the front face of the material is markedly larger than the length of the breakdown region. The corresponding diagrams are given in Figs. 7b and 7c. Furthermore, glass also shows additional splitting off the rear face of the specimen, even when the beam energy is too low to cause volume breakdown. Similar splitting appears when the radiation is focused in the interior, near the rear face. In the latter case, the region of volume breakdown is separated from the region of surface splitting by intact material; the splitting takes place regardless of the fact that the major part of the energy of the light beam has been absorbed in the breakdown region at the focus. This

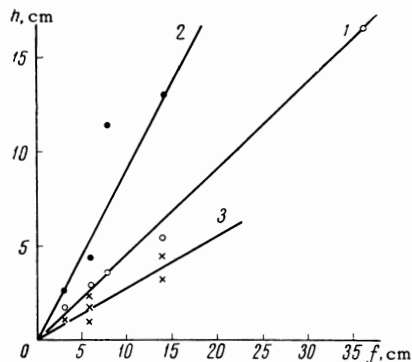


FIG. 8. Breakdown region size h , as a function of focal length f of the lens. 1 – ordinary 12.8-J pulse in polymethyl methacrylate; 2 – giant 1-J pulse in polymethyl methacrylate; 3 – giant 1-J pulse in glass.

shows that in glass surface strength is much lower than volume strength.

Similar experiments with LiF indicated a slight difference between the volume and surface strengths of this material, while no difference whatever was found in the case of polymethyl methacrylate.

The Effect of the Focal Length of the Lens

The investigation also included the effect of the focal length of the lens upon the size and nature of the damage. Figure 8 shows the dependence of the length of the breakdown region for the cases of the ordinary and giant pulses in polymethyl methacrylate and glass. The size of the breakdown region appears linearly related to the focal length in all cases. Short focal length lenses also change the nature of the damage; they facilitate the development of a thermal explosion in the focal region when high-energy pulses are used.

The Effect of Temperature

Some experiments were carried out at depressed and elevated temperatures in order to clarify the breakdown mechanism. These experiments involved polymethyl methacrylate exposed to the ordinary and giant pulses. It was found that

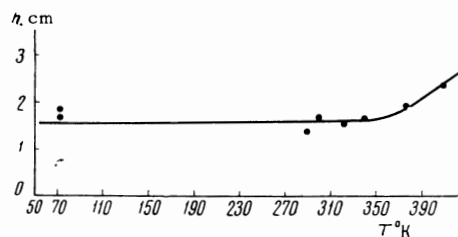


FIG. 9. Breakdown region size h , as a function of temperature in polymethyl methacrylate. Lens $f = 6.1$ cm. Ordinary 10.8-J pulse.

temperature within the range from 77 to 370° K failed to show any noticeable effect upon the nature and size of the damage. At high temperatures, a peculiar melting of the material was observed in the focal region, the cracks began shifting their orientation from an angle of 45° to that approximately perpendicular to the laser beam, and the crack density increased. Figure 9 shows how the temperature affects the size of the breakdown region.

Multiple Irradiation

As pointed out above, the experiments revealed the existence of a critical intensity of the laser beam, which must be reached before noticeable damage begins. There are two possible explanations of this fact: (1) a new mechanism of light absorption arises at threshold intensity and leads to the breakdown; (2) while the critical intensity is related to a certain level reached by the stresses, the threshold intensity of light absorption, even if it exists, must be much lower; however, we fail to observe this absorption (see Fig. 2a) because of the inadequate accuracy of measurement of the transmitted light (5% error). To clarify this problem, experiments were undertaken in which a polymethyl methacrylate specimen was repeatedly exposed at 2 min intervals to a focused laser beam with an intensity below the threshold value. Breakdown was observed to occur even in this case, and the number of exposures necessary to start the breakdown process was inversely related to energy per pulse as compared to the critical energy. The very concepts of "critical" energy and "sudden" breakdown must obviously be relative, since they are strongly dependent upon the accuracy and method of observation. Nevertheless, the multiple-exposure experiments have a definite meaning, since they indicate the absence of a unique breakdown threshold as manifest by the discontinuities in the transmittance oscilloscope traces, and the absence of a unique stimulation threshold for hypersonic phonons.

Microscopic Observations

Microscopic observation of LiF single crystals, selectively etched to reveal dislocations, helped establish the fact that no new dislocations were detected in the irradiated crystals either in the case of intensities below the critical, or in the breakdown region (except for the split-off surface). However, in both cases there was a marked change in the effect of the etch: after etching, the structure of the irradiated region was substantially different from the initial structure.

3. EVALUATION OF RESULTS

The mechanism of breakdown in transparent materials exposed to laser radiation is the most interesting aspect of the problem under consideration. The probable mechanisms may be listed as follows: (1) light pressure; (2) electric breakdown; (3) heating by direct absorption of the laser beam by matter, or by scattering of coherent phonons; (4) direct breakdown by coherent phonons generated in the course of stimulated Mandel'shtam-Brillouin processes.^[1]

Stresses caused by a direct action of light upon matter (designated as light pressure) are due to the following causes: (1) reflection of light from surfaces, (2) electrostriction, (3) transmission of a light pulse by the irradiated portion of the solid volume. In the first two cases, stress is proportional to the power density of the light beam. Critical densities available even in a giant pulse ($\sim 50 \text{ MW/cm}^2$ in polymethyl methacrylate) do not drive the stresses beyond 10^{-3} kg/mm^2 in the case of the reflection of light, or beyond 10^{-5} kg/mm^2 in the case of electrostriction. Stresses caused by the interaction of exposed and unexposed volumes (third case) is proportional to the energy flow density in the pulse and, at critical energies available even in an ordinary pulse (in polymethyl methacrylate $\sim 100 \text{ J/cm}^2$), do not exceed 10^{-5} kg/mm^2 . Consequently, the pressure of light can be neglected.

Nor does electric breakdown apparently occur. In polymethyl methacrylate, for example, electric fields corresponding to the critical intensities amount to only 15 kV/cm for an ordinary pulse and to $\sim 100 \text{ kV/cm}$ for a giant pulse. This, at least in the case of the ordinary pulse, falls considerably below the static breakdown voltage. High-frequency breakdown is all the more impossible, so long as we assume that there are no impurities with a low local electric strength. Furthermore, arguing against the electric breakdown mechanism are also certain qualitative considerations, such as the orientation of cracks in polymers and the difference in the breakdown of the entrance and exit surfaces in glass.

The following remarks are in order with respect to the role played by heating in the breakdown process. Numerical estimate shows that heating cannot be the sole cause of breakdown in polymethyl methacrylate. Given threshold intensities available even in an ordinary pulse (100 J/cm^2), thermal stress does not exceed 0.02 kg/mm^2 ; for a giant pulse (2 J/cm^2), the stress will be approximately 50 times lower. (This corresponds to a heating by $1-2^\circ$ for an or-

dinary pulse.) However, as will be pointed out later, the liberated heat may play a substantial role in certain secondary effects when, under specified experimental conditions, cracks already formed in the incipient breakdown region are subject to a very large concentration of absorbed energy.

The thermal concept has also been contradicted by experiments with fused quartz, whose breakdown hardly differs from that of glass, but whose thermal stresses are almost two orders of magnitude lower. The fairly peculiar nature and orientation of cracks in polymethyl methacrylate further testify against the thermal nature of breakdown. As shown above (Fig. 3a), the cracks in that case are always oriented at 45° to the axis of the light beam. Since cracks in this material tend to be opened by primary normal stresses, and the primary components of the thermal stress field coincide in a cylindrical coordinate system, with the radial, axial, and circumferential stresses, the crack orientation could not have assumed the 45° angle if the breakdown process had a thermal character. One could sooner expect that tangential stresses, $\sigma_{\varphi\varphi}$, would cause the cracks to form a family of planes intersecting along the light-beam axis, as is the case with short focal length lenses and high energies in the focal region.

In view of the experimental data obtained, it is our opinion that the least contradictory breakdown mechanism is based on coherent hypersound generated directly by the laser beam.¹⁾ Of all the above mechanisms, only the last one is apparently capable of explaining the fact, strange as it may seem at a first glance, of the 45° orientation of microcracks in polymethyl methacrylate. To do this, it is enough to assume that the light wave generates two kinds of phonons: axial and transverse.

Indeed, as Davidenkov^[8] has shown, to generate and to open up cracks, two stress components must be present, viz., shear and normal stresses applied, say, parallel and perpendicular to the crack plane. The shear stress is necessary to generate the crack, while the normal stress subsequently forces its opening. The crack-generating shear stress acting in the plane of the crack is caused by the axial hypersonic compression-expansion wave (axial phonons) which, as is seen in Fig. 10, produces shear stress at just the angle

of 45° to the direction of the light beam. On the other hand, stresses normal to the crack plane, tending to open the crack, are created by the hypersonic shear wave (transverse phonons). This wave causes the appearance of maximum normal stresses also at the angle of 45° to the beam direction. Of course, given the axial and transverse hypersonic waves, there are also other directions (such as, perpendicular to the beam) associated with both, tangential and normal stresses. The absence of cracks along these directions is evidence of definite relations between the intensities of the axial and transverse hypersonic waves.

The above considerations may serve as a basis for an attempt to define a strength criterion. Let us assume that a portion of the absorbed light energy is transformed into the energy of coherent hypersound. The scattering of sound during the pulse time is neglected at first (this means that we neglect the loss-of-coherence processes, or processes of elastic-to-thermal energy transformation). Such an approximation is equivalent to an assumption that the relaxation time τ is considerably longer than pulse length t_p . Then, if the energy per pulse is E , the coefficient of transformation of the absorbed energy into hypersound is $\alpha < 1$, and the effective absorption coefficient is k , then the energy E_{ph}^0 of the generated phonons per unit volume will be

$$E_{ph}^0 = \alpha k E / s, \quad (1)$$

where s is the effective beam cross-section area at the point under consideration.

Equating E_{ph}^0 to the total energy of coherent phonons, consisting of elastic energy E_{ph}^e and kinetic energy E_{ph}^k , we get

$$\alpha(E_{ph}^e + E_{ph}^k) = E_{ph}^0. \quad (2)$$

Here $\alpha \approx 3$ is the coefficient accounting for the presence of three kinds of phonons, two transverse and one axial phonon. For the sake of simplicity it is assumed that each kind of phonon carries the

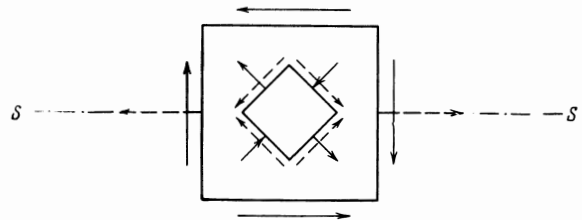


FIG. 10. Stressed state in a specimen due to axial and transverse waves. Solid arrows refer to the transverse wave, dashed arrows, to axial wave. SS — direction of the light beam.

¹⁾The importance of hypersound in breakdown processes involving solids has been considered earlier by B. P. Konstantinov in connection with work on exploding wires^[7].

same energy. Noting further that always $E_{\text{ph}}^e = E_{\text{ph}}^k$, we get

$$2aE_{\text{ph}}^e = E_{\text{ph}}^0. \quad (3)$$

Moreover, we have

$$E_{\text{ph}}^e = b\sigma^2 / G, \quad (4)$$

where σ is the stress amplitude in the hypersonic wave, G is the modulus of elasticity effective in the given problem, and $b \lesssim 0.2$ is a coefficient accounting for the wave shape, inhomogeneity, and the volume distribution of the stressed state. Since

$$s = \pi d^2 h^2 / 4n^2 f^2 + \Delta s, \quad (5)$$

where d is the effective diameter of the initial laser beam, h the distance between the point under consideration and the focal point, n the refractive index, f the focal length of the lens, and $\Delta s \approx 2 \times 10^{-3} \text{ cm}^2$ the cross section of the beam at the focus, the following expression can be derived from (1)–(5) for the stress amplitude in the hypersonic wave:

$$\sigma^2 = \frac{2n^2 f^2 \alpha k G E}{\pi a b d^2 h^2 (1 + 4n^2 f^2 \Delta s / \pi d^2 h^2)}. \quad (6a)$$

For the case of extensive damage, when $\pi d^2 h^2 \gg 4n^2 f^2 \Delta s$, expression (6a) can be simplified to

$$\sigma^2 \approx \frac{2n^2 f^2 \alpha k G E}{\pi a b d^2 h^2}. \quad (6b)$$

Assuming that stress in (6) equals the local strength limit σ_{cr} , one can obtain an expression relating the dimensions of the breakdown region, h_d , to the experimental parameters and properties of the material. The resulting linear relationship between the size of the breakdown region and \sqrt{E} or f (see Figs. 5 and 8) is not, of course, specific for the hypersonic wave damage, but merely corresponds to the assumption that local damage occurs after threshold energy (or power) has been reached. The manifestation of critical energy in the curves $h^2 \sim E$ (see Fig. 5) is due to the finite dimension Δs of the focus:

$$E_{\text{cr}} = \frac{2ab\sigma_{\text{cr}}^2}{\alpha k G} \Delta s.$$

The above interpretation fails to take into account elastic energy relaxation via the coherence loss of hypersonic phonons and their transformation into thermal phonons. Such a process can be approximately accounted for by introducing an appropriate relaxation time (coherence loss time), τ , and by formulating the kinetic equation for the energy density E_{ph} of the coherent phonons as follows:

$$\frac{dE_{\text{ph}}}{dt} = \frac{dE_{\text{ph}}^0}{dt} - \frac{E_{\text{ph}}}{\tau}. \quad (7)$$

Here, dE_{ph}^0/dt is the phonon energy generation rate which, according to (1) and (5), equals

$$\frac{dE_{\text{ph}}^0}{dt} \approx \frac{4n^2 f^2 \alpha k}{\pi \alpha^2 h^2} \frac{dE}{dt}. \quad (8)$$

Solving (7) and (8), and substituting the expression obtained for E_{ph}^0 in (3) and (4), we get

$$\sigma^2 = \frac{2n^2 f^2 \alpha k G}{\pi a b d^2 h^2} e^{-t/\tau} \int_0^t \frac{dE(t')}{dt'} e^{t'/\tau} dt'. \quad (9)$$

Let us consider two limiting cases, $t_p \gg \tau$ and $t_p \ll \tau$, where t_p is the effective pulse length. In the first case, damage occurs when the pulse power reaches a maximum in time (peak power) $dE/dt = W_{\text{max}}$; after integration, this yields

$$\int_0^t e^{t'/\tau} \frac{dE(t')}{dt'} dt' \approx W_{\text{max}} \tau e^{t/\tau} \approx \frac{2}{5} E \frac{\tau}{t_1} e^{t/\tau},$$

where t_1 is time to laser pulse maximum, and the factor $2/5$ corresponds to the real form of the pulse curve (see Fig. 2b).

Substituting the resulting expression into (9), the following criterion for the onset of breakdown can be obtained:

$$\sigma_{\text{ph}}^2 = \frac{4n^2 f^2 \alpha k G E \tau}{5\pi a b d^2 h^2 t_1} \quad (10)$$

In the case of the second limit, when $\tau \gg t_p$, $e^{t/\tau} \rightarrow 1$, and

$$\int_0^t \frac{dE(t')}{dt'} dt' = E,$$

Eq. (9) assumes the form (6b). The results of an experimental realization of both limiting cases may be used to obtain τ . Just such a situation occurred in our experiments with polymethyl methacrylate exposed to an ordinary (o) and giant (g) pulses. Comparing the breakdown criteria obtained, we have

$$\tau = {}^5/2 t_1 (f/h)_g^2 E_g / (f/h)_o^2 E_o \quad (11)$$

Substituting data from the graphs, we can find $\tau \approx 6 \times 10^{-2} t_1 \approx (6 \pm 2) \times 10^{-6} \text{ sec}$. In the derivation of equation (11), it was assumed that σ_{cr} in polymethyl methacrylate has the same breakdown value for an ordinary and a giant pulse, i.e., that strength is not time dependent. The last assumption seems to be justified, since Fig. 9 shows that strength is independent of temperature within a wide temperature range which, in the case of polymethyl methacrylate, is known to mean an absence of a pronounced time dependence of the strength.

According to the above estimates, the decisive factor in giant pulse breakdown (see Fig. 6b) is the total pulse energy, while the pulse shape and length have no noticeable effect. Conversely, in the case of an ordinary pulse, the decisive factor is the peak power which may be expressed for any smooth pulse in terms of its total energy E , rise time t_1 , and a coefficient depending upon the pulse shape.

The analysis shows that, given uniform generation of the hypersound, the stresses caused by the acoustic wave are at least an order of magnitude smaller than the macroscopic strength. Apparently this means either a low local microscopic strength, or an inhomogeneous generation or absorption of hypersound, or both. The local nature of the breakdown is an additional evidence in favor of the above conclusion.

The problem of the kinetics of breakdown development is of considerable interest, along with the breakdown mechanism itself. It should be noted, first, that the cracks are formed in a time interval which does not exceed the effective duration of the pulse, and that the breakdown starts in the focal region and propagates backward. This is true for both the ordinary and the giant pulse, although the length of the latter amounts to only 3×10^{-8} sec.

The above can be substantiated by the following arguments:

1. First, the absence of breakdown beyond the focal point. Since the radiation intensity is maximum in the focus, the breakdown process naturally begins here first, and the resulting cracks effectively screen the beam. Screening of the ordinary pulse, as is seen from Fig. 2b, results in a sharp reduction of the transmitted light; this is manifested by a drop in the photocurrent curve for the photodiode which registers the transmitted light.²⁾ The region in front of the focus is deprived of the screening effect and is destroyed as the critical density of elastic energy is reached. In a parallel, or weakly divergent beam, the breakdown naturally propagates in the forward direction. This is the explanation for the breakdown in polymethyl methacrylate (see curve 1 in Fig. 6) observed at a considerable depth when the focal point was situated in front of the front face.

2. Furthermore, light incident upon the interior surface at the total internal reflection angle causes damage by both, the incident and reflected beams

(Fig. 4). This is possible only when light is reflected from the intact surface, and is also evidence of the fact that the breakdown begins near the focal point and propagates in the backward direction.

3. Finally, there is the evidence of the secondary damage caused by light reflected from previously formed cracks (Fig. 3b).

If the above conclusions concerning the kinetics of breakdown development caused by a laser pulse are valid, a giant pulse delivering energy considerably in excess of the threshold value may be expected to cause damage in the focal region within a time interval substantially shorter than 10^{-9} sec.

Furthermore, the above considerations indicate that the breakdown develops independently in each region, and the focal region is not the site where the breakdown is initiated. This is further confirmed by two facts: that the cracks are separated by extensive regions of intact material and that the breakdown nature does not change when the focal point is brought out to the rear face.

In conclusion, we shall once again emphasize the fact that the above considerations are evidence in favor of the hypersonic conception of the breakdown and basically contradict the thermal hypothesis^[4] which holds that thermal explosion at the focus is the cause of the breakdown. In our view, thermal effects may play a role at moderate energies only in the direct vicinity of the focus; at high energies, secondary thermal effects are possible also at large distances from the focus, if considerable amount of laser light has been absorbed in the incipient breakdown region. Such an absorption is most substantial in the case of an ordinary pulse which starts the breakdown process at the intensity peak, and following which the resulting defect is still capable of absorbing up to 80% of the radiation energy (apparently, this may be the explanation for the strong splitting of crystals).

CONCLUSION

1. The nature of breakdown caused by a powerful laser radiation observed within a broad class of transparent materials (crystals, polymers, glasses), can at this time be explained only as due to the action of coherent acoustic phonons generated in the course of a stimulated Mandel'shtam-Brillouin process. The thermal explosion mechanism comes into play only as a secondary effect.

2. The breakdown first begins in locations exposed to a high intensity of the light flux and gradually spreads to a region marked by a lower in-

²⁾It should be once again emphasized that even for minimum threshold light intensities, the breakdown takes place in a time interval that does not exceed the length of an ordinary pulse, as evidenced by the drop in the oscilloscopic traces for transmitted light.

tensity. The forming breakdown region is being screened by the light beam, so that there is no destruction behind the focal point. Consequently, focused beams cause the breakdown front to move backward from the focus.

3. It has been shown that laser-induced breakdown occurs within very short time intervals, shorter than the length of a light pulse. This affords the opportunity to use a giant pulse in the study of superfast breakdown processes occurring in time periods shorter than 10^{-9} sec; this is at least three orders of magnitude less than what can currently be handled by other methods.

4. Laser-induced breakdown develops independently at various points of the solid. Estimates of stresses caused by the hypersonic wave indicate that local effects play a substantial role in the breakdown process.

5. A difference in the breakdown initiation criteria has been shown to exist between the cases of an ordinary and a giant pulse. The peak power is significant in an ordinary pulse, while the total energy is significant in the giant pulse.

6. Damage comparison between an ordinary and a giant pulse made it possible to evaluate the time of phonon coherence loss.

7. Breakdown by powerful light beams can be used as a method of comparing volume and surface strength.

The authors thank B. P. Konstantinov for constant attention and valuable consultation, and also A. M. Prokhorov, P. P. Pashinin, A. V. Prokhindeev, I. N. Filimonova, G. V. Vladimirova, G. M. Malyshev, F. F. Vitman, V. P. Pukh, and G. A. Malygin for help in experiments and in discussion.

¹R. J. Chiao, C. H. Townes, and B. P. Stoicheff, *Phys. Rev. Lett.*, **12**, 592 (1964).

²M. Hercher, *J. Opt. Soc. Amer.*, **54**, 563 (1964).

³C. R. Giuliano, *Appl. Phys. Lett.*, **5**, 137 (1964).

⁴D. H. Happer, *Brit. J. Appl. Phys.*, **16**, 751 (1965).

⁵T. P. Belikova, E. A. Sviridenkov, *JETP Letters* **1**, No. 6, 37 (1965), transl. p. 171.

⁶D. I. Mash, V. V. Morozov, V. S. Starunov, E. V. Tiganov, I. L. Fabelinskiĭ, *JETP Letters* **2**, 246 (1965), transl. p. 157.

⁷B. P. Peregud, K. B. Abramova, *DAN SSSR* **157**, 837 (1964), *Soviet Phys. Doklady* **9**, 665 (1965).

⁸N. N. Davidenkov, *Collection: Issledovaniya po zharoprochnym splavam* (Research on Heat-resistant Alloys), *AN SSSR* **4**, 13 (1959).

Translated by S. Kassel
145