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DESTRUCTION OF TRANSPARENT MATERIALS BY LASER RADIATION. FORMATION OF GAS BUBBLES AND WEDGING OF THE MATERIAL BY GAS PRESSURE.

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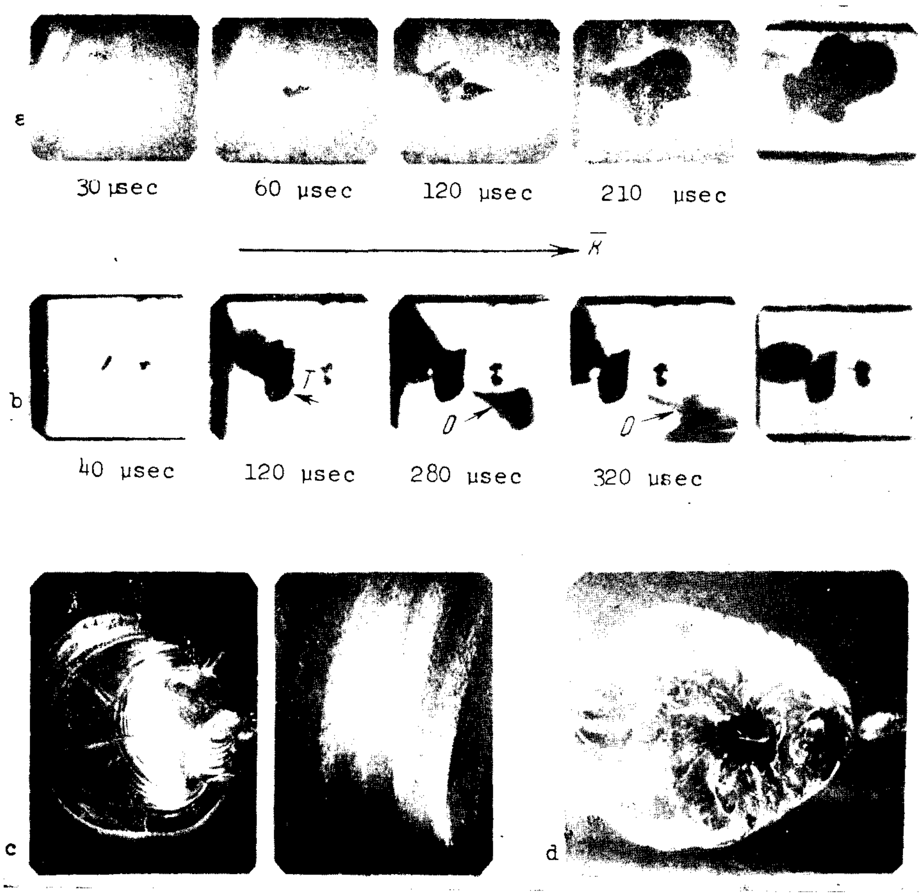
In most cases the region in which transparent materials are damaged by focused laser radiation is an aggregate of cracks [1-3]. There are two points of view concerning the damage mechanism: (1) The cracks are produced exclusively under the influence of hypersonic waves generated in conjunction with stimulated Mandel'shtam-Brillouin scattering [4]. (2) The damage is the consequence of light absorption accompanied by formation of high-temperature centers [5]. Neither theory nor experiment can determine uniquely as yet the role (and character of interaction) of these two mechanisms.

We present here the results of experiments with materials of the organic-glass type (polymethylmethacrylate, polystyrene). The experiments offer evidence that high-temperature centers and high-pressure centers are produced in the form of gas bubbles, the expansion of which leads to wedging of the material and to formation of cracks.

Typical high-speed photographs of the damage process in a polystyrene sample are shown in Figs. a and b. From Fig. a we see that, within 30 µsec following the start of generation, two glowing spots were produced in the focal regions - these are high-temperature centers. The ends of the samples are outside the borders of the frame. The glow was photographed through a lateral surface of the sample, at 90° to the beam direction. Of the two bright points on the frame marked a, 20 µsec, the right-side one coincides with the location of the focal point. After 60 µsec, these two points have already inititated a crack (whose form recalls the point of a lance). By that time there have also been produced (closer to the lens) three new bright points. In the succeeding frames we see how a dark cavity - made up of cracks - grows in this location. The damage grows opposite to the beam direction (indicated by the arrow). The linear dimensions of the cracks cease to grow after ~300 µsec (pulse duration = 800 µsec). The last frame shows the final damage.

That the cracks become wedged apart by heated gas is convincingly demonstrated by the next series of photographs (Fig. b). In this experiment the focal point and the photography conditions were chosen such as to make the crack emerge during its growth on the photographed lateral surface of the sample (instant 120 µsec after the start of generation, point "T" with arrow). We see how a jet of gas struck out through the produced opening (the gas cloud is marked by "O" and an arrow). The escape of gas (slight haze) could be observed with the unaided eye. In addition, when the cracks emerge to the surface, the gas singes the surrounding part of the sample surface, and this can also be readily seen. The initial



a, b - High-speed photographs; a - glowing gas bubbles precede the formation of the cracks; b - emergence of gas from the crack; c - appearance of individual crack (×6) alongside part of the surface of the crack (×24); d - a gas bubble expands in heated material in place of a crack (×6).

velocity of the gas cloud, estimated from the photographs, is ~250 m/sec, and after 250 μsec the cloud expands at a rate ~80 m/sec. The initial rate of crack growth, estimated from the photograph, is ~65 m/sec. The rate drops to a low value at 150 μsec.

In many cases the cracks have a wave surface (see Fig. c), which indicates that they propagate jumpwise. Such a wavy damage surface can be produced artificially by a slowly advancing wedge, owing to the instability of stationary propagation of the cracks and to the occurrence of self-oscillations [6].

We assume the damage mechanism to be as follows: Dynamic stresses are produced first in the region of the light channel by heat and possibly by hypersound. Minute shear defects are produced in the planes of maximum tangential stress, which are inclined ~45° to the perturbation axis, i.e., the beam axis. Further, light is absorbed in the produced inhomogeneities, the material is evaporated, is partially burned, and this gives rise to gas bubbles of high pressure and temperature. The gas pressure produces near the bubbles large stresses and initiates the development of cracks which proceeds, in the main, via wedging of the previously produced shear defects by the gas. During the course of crack expansion, the hot gas carburizes the crack walls, enhancing further light absorption and further heating of the gas. Owing to absorption as well as reflection of light by the produced cracks, other cracks located closer to the focus are shielded and always have smaller dimensions.

Assuming that during the crack propagation the gas pressure in the main part of the crack surface is constant and is sharply reduced by viscosity only near the crack edge in the zone where the crack abruptly narrows down, we obtain for the crack radius (see [7]) the expression $R = k^2/2p^2$, where p is the running pressure of the gas, $k = [\pi E\gamma/(1 - \nu)^2]^{1/2} \sim 3 \times 10^6$ dyn/cm$^{3/2}$ is the cohesion modulus, γ is the surface tension of the material, $E \sim (2 - 3) \times 10^{10}$ dyn/cm^2 is Young's modulus, and $\nu \sim 0.3$ is the Poisson coefficient. The running volume of the crack V is approximately equal to $V = 4k^3/Ep^2$. Eliminating p, we can relate the important crack parameters V and R, viz., $V = 8kR/E$.

The foregoing considerations concerning the mechanism of crack development are confirmed by results of studies of damage in heated samples [8]. With increasing temperature, the viscosity grows rapidly and the material ceases to be brittle. In this case no wedging of the material takes place, and expansion of the gas bubbles is observed (see Fig. d, which was kindly furnished by N. P. Novikov).

To obtain complete information on the damage mechanism and also to estimate the dynamic parameters by means of the foregoing relations, it is necessary to know the running mass of the gas filling the cavity, and its temperature. We hope to obtain some of the missing information by high-speed measurements of the gas-bubble temperature. These measurements, which are now under way, will also yield data on the absorption of laser radiation in matter.

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