ON DAMAGE CAUSED BY A LASER BEAM IN TRANSPARENT DIELECTRICS

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ON DAMAGE CAUSED BY A LASER BEAM IN TRANSPARENT DIELECTRICS

(Presented by Academician B. P. Konstantinov, 27 XI 1965)

In publications that have appeared recently, the fact has been noted that some transparent dielectrics (mainly glasses) are destroyed under the action of intense laser radiation ($^{1-3}$). In the present work we give the principal results of a study of the destruction of a broad class of substances (alkali-halide single crystals, polymers, glasses) caused by the action of an ordinary (o.i.) and a giant (g.i.) laser pulse. It is shown that the nature of the destruction depends strongly on the material studied and on the operating regime of the laser (o.i. and g.i.).

In polymethyl methacrylate (PMMA), under the action of o.i., flat cracks are formed, situated at an angle of 45° to the direction of the laser beam and chaotically distributed with respect to rotation of the crack plane about this axis. At beam energies substantially greater than the threshold energy (at which destruction begins), the number of cracks is large, and they are separated from one another by regions of undamaged material. In glasses, o.i. (at the energy used $E = 20$ J and lens focal length $f = 6$ cm) causes destruction only when focused on the rear face. The same pulse in alkali-halide crystals leads to complete destruction along cleavage planes already at energies only slightly exceeding the threshold.

When g.i. is focused inside the specimen, destruction is observed in all the materials studied. In single crystals it occurs along all three cleavage planes; in PMMA it has the form of a strongly elongated cone consisting of separate small cracks, of the order of 0.1–0.5 mm, while in glass the destruction has a sharply expressed filamentary character with a thickening in the focus region. Figs. 1 and 2 present the corresponding schemes of destruction.

In order to clarify the mechanism and kinetics of destruction, the influence of the pulse energy, the position of the focus, the temperature, and the focal length on the character and size of the destruction zone was studied. It was found that the size of the destruction region h for the materials studied is related to the pulse energy E and the focal length of the lens f by the relation

Figure 1

Figure 1: Figure 1

$$h = Af\sqrt{E - E\ }\,, \tag{1}$$

where A and E are certain constants depending on the material studied and on the laser parameters. The size of the destruction region reaches saturation when the focus is located sufficiently deep inside the specimen and decreases when it is brought outward. If, in this case, the focus is located inside the specimen, then no destruction behind the focus is ever observed, except for spalling of the rear face in substances with low surface strength (glasses). In PMMA, temperature in the interval 77-370° K does not affect the destruction.

The experiments performed made it possible to conclude that destruction at each site begins independently and requires for its onset a critical energy density of the light flux. The critical energies turned out to be very small. For example, for PMMA they amount to only about 2 J/cm^2 in the visible region and approximately 100 J/cm^2 in the infrared. This circumstance makes it possible to draw certain conclusions about the mechanism of destruction. The observed critical energies are insufficient for the onset of destruction

Fig. 1. Various types of destruction caused by laser beams (schematic). *a*—ordinary pulse in PMMA; *b*—the same in alkali-halide crystals; *v*—the same in the presence of secondary reflections in PMMA; *g*—giant pulse in PMMA; *d* —the same in crystals; *e*—the same in glass; *zh*—the same with total internal reflection in PMMA. The arrows indicate the direction of propagation of the light; *f*—position of the focus

could be due to such mechanisms, for example, as light pressure, electrical breakdown, thermal heating, a shock wave, etc. In our opinion, the most consistent mechanism of destruction from the point of view of the experimental data obtained is the destruction of the material under the action of coherent hypersonic phonons generated as a result of stimulated Mandelstam-Brillouin processes*. Apparently, only this mechanism makes it possible to explain such a fact, strange at first glance, as the 45-degree orientation of microcracks in PMMA. As a secondary effect, the mechanism of thermal explosion may also prove important if, in the destruction that has originated due to hypersonic sound, strong absorption of light occurs. The experiments showed that thermal explosion takes place mainly near the focus; naturally, its role is not the same in different materials and increases with increasing localization of the energy.

Experiments also made it possible to establish that cracks form within a time

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* We note that considerations regarding the essential role of hypersonic sound in the processes of destruction of solid bodies were expressed earlier by B. P. Konstantinov in connection with work on the explosion of wires (4).

Fig. 2. Photograph of destruction in PMMA under the action of an ordinary pulse.

Figure 2: Fig. 2. Photograph of destruction in PMMA under the action of an ordinary pulse.

not exceeding the duration of the pulse, and that the destruction begins in the region of the focus and propagates backward from it. This is true both for the ordinary and for the giant pulse, although the duration of the latter is only $3 \cdot 10^{-8}$ sec. The following arguments may be cited as proof:

1. The absence of destruction beyond the focus. Since the radiation intensity at the focus is maximal, destruction naturally begins there earliest of all, and the cracks that form strongly screen the beam (which is registered directly by the photodiode). The region lying in front of the focus does not experience such screening, and therefore, as the critical density of elastic energy is reached, it is destroyed; accordingly the front of destruction moves backward from the focus.

Fig. 2. Photograph of destruction in PMMA under the action of an ordinary pulse.

2. Light incident on the inner surface at the angle of total internal reflection produces destruction both in the incident and in the reflected beam (Fig. 1).

3. The presence of secondary destructions caused by light reflected from cracks already formed (Fig. 1).

It should be noted that destruction at the focus, at sufficiently high energies, may occur in a time substantially shorter than the pulse duration. When a giant pulse is used, this makes it possible to study destruction at times of 10^{-9} sec.

Estimates show that, under the condition of uniform generation of hypersound, the stresses caused by the sound wave are at least an order of magnitude smaller than the macroscopic strength. This apparently indicates either the presence of low local microstrength, or nonuniformity of the generation or absorption of hypersound, or both together. The local character of the destruction provides additional evidence in favor of what has been said.

A significant point is the difference in the criteria for the onset of destruction for an ordinary pulse and a giant pulse: for an ordinary pulse its peak power is important, whereas for a giant pulse the total energy is important. This is explained by the fact that the loss-of-coherence time τ of hypersound phonons in the materials studied turns out to be shorter than the duration of an ordinary pulse and longer than the duration of a giant pulse. Comparison of destruction under the action of a giant pulse and an ordinary pulse makes it possible to estimate τ, which in PMMA, in particular, proved to be of the order of 10^{-6} sec.

In conclusion, we note that destruction under the action of powerful light beams may be used as a method for comparing bulk and surface strength.

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