VOLUME AND SURFACE EFFECTS ARISING FROM THE ACTION OF LASER RADIATION ON OPTICAL GLASS

N. G. Basov, O. N. Krokhin,
N. V. Morachevskii, and G. V. Sklizkov

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The effects arising from the action of radiation from a laser operating in the free generation mode on optical glass are studied. The method of velocity interferometry is employed to establish that, when the laser radiation is focused within the specimen, optical inhomogeneities arise within the latter. The magnitudes of these inhomogeneities within the caustic of the focusing lens are measured. On the basis of the time lapse required for the rise of such inhomogeneities, the proposition is made that they are caused by thermoelastic stresses. Using the methods of thermoelasticity, the magnitudes of these strains and the temperature are calculated. It was also discovered that focusing the radiation on the surface of the sample produces evaporation of the specimen material. A qualitative description is given, and this effect is compared to the surface evaporation which occurs under laser action on condensed opaque media.

Many interesting effects are observed when laser radiation acts upon transparent dielectrics. One of these is breakdown of the material. Depending on the conditions of the experiment, the breakdown occurs in various ways: structural changes, fissures, etc. A significant number of basically experimental studies have been dedicated to explanation of the causes of such breakdown. A series of hypotheses have been proposed on the mechanism whereby the electromagnetic energy is transformed into mechanical stress energy.

One of the first of these was the proposal that a powerful hypersonic wave develops, excited by forced Mandelstam-Brillouin scattering (FMBS) [1-3]. However, the authors of these studies did not regard this problem as definitively solved. In [2], evaluations of the magnitude of mechanical stress produced by a hypersonic wave were made. It was shown that, assuming uniform generation of hypersound, the magnitude of this stress is at least one order lower than the macroscopic strength. Moreover, direct observation of matter breakdown below the threshold level for FMBS does not support a basic role for that phenomenon in the breakdown process.

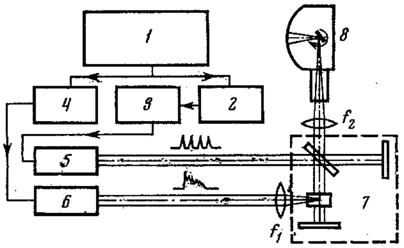

Fig. 1

A second proposal for a breakdown mechanism was the "thermal" hypothesis. According to this hypothesis, the cause of breakdown is thermoelastic stress, arising due to direct absorption of radiation [5]. For transparent media containing microinhomogeneities, within the bounds of the same hypothesis a proposal was made that there exists localized absorption of light energy at points of thermal rupture [6] or in gas bubbles "cleaving" the material [7]. It is possible to assume that, depending on the material studied, as well as the flux density and radiation energy, the breakdown mechanism may be varied. From this viewpoint, it becomes important

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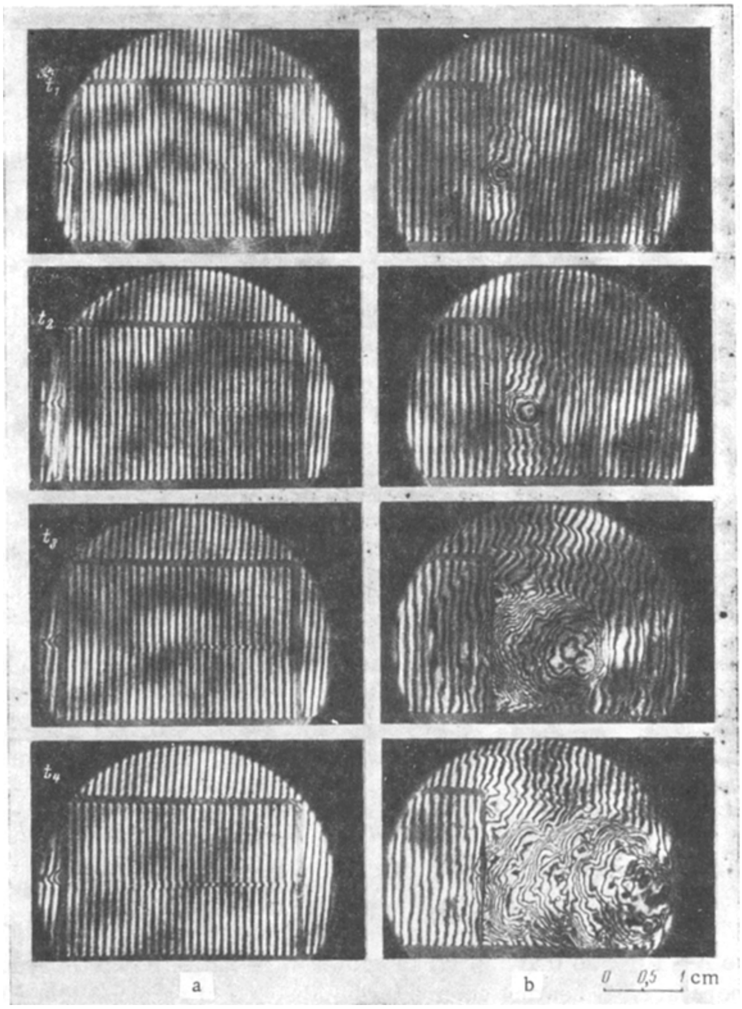

Fig. 2

to study the effects occurring in transparent materials exposed to laser radiation at the stage preceding breakdown.

Experimental Method. The method of velocity interferometry was employed to study the effects occurring upon passage of a laser beam through a transparent substance. A schematic diagram of the experimental apparatus is shown in Fig. 1, in which 1 is the moving image camera control panel, 2 is the control pulse electronic delay circuit, 3, 4 are the ruby and neodymium laser control circuits respectively, 5 is the ruby laser, operating in repetitive giant pulse mode, 6 is the neodymium laser, 7 is the Michelson interferometer with specimen to be studied, 8 is the moving image camera, f_1 is the lens which focuses the neodymium laser, and f_2 is the objective which transfers the specimen image to the film.

Moving image photography was accomplished by simultaneous use of an SFR-2M moving image camera and the ruby laser operating in the repetitive giant pulse mode [8]. The pulses, 15-20 nsec in length, occur at intervals of 50-150 μsec. Such a mode can be produced by introduction into the resonator of a cuvette type nonlinear element with a solution of vanadium phthalocyanine in nitrobenzol, or with plates of type KS-17 or KS-18 glass. The specimen to be studied, in the form of a rectangular parallelepiped with carefully polished faces, is situated in one of the arms of the Michelson interferometer.

In order to exclude as much as possible the effects of macroinhomogeneities (cords, bubbles) brand K-8 optical glass was chosen as the specimen material. A lens with $f = 20$ cm focused the neodymium laser radiation with energy of ~ 100 J and pulse length $\sim 10^{-3}$ on the specimen. Interferogram processing was accomplished by a method which permitted obtaining quantitative data for the axisymmetric case (see, for example [9]).

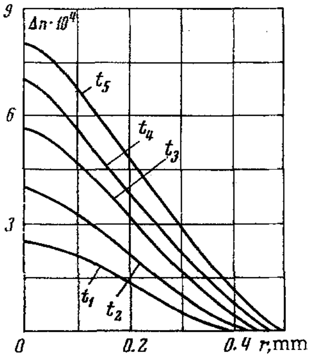

Fig. 3

Experimental Results and Evaluation. Typical interferograms of optical inhomogeneities occurring at times t = 290, 440, 620, 800 μsec with the neodymium laser at an energy level of W ≈ 100 J and pulse length $\tau \approx 1.5 \cdot 10^{-3}$ sec focused within the specimen are presented in Fig. 2a.

In processing the interferograms, the optical axis of the Nd laser-focusing lens system was chosen as an axis of symmetry. The results of quantitative interferogram processing, changes in the index of refraction Δn versus distance from the axis of symmetry for times $t_1 = 180$, $t_2 = 290$, $t_3 = 440$, $t_4 = 620$, $t_5 = 800\,\mu$sec, are presented in Fig. 3. It is obvious that the value at every point increases monotonically with time; the monotonicity of this increase was verified by a large number of independent measurements.

The absence of a time correlation between inhomogeneity development and the structure of the Nd laser radiation, operating in the free generation regime, allows one to assume an integral character for the inhomogeneity formation mechanism.

We define "integral" as follows: the magnitude of the inhomogeneity at every point at a given time t_0 is determined not by the peak value of radiation power, but by the total energy radiated by the Nd laser up to the moment t_0. The most probable mechanism of such character is the rise of thermoelastic stresses due to direct absorption of electromagnetic radiation.

For thermoelastic stresses to occur it is necessary that two conditions be fulfilled; the first:

$$\operatorname{grad}(kq) \neq 0 \tag{1}$$

where k is the coefficient of absorption and q is the radiation flux density; and the second condition:

$$\Lambda = \frac{\lambda \nabla^2 T}{kq} \ll 1 \tag{2}$$

where λ is the coefficient of thermal conductivity, and T the temperature.

For fulfillment of Eq. (1) it is sufficient that the light path not leave the limits of the specimen studied.

In our experiments $\Lambda \sim 10^{-4}$, so that Eq. (2) is known to be satisfied up to temperatures of the order of the vaporization temperature. If heating occurs in the absence of external loads and bonds, the magnitude of the stress and deformation components will be determined by the temperature profile and the geometry of the object heated (for a concrete material). In the case of axial symmetry, the stress and deformation tensors contain only diagonal components. In that case, the component magnitude of the stress tensor and the sum of the components of the deformation tensor are given by the following equations [10]:

$$\begin{gathered}
\sigma_{rr} = \frac{\alpha E}{1-\nu}\left[\frac{1}{R^2}\int_0^R Trdr - \frac{1}{r^2}\int_0^r Trdr\right] \\
\sigma_{\theta\theta} = \frac{\alpha E}{1-\nu}\left[\frac{1}{R^2}\int_0^R Trdr + \frac{1}{r^2}\int_0^r Trdr - T\right] \\
\sigma_{zz} = \frac{\alpha E}{1-\nu}\left[\frac{2}{R^2}\int_0^R Trdr - T\right] \\
U = \frac{\alpha(1+\nu)}{1-\nu}\left[T + 4\frac{1-2\nu}{1+\nu}\frac{1}{R^2}\int_0^R Trdr\right]
\end{gathered} \tag{3}$$

Here σ_{rr}, $\sigma_{\theta\theta}$, σ_{zz} are the stress tensor components in a cylindrical coordinate system, U is the volume deformation, which for small deformations is, to an accuracy up to magnitudes of the second order of smallness, none other than the relative volume change $V^{-1}\delta V$, and α is the coefficient of linear thermal expansion, E is Young's modulus, ν is the Poisson coefficient, R is the radius of the cylinder, and T is the temperature.

To transform the data obtained experimentally for Δn values into changes in specific volume and temperature, the following equations were employed:

$$\Delta n = \Delta n_V + \Delta n_T \tag{4}$$

$$\Delta n_V \approx -\frac{(n_0^2-1)(n_0^2+2)}{6n_0}\frac{\delta V}{V} \qquad \left(\frac{\Delta n}{n_0} \ll 1\right)$$

$$\Delta n_T \approx \left[\beta + \frac{3(n_0^2-1)(n_0^2+2)}{2n_0}\alpha\right]\Delta T$$

where β is a tabular coefficient, giving the increment in Δn for 1°. Equation (4) and Eqs. (3) permit determination of all the unknown quantities. We will present the results of this calculation for $r=0$, i.e., on the axis of the cylinder, for certain values of t (stress is given in kg/cm^2).

$t \cdot 10^6$ sec	ΔT	$\lvert\sigma_{rr}\rvert$, $\lvert\sigma_{\theta\theta}\rvert$	$\lvert\sigma_{zz}\rvert$
180	25	88	196
290	40	155	310
440	56	218	436
620	78	305	610
800	81	315	630

It is evident from these data that the magnitude of σ_{zz} toward the end of the laser impulse attains a value close to the strength limit of the glass under tension [11]. It should also be noted that, under the conditions of our experiment, an increase in the Nd laser radiation energy of 10-15% leads to breakdown of the specimen. From this one may draw the conclusion that the cause of breakdown may be thermoelastic stresses arising from laser radiation absorption.

Figure 2b presents typical interferograms of the flare obtained when the Nd laser is focused on the surface of the sample for t = 100, 210, 340, 520 μsec. It is evident from these interferograms that increase in the radiation flux density on the surface (to 10^6-10^7 W/cm^2) leads to vaporization of specimen material. With this, the surface becomes practically opaque for incident radiation. Dispersal of the vapors is accompanied by a strongly developed turbulence.

The interferograms also trace the structure of the shock waves formed upon vaporization of the material at every Nd laser flash. The parameters of the shock waves are determined by the energy of the corresponding flashes and coincide with parameters of shock waves obtained with shadow photography in interaction of laser radiation with opaque materials [12, 13]. It should be noted that the method proposed above permits, in principle, measurement of the local coefficient of absorption. As an evaluation, the following formula may be used:

$$k \approx \frac{1}{W}\left[\frac{E}{3(1-2\nu)}U + cT\right] \tag{5}$$

where c is the heat capacity per unit volume of the substance studied. Calculations conducted on the basis of the above values give a value for the absorption coefficient $k \approx 2 \cdot 10^{-2}$ cm^{-1}, which, to an accuracy within the limits of experimental error, may be regarded as constant over the duration of a laser pulse. It should also be noted that a similar method of absorption coefficient measurement permits neglect of reflection from the specimen surface and the processes of volume scattering, as well as the use of specimens of small dimensions.

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