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POLARIZATIONAL-OPTICAL INVESTIGATION OF THE FAILURE OF TRANSPARENT DIELECTRICS BY LASER RADIATION

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The mechanism of failure of transparent dielectrics, which consists in the general case of the simultaneous development of several basic processes leading to the appearance of stresses in the medium, is formulated in qualitative terms. Experiments with optically active dielectrics using the dynamic photoelasticity method make it possible to observe different kinds of failure, depending on the properties of the substance under study. Registration of the wave pattern shows that the stresses arising in a dielectric are simple compression waves propagated at the velocity of sound. The magnitudes of the flowing and residual stresses are estimated; the flowing stresses near a cavern are close to the ultimate strength of the material under study, i.e., they are the source of the brittle failure of transparent dielectrics.

1. INTRODUCTION

EXPERIMENTAL investigations of the interaction mechanism show that the failure of a substance when it absorbs laser radiation is manifested both in thermal (melting and vaporization) and in mechanical processes (ejection of vapor, washing away of melt, formation of faults and cracks). In contradistinction to metals, for solid dielectrics the mechanical character of failure by means of cleavages and disintegration is basic, especially for substances with high transparency at the laser frequency.

One of the first hypotheses of the failure of transparent dielectrics by laser radiation was based on the possibility of the occurrence of strong ultrasonic waves excited by stimulated Mandel'shtam-Brillouin scattering (SMBS).[1] From this point of view, attempts were made to explain the numerous experimental results obtained in the failure of transparent media ([2,3] and others); however, the authors themselves did not consider this question to be finally resolved. In addition, the direct observation of the failure of a substance below the threshold for the appearance of SMBS precluded a basic role for this effect in the process of failure.[4,5]

A number of authors have regarded the action of the thermal stresses themselves[6] or the elastic wave evoked by them[7,8] as the source of the failure of transparent materials. A sharp rise in pressure can occur during local absorption of light energy at sites of a "heat burst"[9] or in gas bubbles that "loosen up" a material.[10]

Other authors associate the failure of transparent dielectrics with the action of the strong fields in a laser beam: the development of electrical breakdown or the influence of electrodynamic forces (see, for example,[11,12]). We remark that in this extremely brief survey of the literature it is impossible to discuss any of the studies on the features of the action on crystals, glasses, and other materials, on the investigation of changes in their dislocation structure, the generation of high-frequency vibrations, the appearance of photoconductivity, and other effects.

A common feature of the proposed hypotheses about the failure of transparent materials by laser radiation is the establishment of just one mechanism of failure that would be the same for different substances. However, the action of such a mechanism is more or less well confirmed experimentally only for a specific class of materials. On the basis of an analysis of published work and of the investigations of the authors themselves, a qualitative picture of the failure of transparent substances can be formulated in the following fashion.

In the general case, the action of a light pulse evokes several mechanisms of failure of the substance, and these can act simultaneously. In a certain range of laser flux densities, and also depending on the material properties, one of the failure mechanisms may become the main one responsible for the kinetics and final result of the interaction. Four physical processes appear at present as the most important in the failure of transparent media and, apparently, are the most frequently realized in experiments: a) local absorption of light at inclusions and inhomogeneities; b) thermoelastic stresses; c) elastic waves evoked by rapid heating of the medium ("elastic bursts") and creation of bubbles with vaporization of the substance; d) electrical breakdown of the dielectric by an avalanche of electrons accelerated in the field of the light wave.

The effect of electromagnetic radiation can also be manifested in electrodynamic forces which facilitate the process of failure. Under "sharp" focusing of the laser beam melting and evaporation of a specific volume of the substance leads to additional destruction. The action of ultrasonic waves is not so probable, since the SMBS process cannot develop intensively because of the absence of coherence of the laser radiation in the far field in the multimode regime (high energies).

Since all the basic forms of failure are associated with the development in the medium of large mechanical forces, a qualitative investigation of the force pattern of the interaction in connection with the kinetics of material failure is the most important experimental problem at the present time. This paper is a first step toward solving this problem.

2. EXPERIMENTAL METHOD

In this work, which aims at investigating the force characteristics of the interaction of laser radiation with transparent dielectrics, we used the polarizational-optical method (POM) of determining strained states. This method permits obtaining an image of the force field in a specific region of the material and estimating the absolute magnitudes of the stresses in transparent media which become birefringent under load. The pattern of the strains observed in polarized light is a consequence of the occurrence of a difference in path of the beam when light passes through a medium which becomes optically anisotropic under an applied load. The magnitude of the optical path difference Δ is proportional to the thickness of the sample d and the difference between the corresponding principal refractive indices. The dependence of the refractive indices on load is given in general by the relation between the components of the dielectric permeability and strain tensors of the medium. For a planar stressed state the path difference is given by the Wertheim law[13]:

$$\Delta = c_{\lambda} d(\sigma_1 - \sigma_2),$$

where c_λ is the optical constant at the wavelength of the illumination, and $\sigma_1 - \sigma_2$ is the difference between the principal strains. A more detailed treatment of problems in the optics of strains may be found, for example, in the book by Frocht.[13]

The experimental studies of the force pattern of the interaction were carried out on the most optically active materials. We used samples of different shapes made out of an epoxy resin (ED6-M), an organic glass (PMMA), K-8 silicate glass, celluloid, polystyrene, and the transparent pyroceram first used for POM. The polarizational-optical apparatus assembled for this purpose with a working field diameter of 200 mm makes it possible to follow the pattern of development of the strained zone and to register the propagation of strain waves with a time resolution of 2×10^{-6} sec and higher. The optical scheme of the apparatus is shown in Fig. 1.

To register the patterns we used an SFR-2M superspeed camera in both the frame-by-frame mode with a rate of up to 1,250,000 frames/sec and in the photoscan mode with a rate of 0.5 km/sec. By means of filters introduced into the optical system of the SFR, a narrow region of the spectrum ($\lambda = 0.546\ \mu$m) was isolated in order to obtain monochromatic illumination. The scale of the image was magnified by using supplementary lenses and amounted to 2 : 1 or 3 : 1, depending on the sample dimensions. An IFK-20000 flash lamp with a spherical bright body served as the source of illumination. The lamp was fired simultaneously with the pumping lamps of the laser, so that the lamp achieved maximum brightness at the start of the laser radiation and subsequent loading of the sample. The polarizing system, consisting of two cemented polaroid films, was supplemented in a number of experiments by compensating quarter-wave plates to isolate an isochromatic picture of the strains. Use of type A2 film provided normal darkening density with the IFK-20000 lamp in the described optical system with filters. In the absence of load and with crossed polaroids the light of the lamp was not registered on the film.

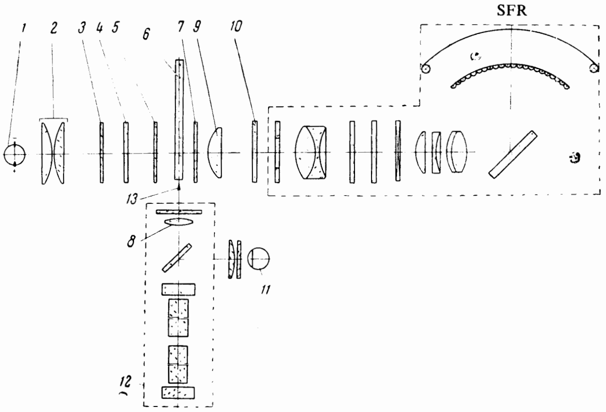

FIG. 1. Optical schematic of the apparatus: 1 – light source (IFK-20000 pulsed lamp), 2 – condenser, 3 – ground glass, 4, 10 – polaroids, 5, 7 – protective glass, 6 – test body, 8 – focusing lens, 9 – objective, 11 – calorimeter, 12 – laser, 13 – beam.

For qualitative investigations of the change in the field of the strains and the determination of their sign, samples of various optically-active materials of arbitrary dimensions with rectangular cross section were used. Propagation of the stress waves was fixed in beams of cross section 3 × 7 and length 200–250 mm, in which the action of the load created a practically plane-stressed state. In this case the epoxide resin ED6-M and the optical glass K-8 were used as materials. Loading of the samples was accomplished by focusing the laser radiation on the end surfaces of the beam or in the middle of the sample by a lens with a local length of 100 mm.

The pulsed neodymium-glass laser, working in the free generation regime, generated light pulses with a length of the order of 2×10^{-3} sec, consisting of an irregular sequence of separate "spikes" of emission with randomly varying amplitude. The energy of the radiation, as a rule, amounted to 100 J in the pulse and was measured in each experiment directly by branching off a part of the energy by a plane-parallel plate to an IF-68 vacuum calorimeter.

The initial moment of incidence of the laser radiation on the surface of the sample was fixed by the appearance of the characteristic luminescence of the material. When the picture-taking rate was high, the luminescence of the optically active material itself was weak, and so a thin metal foil was applied to its end surface. This foil did not affect the action of the radiation and permitted accurate registration of the beginning of the process.

3. RESULTS AND DISCUSSION

A pulse of laser radiation focused close to the surface forms a failure zone (a cavern) with dimensions of the order of several millimeters. In transparent dielectrics the cavern, as a rule, has uneven edges and is accompanied by cracks. In polarized light one clearly sees luminous petals symmetrically arranged around the cavern. Figure 2 shows the view of the face of a sample of the ED6-M resin after failure. The observed residual strains are as a whole symmetrical relative to the cavern and are visualized with the aid of the

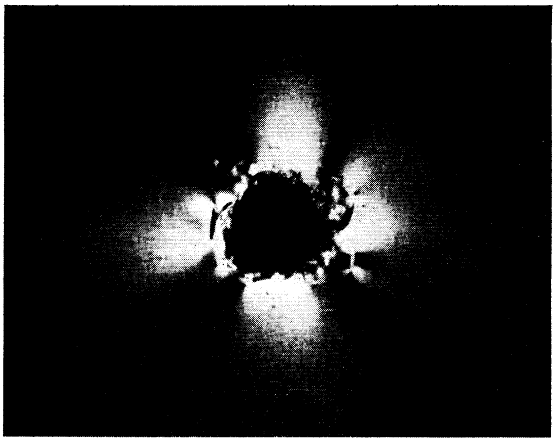

FIG. 2. Distribution of residual stresses in a sample of epoxy resin. Magnification 20 : 1.

polarizing system in the form of four ellipses oriented by the position of the planes of polarization. Strict regularity of the pattern is spoiled by local distortions from separate cracks.

High-speed photography shows differences in the character of the failure of transparent dielectrics which differ in their properties. In inhomogeneous materials the centers of failure are local inclusions or sites of thermal expansion of the substance. The development of a large number of such hot spots is particularly distinct in the plasticized epoxy (Fig. 3). The occurrence of strains as a consequence of increasing pressure in gas bubbles shows up in the form of local strained zones having the shape of four centro-symmetric luminous petals. The increase of absorption in the failure sites and the rise of the temperature of the substance increase the dimensions of the strained zones, which are observable on the photographs as white regions, until they completely overlap.

The expansion of the strained zones proceeds intermittently in accordance with the pulses of laser radiation. After several hundreds of microseconds from the beginning of exposure, the entire volume of the sample becomes strained. At the same time, at the place where the stresses are the greatest at the focus of the lens, a cavern is generated on the sample surface, which is observed as a dark region where material has been thrown off during failure.

The behavior of celluloid differs by the formation of a large number of fine cracks which are generated at inhomogeneities in the material. As they grow, the little cracks join together and the sample falls apart into chips. The biggest cracks continue to grow slowly for several hours after exposure until they reach the free surface.

Brittle substances (glass, PMMA, transparent pyroceramic) are destroyed by laser radiation by means of the formation of big cracks and cleavages which start out from developing caverns simultaneously with the origination of local hot spots in the volume of the substance which lead to a loosening up of the material. Formation of failure zones both at the place where the beam is focused (facial splitting) and at the rear surface of the sample (back splitting) is evidence of the wave nature of the crack formation as the result of interfering strain waves. Thermoelastic stresses due to strong heating of the substance by the radiation also participate in the formation of caverns on the face. A photochronogram of the development of failure in PMMA is shown in Fig. 4.

The growth of the cavern (the dark expanding band in the photograph) proceeds intermittently with the joining together of individual cracks. A delay in the start of cavern formation from the moment of incidence of radiation on the sample is observed. This delay is about 150 to 200 μsec for glass, PMMA, and the epoxy resin ($E = 180$ J). The existence of a time for the establishment of the failure process is explained by the absorbed energy filling up the irradiated volume, the development of thermal stresses, and the growth of pressure in gas bubbles. At some moment, as a consequence of large absorption of light in hot spots and microcracks, the amplitude of the waves of pressure and thermoelastic stress becomes sufficient for the formation of splits and for the joining of cracks, which leads to the appearance of a cavern.

The investigation of the propagation of elastic waves during development of a cavern was carried out on one-dimensional bars of K-8 glass and ED6-M epoxy exposed to a pulsed laser on their end faces. Photochronograms of the formation of stress waves near the failure zone show that in this region regular waves have still not formed, but interference of a large number of stress waves is observed, which makes it difficult to decipher them. The established wave pattern was photographed at a distance of 50 to 60 mm from

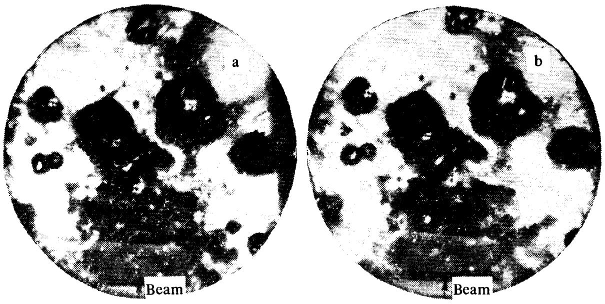

FIG. 3. Development of stresses at failure sites (inhomogeneities) in plasticized epoxy resin. Frame-by-frame mode (1,250,000 frame/sec); two consecutive frames are shown. Magnification 4 : 1.

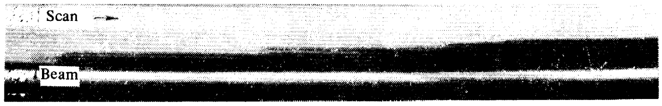

FIG. 4. Photochronogram of development of failure in PMMA. Scan rate, 500 m/sec. Magnification 3 : 1.

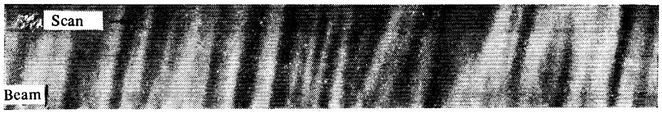

FIG. 5. Photochronogram of establishment of wave pattern at a distance of 50 mm from the failure zone. Scan rate, 500 m/sec. Magnification 3 : 1.

the point of load. A typical photoscan of this zone is shown in Fig. 5.

Each elastic wave corresponds to 1 or 2 fine bands, which correspond to the amplitude of the stresses. The experimentally determined time interval between the individual waves (5 to 10 μsec) correlates well with the repetition frequency of the spikes in the laser radiation, and special experiments showed that the elastic waves from each light spike begin to propagate approximately 5 μsec after it impinges on the sample. This time characterizes the inertia of the transfer of the pressure pulse from a small vaporized volume to the solid wall.

The constancy of the angle of inclination of the bands which determine the intensities in the elastic wave and the invariance of the distance between them is evidence of wave motion with an established velocity and distribution of pressure. The velocity of propagation of the waves was determined from the angle of inclination; it was 1420 m/sec for the ED6-M and 2800 m/sec for the K-8 glass. These values agree with the speed of sound in these materials. As was to be expected, pressure pulses with relatively small amplitude are propagated in a solid with the speed of sound.

The sign of the strains evoked by irradiation were determined on bars of the epoxy that were preliminarily loaded by a static bending moment such that one half of the sample was in compression and the other in tension. A laser was focused on the surface of the stretched region, producing local failure of the substance. Bands of equal stress where thereby bent to the side of the developing cavern, i.e., the magnitude of the tensile stresses was decreased when added to that induced by the laser. Upon further propagation of the applied stresses beyond the neutral band into the region of compression, the bend of the bands of equal stress proceeded away from the cavern, i.e., addition of the laser-induced and static stresses increases their amplitude. This experiment shows that the laser-induced stresses are compressive, confirming the logical conclusion about the sign of the pressure in the waves which are formed and in the thermal stresses.

The pressure amplitude was estimated from the order of the bands in the wave from an individual spike of radiation. The number of fine light and dark bands in each stress wave never exceeds two and on the average equals one. Using known relations of photoelasticity, one can determine the fixed stresses from the value of the band and the order of the bands. The dynamic value of the band in ED6-M was taken as equal to 10 (kg/cm^2)(cm/band).[14] The average value, calculated for all waves, of the difference between the principal stresses $\Delta\sigma$ is 14 kg/cm^2. At a short distance from the cavern, where the pattern is irregular but it is still possible to discern individual waves, in each elastic wave up to three bands are mixed, corresponding to a magnitude $\Delta\sigma \approx 40$ kg/cm^2. The magnitude of the tangential stresses $\tau_{\max}$ found in this way for the epoxy is about 20 kg/cm^2. The value of $\tau_{\max}$ increases at short distances from the cavern with decreasing distance to it as $1/R$ (spherical wave), and at the wall of the cavern, it is evidently equal to the yield strength of the material. The pressure in the cavern itself at a given moment may markedly exceed the magnitude of material-destroying pressures; however, the boundary of the cavern will ''transmit'' to the solid waves with an amplitude that is not greater than the yield strength of the given substance.

As has already been said, after cessation of the action of the light pulse and after cooling down of the sample, residual stresses arranged symmetrically relative to the cavern were observed (Fig. 2). The observation of an unchanged pattern upon removal from the polarizing system of the quarter-wave plates is evidence for the coincidence of the distribution of isochromes and isoclines. Consequently, a radially-symmetric compression of the material of the sample exists. The direction of the difference in the stresses (isoclines) always coincides with the radius, whereas the quantities $\Delta\sigma$ themselves depend only on the distance to the cavern, which is easy to see by rotating the sample in the polariscope.

Comparison of the residual stresses in ED6-M, PMMA, and the transparent pyroceramic was carried out in a KSP-5 polariscope. The stress state in this case differed somewhat from planar, hence it was possible only to make a qualitative comparison of the stresses, which are 2 to 3 orders lower than the effective stresses. The greatest residual stresses were found in the epoxy resin; in PMMA they were less by several orders. The pyroceram took an intermediate position; however, its optical constant is still not known with certainty.

The appearance of residual stresses is usually brought about by irreversible bulk changes caused by local deformations by heating and loading of the material. The retardation of the relaxation of polarization in optically active substances by the simultaneous action of pressure and temperature may also play some role. A well-known method for stabilization of the birefringent state of a material under static load by means of special heat treatment and tempering goes by the name ''freezing.'' Since the region of residual stresses is many times larger than the zone of plastic deformation near a cavern, there occurs a partial fixation of elastic stresses in the material under the action of heat from the source which brings about the stresses themselves (the laser). We shall call such a process ''self-freezing.'' If this effect takes place stably for optically active substances and is uniquely associated with controlled parameters of the substance and radiation, it appears possible to develop a simple method for the determination of dynamic stresses from residual ones.

4. CONCLUSION

On the basis of experiments investigating the force patterns of the failure of transparent dielectrics under the action of laser radiation and on the basis of estimates of the stresses arising thereby, the mechanism of failure can be described in the following way.

In a small volume around the focus the maximum light flux density leads to evaporation and, possibly, melting of the substance. We remark that, as a rule, the volume destroyed by phase transitions in dielectrics is very small compared to the size of the entire failure zone.

The non-stationary heating evoked by absorption of light in the substance creates thermal stresses, the intensity of which decreases with distance from the focus as a consequence of the non-onedimensionality of propagation of the heat wave and dissipative losses. In some region about the evaporated volume, the magnitude of the thermal stresses exceeds the yield strength of the material of the sample, which causes failure of the substance in this region. The dimension of this zone exceed the evaporated volume and depend on the elastic properties of the material and its transparency, as well as on the pulse energy and the temperature gradient created by the radiation.

With rapid vaporization of a small initial volume and the ejection of the products of destruction, under the action of each spike of radiation a pressure pulse in the cavern gives rise to a compression wave, which then propagates throughout the substance. Reflection of this wave from the free boundaries of the sample in the form of tension waves and superposition of the incident and reflected waves, as already mentioned, can lead to the appearance of cleavages and internal cracks in the material. Split "funnels" are formed concentrically with the aforementioned failure zones and increase the total mass of destroyed substance.

Experiment shows that the above regular pattern of the failure process as a combined action of three different mechanisms is to a greater or lesser degree complicated by additional phenomena associated with the application of technically pure optically active materials. As a consequence of the strong absorption of light energy by inhomogeneities and impurity inclusions in the material, which act as stress concentrators or sources of additional thermal and mechanical waves, failure occurs in the form of separate cracks, cleavages, and bubbles. In addition to this, optical inhomogeneities that exist in transparent materials (waviness, bubbles) lead to nonuniform light flux density, i.e., points with high density also are centers for additional failure.

Thus, these investigations have permitted the exposition of a qualitative picture of the failure of transparent plastics and glasses (among them structured ones) and to obtain certain quantitative characteristics of the kinetics of the process. The application of the polarizational-optical method has made it possible to study the force pattern and estimate the magnitudes of the stresses in the interaction of radiation with dielectrics.

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