LASER-INDUCED CRACK UNDER PULSE-PERIODIC RADIATION

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It is well known that disk-like cracks [1, 2] are formed in the bulk of polymer glass subjected to a laser pulse of duration $\tau_u \sim 10^{-3}$ sec and power density q exceeding the rupture threshold $q \sim 10^5$ W/cm^2. In this case cracks occur because of an internal micro-explosion absorbing the light with the formation of a microcrack [3]. Its further development occurs because of the cleaving action of the gas being formed in the laser thermal destruction of the polymer [4]. The energy to evaporate the polymer is supplied here because of radiation absorption by the crack gas [4] while the gas particles are evaporated from the crack surface.

The regime of crack growth from a microcrack under the pulse-periodic action of a low-power focused laser beam is investigated in this paper. In this regime the growth of the crack 2 is accompanied by the occurrence of an absorption wave 1 being propagated [5, 6] towards the laser beam 3 along a caustic (Fig. 1a), where gas particle formation occurs not on the surfaces constraining the crack but in the irradiated tip of the absorption wave. The brightness temperature, measured by a photographic method, reached 1200°K in the area of progress of laser pyrolysis (at the tip of the absorption wave).

The investigations were performed using a LTIPCh-8 pulse-periodic laser-periodic laser on specimens of oriented polymethylmethacrylate [7]. The crack growth was recorded on movie film. Presented in Fig. 1b are dependences of the crack diameter D and the absorption wave dimension ℓ on the irradiation time for a 50 Hz pulse repetition rate and $6\cdot10^{-2}$ W mean power. It turns out that the crack size increases with time according to the law $D \sim \sqrt{t}$ (line 1) while the absorption wave length grows linearly with time ($\ell \sim t$) (line 2). For large times the deviation from these dependences is visibly associated with the emergence of the absorption wave beyond the limits of the beam caustic, resulting in a reduction in the irradiating radiation intensity.

Linear growth of the absorption wavelength with time when its section is constant affords a foundation for considering that an identical fraction of gas particles ΔN proportional to the impulse energy ε: $\Delta N = \varepsilon/H$ is formed after one laser pulse, where H is the effective energy needed to form one gas particle [8]. Let us find the connection between the change in the crack diameter after an impulse ΔD and the quantity of particles ΔN. We shall consider the crack to grow within the limits of one laser pulse while remaining in an ultimate equilibrium state, i.e., the stress intensity factor at the crack tip $K = p\sqrt{D}$ is constant (p is the gas pressure and D is the crack diameter) and equal to the adhesion modulus K* [9]. Then using the known relationship $V = \xi D^3 p$ [10] that connects the crack volume to its diameter and the pressure therein, we obtain the law of crack growth after one laser pulse: $p^5V = \text{const}$.

We take the equation of state for the gas in the crack in the form pV = NkT, where T is the gas temperature and N is the number of particles.† The rate of gas particle formation dN/dt is connected with the instantaneous laser pulse power W by the relationship dN/dt = W/H. Hence, by using the law of crack growth we have (under the assumption of an isothermal process)

$$p_{n+1} = p_n\left(1+\frac{\Delta N}{N_n}\right)^{-1/4},\quad V_{n+1} = V_n\left(1+\frac{\Delta N}{N_n}\right)^{5/4},\quad D_{n+1} = D_n\left(1+\frac{\Delta N}{N_n}\right)^{1/2}. \tag{1}$$

†Additional experiments performed by Yu. V. Sidorin by the method of [11] showed that the gas in the cracks formed by pulse-periodic exposure differs slightly from an ideal gas.

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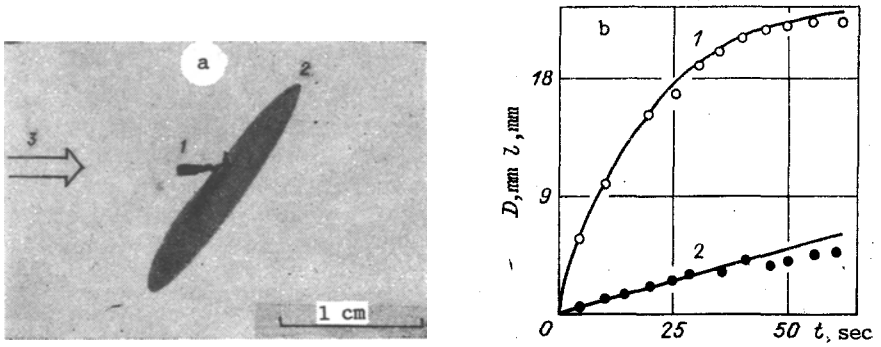

Fig. 1

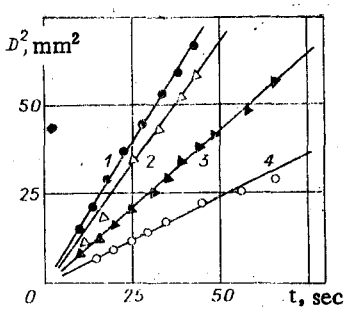

Fig. 2

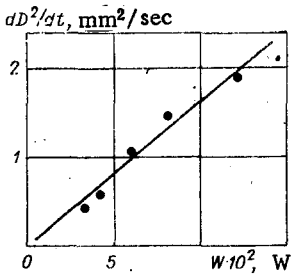

Fig. 3

where the subscripts n and n + 1 refer to values of the quantities at the beginning and termination of the laser pulse action, respectively. Since the relative increments in the number of particles in the gas phase $\Delta N/N$ and the crack diameter $\Delta D/D$ after one impulse are small, by using the last of the relationships (1), the desired connection can be formed

$$\Delta D = \frac{1}{2} D_0 \frac{\Delta N}{N_0}. \tag{2}$$

In order to explain the experimental results obtained within the framework of this model, it is necessary to assume that the quantity of gas particles in the crack does not vary between laser pulses. This is valid if the power released into the medium surrounding the crack due to heat conduction, governing the velocity of gas condensation is much less than the mean laser radiation power controlling the rate of gas formation. Such a constraint imposes strict conditions on the difference between the temperature ΔT of the gas and the surrounding polymer: $\Delta T \ll \varepsilon\nu\sqrt{\chi t}/\varkappa\pi D^2$, where ν is the pulse repetition rate, χ is the thermal diffusivity coefficient, $\varkappa$ is the heat conduction coefficient, and t is the time of irradiation. For the conditions characteristic for our experiment, the constraint has the form $\Delta T < 100°C$. The reason for the low temperature of the cleaving gas is visibly the cooling of the gas as it diffuses into the porous medium of the absorption wave.

The absence of relaxation of the numbers of gas particles between the laser pulses permits rewriting (2) as a differential equation

$$\frac{dD}{D} = \frac{1}{2}\frac{dN}{N},$$

whose solution has the form

$$D = D_0\sqrt{1 + \frac{\varepsilon\nu t}{HN_0}}. \tag{3}$$

Here D_0 and N_0 are the diameter and number of particles in the initial microcrack.

Presented in Fig. 2 are experimental dependences of the square of the crack diameter D^2 on the time t for $\varepsilon = 2.5\cdot10^{-3}$; $3.5\cdot10^{-3}$; $2.5\cdot10^{-3}$; $2.5\cdot10^{-3}$ J and $\nu = 50$; 25; 25; 12.5 Hz (lines 1-4, respectively).

According to the relationship (3), these dependences are linear to good accuracy. Represented in Fig. 3 are experimental points of the dependence of dD^2/dt on the mean power of the illuminating radiation $\varepsilon\nu$, the line is drawn by the method of least squares. The good

agreement between the deductions of this model and the experimental results is seen. A simple estimate for H from the dependences of Fig. 3 yields a quantity ~10 eV for $K^* = 120$ kg/cm$^{3/2}$ [11].

Therefore, the growth regime of a single laser crack subjected to pulse-period action is investigated in this paper. It is shown that the crack diameter grows with time according to a square-root law $D \sim \sqrt{t}$ while its growth rate is determined by the mean power of the laser radiation. An estimate is obtained for the effective energy needed to form one gas particle under the laser pyrolysis of PMMA.

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