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Mechanical damage in transparent solids caused by laser pulses of different durations

M.F.Koldunov, A.A.Manenkov, I.L.Pokotilo

***Abstract*. A mechanical damage of transparent solids caused by local laser-produced heating is considered. Applicability of thermoelasticity equations to the analysis of the mechanical stage of laser damage is substantiated for both short and ultrashort pulses. Damage criteria have been obtained for the crack-formation mechanism. On the basis of these criteria, the conditions for the transition from the crack-formation damage to defect generation and ablation have been clarified. The analysis can be applied to both intrinsic (impact and multiphoton ionization) and extrinsic (initiated by absorbing inclusions) absorption mechanisms of laser radiation.**

Keywords: *laser damage, mechanical damage, crack formation, ablation, defect formation.*

1. Introduction

The interaction of high-power ultrashort laser pulses with transparent solids has been extensively studied in recent years [1 – 4]. An interest in these studies is determined by the specific features of this interaction: as the pulse duration decreases, the damage character in a transparent solid changes. Upon irradiation by long pulses (nanosecond pulses), damage with a crack formation is observed, whereas irradiation by ultrashort femtosecond pulses causes damage due to ablation. The type of damage changes when the pulse duration is several picoseconds.

It was assumed in some papers that the change in the type of damage was caused by the change in the mechanism of nonresonance interaction of laser pulses with transparent solids in the case of ultrashort pulse durations. In particular, it was pointed out that the spectral width of ultrashort pulses and some other features should be taken into account. In the opinion of the authors of papers [1 – 4], damage produced by nanosecond pulses is determined by the absorption by foreign inclusions (i.e., by an extrinsic absorption mechanism), while the damage under the action of femtosecond pulses is caused by an intrinsic absorption mechanism (impact and multiphoton ionisation).

M.F.Koldunov, I.L.Pokotilo Optronika Research and Devices Enterprise, POB 3, 141700 Dolgoprudnyi, Moscow oblast, Russia;
A.A.Manenkov General Physics Institute, ul. Vavilova 38, 119991 Moscow, Russia

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Dividing the laser damage mechanisms into intrinsic and extrinsic ones is based on the difference in the mechanisms of absorption of laser radiation. However, there is no reason to believe that the final stage of a damage, formation of a fracture, is determined by the energy absorption mechanism. The viewpoint formulated in [5], according to which the character of a damage is determined by the energy absorbed during the action of a laser pulse, the size of the interaction region, and the heat removal from this region and is independent of the radiation-absorption mechanism, seems to be more natural. The mechanical damage criterion for the absorption of laser radiation by inclusions formulated in [5] admits a natural generalisation for the case of intrinsic radiation-absorption mechanisms. In other words, a change in the damage character with decreasing the laser pulse duration cannot indicate to a change in the mechanism of laser radiation absorption.

The aim of this study is to analyse the processes of mechanical damage of transparent solids exposed to laser pulses of different durations and to reveal their features upon change from short (nanosecond) to ultrashort (femtosecond) pulses.

2. Physical formulation of the problem and basic equations describing thermoelastic damage

The characteristic times of the processes playing an important role in the problem of mechanical damage of transparent solids caused by local absorption of laser radiation, which correspond to the electron – phonon relaxation (τ_{eph}), the establishment of thermoelastic stresses in the region of local heating of size ~ 1 μm (τ_s), and the crack formation (τ_{fr}), are of the order of 10^{-12} s, 10^{-9} s, and 10^{-8} s, respectively. Comparing these times shows that the crack formation is the slowest process. When analysing the effect of ultrashort pulses, we can distinguish three sequential stages of damage: the energy absorption and formation of a nonequilibrium electronic state during the laser pulse action, relaxation of the nonequilibrium state to a local thermodynamic equilibrium, and the development of a mechanical damage.

It is important that a mechanical damage has no enough time to develop in the course of the first two stages. In the case of ultrashort pulses, the radiation energy is absorbed by the electron subsystem during the action of the laser pulse, and the matrix heating and damage occur after the pulse passage through the interaction region. For a damage to appear, it is, of course, necessary that, during the action of a laser pulse, the electron subsystem should absorb a sufficient amount of energy for the subsequent heating of the solid lattice (through electron–phonon relaxation) to a temperature above which a mechanical damage develops.

In the scheme considered above, the mechanical damage development is independent of the energy absorption mechanism. Therefore, a change in the damage morphology does not allow us to discriminate between the laser-radiation absorption mechanisms. This scheme implies that the mechanical damage process under both long and ultrashort pulses can be analysed using a system of thermoelasticity equations. In other words, if we are interested in the damage character of a solid exposed to laser radiation, only the last (mechanical) stage of this process can be considered irrespectively of the mechanism of laser-radiation absorption by a transparent solid (impact ionisation, multiphoton absorption, or absorbing inclusions).

When investigating the conditions for the development of a crack in a transparent solid due to local laser heating, we assume that radiation is absorbed within a spherical region of radius R and neglect dynamic effects.

The dynamic effects determined by a mechanical inertia play a decisive role in the crack formation. However, our aim is not to analyse the crack development but to elucidate the conditions under which a crack forms. For this purpose, it is sufficient to investigate the character of stresses at the stage of local laser heating, which precedes the crack formation stage. At the local heating stage, the displacements of atoms in the lattice and their velocities are small. Therefore, the analysis of the conditions for the appearance of a damage can be performed using a system of equations of the quasi-stationary thermoelasticity theory. For a spherically symmetric problem, this system of equations has the form [6]

$$\rho c(1+\vartheta)\frac{\partial\theta(r,t)}{\partial t}=\frac{\chi}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial\theta(r,t)}{\partial r}\right)+B, \tag{1}$$

$$\frac{\partial}{\partial r}\left[r^{-2}\frac{\partial}{\partial r}\left(r^2u_r\right)\right]=\alpha\frac{1+v}{1-v}\frac{\partial\theta(r,t)}{\partial t}, \tag{2}$$

where $\theta=T-T_0$ is the excess of the temperature T at the damage location over the initial temperature T_0; χ, ρ and c are, respectively, the thermal conductivity, density, and specific heat of a solid at a constant strain; B is the power density of heat sources; u_r is the radial component of the displacement vector; α is the linear expansion coefficient; v is the Poisson ratio; $\vartheta=(T_0/9c_V)[(1+v)(1-v)]^2\alpha^2c_{\mathrm{L}}^2$ is the coupling coefficient; c_V is the specific heat at constant volume; and c_{L} is the longitudinal velocity of sound.

The strain fields ε_r and ε_ϕ for known u_r are calculated from the expressions

$$\varepsilon_r=\frac{\mathrm{d}u_r}{\mathrm{d}r},\quad \varepsilon_\phi=\frac{u_r}{r}, \tag{3}$$

and the stress components σ_r and σ_ϕ are found from the Duhamel–Neumann relations

$$\varepsilon_r-\alpha T=\frac{1}{E}(\sigma_r-2v\sigma_\phi), \tag{4}$$

$$\varepsilon_\phi-\alpha T=\frac{1}{E}[\sigma_\phi-v(\sigma_r-\sigma_\phi)]. \tag{5}$$

To analyse the conditions for the crack development, Eqns (1) and (2) should be complemented with a mechanical damage criterion. In a general case, this criterion has the form [7]

$$f(\sigma_1,\sigma_2,\sigma_3)=C(T,\mathrm{d}\varepsilon/\mathrm{d}t), \tag{6}$$

where σ_1, σ_2, and σ_3 are the principal stresses and $\mathrm{d}\varepsilon/\mathrm{d}t$ is the strain rate. According to relation (6), the form of the damage criterion substantially depends on the temperature T in the damage region and on the strain rate. The criterion can be adequately selected only after a preliminary study of the thermoelastic state of a transparent solid in the vicinity of the locally heated region.

3. Criterion for the mechanical damage formation

3.1 Strain and temperature fields

A solution to Eqn (2) for known $\theta(r,t)$ can be obtained in a general form [6]. Jointly with relations (3)–(5), this solution makes it possible to calculate the strain and stress fields. In particular, for the tangential stress component $\sigma_\phi(r,t)$ that determines the damage, we have

$$\sigma_\phi(r,t)=\frac{\alpha E}{1-v}\frac{1}{r^3}\left[\int_0^r\theta(s,t)s^2\mathrm{d}s-r^3\theta(r,t)\right]. \tag{7}$$

According to (7), when a transparent solid is locally heated, a tensile stress formed in the vicinity of the heated region may lead to a damage according to the tearing off mechanism.

To calculate $\sigma_\phi(r,t)$ in the explicit form, we represent $\theta(r,t)$, following [8], in the model form

$$\theta(r,t)=\theta(t)\left\{\eta(R-r)+\frac{R}{r}\left[\frac{z(t)-r}{z(t)-R}\right]^2\eta(r-R)\eta[z(t)-r]\right\}, \tag{8}$$

where $\theta(t)$ is the temperature in the energy absorption region, $z(t)$ is the heating depth, and $\eta(x)=0$ for $x<0$ and $\eta(x)=1$ for $x\geqslant 0$. Substituting (8) into (7) and integrating, we obtain

$$\bar{\sigma}_\phi(\bar{r},\delta)=\frac{1}{(1+\bar{r})^3}\left\{\frac{1}{3}+\frac{\delta(\delta+1)}{3}-\frac{\delta^2}{4}-\left[\frac{(\delta+1)(\delta-\bar{r})^3}{3\delta^2}\right.\right.$$
$$\left.\left.-\frac{(\delta-\bar{r})^4}{4\delta^2}\right]\eta(\delta-\bar{r})\right\}-\frac{1}{1+\bar{r}}\frac{(\delta-\bar{r})^2}{\delta^2}\eta(\delta-\bar{r}), \tag{9}$$

where dimensionless variables $\bar{r}=(r-R)/R$ and $\delta(t)=[z(t)-R]/R$ are introduced and

$$\bar{\sigma}_\phi(\bar{r},\delta)=\frac{\sigma_\phi(r,t)(1-v)}{\alpha\theta(t)E}. \tag{10}$$

The temperature kinetics in the heated region is determined, according to (8), by the time dependences $\theta(t)$ and $z(t)$ [or, which is equivalent, by $\delta(t)$ in (9)]. Substituting (8) into (1) and imposing the conditions for the conservation of energy, we obtain the equations

$$\frac{d\theta}{dt} = -\frac{1}{\tau}\left(1 + \frac{2}{\delta}\right)\theta + \frac{B}{C}, \tag{11}$$

$$\frac{d(\theta\delta)}{dt} = \frac{2\,\theta}{\tau\,d}, \tag{12}$$

where $C = c\rho(1+\vartheta)$ and $\tau = c\rho R^2/\chi$. The solutions to (11) and (12) with the initial conditions

$$\theta(0) = 0 \quad \text{and} \quad \delta(0) = 0 \tag{13}$$

detemine the temperature kinetics in the laser-radiation absorption region. The variation dynamics of the tangential stress component for known $\theta(t)$ and $\delta(t)$ is determined by relation (9).

The calculated dimensionless quantities $\bar\sigma_\phi(\bar r, \bar t) = [\theta(t)/T_0]\bar\sigma(\bar r, \delta)$ and $\bar\theta(\bar r, \bar t) = [\theta(r,t)/T_0]$ obtained using relations (8) and (9) and Eqns (11) and (12) are presented in Fig. 1. It was assumed in calculations that $B = \kappa I$, where κ is the absorption coefficient in the interaction region and I is the laser radiation intensity.

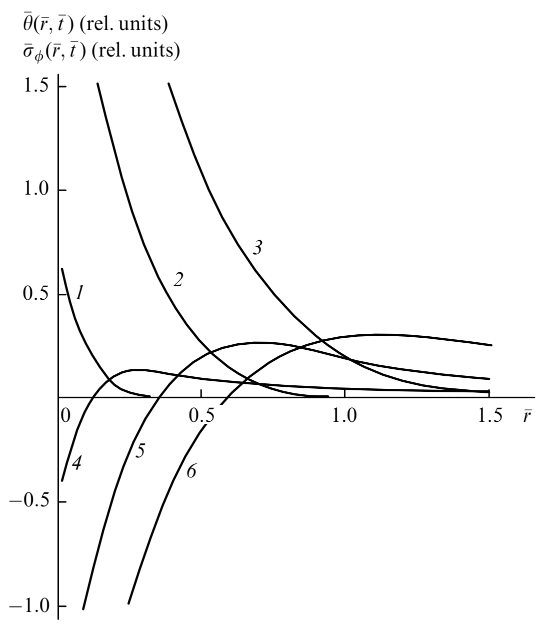

Figure 1. Dependences of the (*1–3*) temperature $\bar\theta(\bar r, \bar t)$ and (*4–6*) tangential stress component $\bar\sigma_\phi(\bar r, \bar t)$ on the distance $\bar r$ to the heated region at successive moments $t = 0.075\tau$ (*1, 4*), 0.62τ (*2, 5*), and 1.64τ (*3, 6*).

Fig. 1 demonstrates substantial features of the stress variation in the vicinity of the heated region. First of all, we see that $\max\sigma_\phi(r,t)$ always lies in the 'cold' region of the transparent solid. Numerical estimates give

$$\theta_{\max\sigma}(t) \leqslant 0.02\theta(t). \tag{14}$$

Here, $\theta_{\max\sigma}(t)$ is the temperature at the point where $\sigma_\phi(r,t)$ is maximum at a given time instant. It is important that the fulfilment of inequality (14) is not related to the model form (8) taken for $\theta(r,t)$. Variations of (8) show that the features of the $\bar\sigma_\phi(\bar r, \bar t)$ and $\bar\theta(\bar r, \bar t)$ behaviour presented in Fig. 1 remain unaltered, and so does inequality (14).

3.2 Crack formation criterion

According to inequality (14), the temperature in the crack formation region is not high. Indeed, assuming for an estimate that $\theta(t) = 10^4$ K (such temperatures in the absorption region are typical of laser damage [9]), we obtain from (14) that, in the region of the $\sigma_\phi(r,t)$ maximum, the temperature is within 500 K.

Since, according to the data in Fig. 1, a significant tensile stress arises in the 'cold' region of a locally heated transparent solid, a damage will develop according to the tearing off mechanism. An adequate criterion for a mechanical damage is then [10] given by the inequality

$$\max_{r,t} \sigma_\phi(r,t) \geqslant \sigma_{\rm th}, \tag{15}$$

where $\sigma_{\rm th}$ is the ultimate stress, an excess of which causes a crack formation.

3.3 Laser damage criterion

Numerically calculated functions $\max_r \sigma_\phi(r,t)$ are shown in Fig. 2. According to these plots, the maximum stress rises for $t \leqslant 1.15\tau$ and then monotonically falls. Such a stress behaviour is physically natural. Since the stress is proportional to the temperature gradient, a temperature rise at the initial stage of energy absorption determines a stress increase. At $t > 1.15\tau$, the heat diffusion into the transparent solid bulk reduces the temperature gradient and, thus, the pressure.

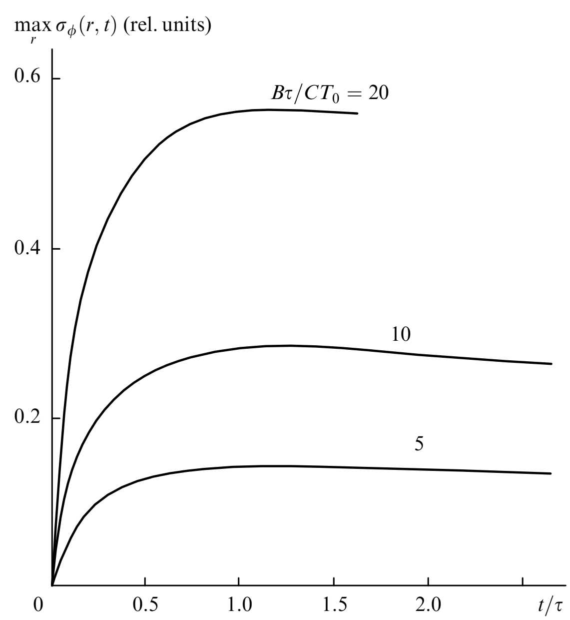

Figure 2. Dependences of the maximum stress in the vicinity of a locally heated region on time for the heat release power $B\tau/CT_0$.

Taking into account the numerically calculated data shown in Fig. 2 and relations (10) and (15), we derive the criteria for laser damage through the crack formation mechanism:

$$\theta \geqslant \theta_{\rm cr}, \quad \theta_{\rm cr} = \frac{\sigma_{\rm th}(1-\nu)}{E\alpha}, \tag{16}$$

$$\frac{\mathrm{d}\theta}{\mathrm{d}t} \geqslant 0.9\frac{\theta_{\mathrm{cr}}}{\tau}. \quad (17)$$

Inequality (17) implies that, if the heating rate is sufficiently low, the stress does not reach its ultimate value and, therefore, a crack does not develop.

4. Crack formation

If $\sigma_\phi(r, t)$ reaches the threshold value σ_{th} in the course of local heating, then, according to (15), a crack appears within a certain vicinity of the heated region of a transparent solid. We denote its boundaries as r_1 and r_2 ($r_1 < r_2$) or, in the dimensionless variables, $\bar{r}_1$ and $\bar{r}_2$. Within the crack region ($r_1 \leqslant r \leqslant r_2$), the tangential component of the stress tensor vanishes: $\sigma_\phi(\bar{r}, t) = 0$. Equation (2) is incompatible with this requirement and does not allow us to calculate the thermoelastic state in the crack region, but it is still applicable beyond the region $r_1 \leqslant r \leqslant r_2$.

The thermoelastic state in the crack region can be calculated using the thermoelasticity equation for stresses. This system of equations allows us to take the requirement $\sigma_\phi(\bar{r}, t) = 0$ into account in an explicit form. For a spherically symmetric problem, the thermoelasticity equation for stresses, which determines the radial component of the stress tensor $\sigma_r(r, t)$, has the form [6]

$$\frac{\mathrm{d}\bar{\sigma}_r}{\mathrm{d}\bar{r}} + \frac{2}{\bar{r}}\bar{\sigma}_r = 0. \quad (18)$$

Formula (18) takes into account that $\bar{\sigma}_\phi = 0$ in the crack region, and the dimensionless stress is defined similar to (10):

$$\bar{\sigma}_r(\bar{r}, t) = \frac{\sigma_r(r, t)(1-\nu)}{\alpha\theta(t)E}. \quad (19)$$

The solution to equation (18) is

$$\bar{\sigma}_r = \frac{C_1}{(1+\bar{r})^2}. \quad (20)$$

Using the definition of ε_r [see (3)] and relation (4), we derive the equation that determines the displacement vector in the region $r_1 \leqslant r \leqslant r_2$. By introducing the dimensionless quantities

$$\bar{u}_r = \frac{u_r(1-\nu)}{R\alpha\theta(t)}, \quad \bar{C}_1 = \frac{C_1(1-\nu)}{R^2\alpha\theta(t)}, \quad (21)$$

we write the solution as

$$\frac{\mathrm{d}\bar{u}_r}{\mathrm{d}\bar{r}} = -\frac{\bar{C}_1}{(1+\bar{r})^2} + (1-\nu)\bar{\theta}. \quad (22)$$

The solution to (22) has the form

$$\bar{u}_r = -\frac{\bar{C}_1}{1+\bar{r}} + (1-\nu)\int_{\bar{r}_1}^{\bar{r}} \bar{\theta}(s, t)\mathrm{d}s + C_2. \quad (23)$$

Outside the crack region, the solutions to Eqn (2) are as follows:

$$\bar{u}_r(\bar{r}, t) = \frac{1+\nu}{(1+\bar{r})^2}\int_{-1}^{\bar{r}} \bar{\theta}(s, t)(1+s)^2\mathrm{d}s + A(1+\bar{r})$$

$$\text{at} \quad -1 < \bar{r} \leqslant \bar{r}_1, \quad (24)$$

$$\bar{u}_r(\bar{r}, t) = \frac{1+\nu}{(1+\bar{r})^2}\int_{\bar{r}_2}^{\bar{r}} \bar{\theta}(s, t)(1+s)^2\mathrm{d}s + \frac{B}{(1+\bar{r})^2}$$

$$\text{at} \quad \bar{r}_2 \leqslant \bar{r}. \quad (25)$$

Relations (23)–(25) make it possible to determine the strain and stress fields over the entire region of a transparent solid in the presence of a crack. They contain four integration constants A, B, C_1, and C_2 and unknown boundaries of the damage region $\bar{r}_1$ and $\bar{r}_2$. These constants are found from the requirement of the continuity of $\bar{\sigma}_r$ and $\bar{u}_r$ and also from the fulfilment of the equalities $\bar{\sigma}_\phi = \bar{\sigma}_{\mathrm{th}}$ at $\bar{r} = \bar{r}_1$ and $\bar{r} = \bar{r}_2$. Excluding A, B, C_1, and C_2 from (23)–(25) and using the above conditions, we come to a system of equations specifying the boundaries of the damaged region:

$$\frac{3}{(1+\bar{r}_1)^3}\int_{-1}^{\bar{r}_1} \bar{\theta}(1+s)^2\mathrm{d}s = \left[\sigma_{\mathrm{th}} + \bar{\theta}(\bar{r}_1)\right]$$

$$+\left[\sigma_{\mathrm{th}} + \bar{\theta}(\bar{r}_2)\right]\left(\frac{1+\bar{r}_2}{1+\bar{r}_1}\right)^2, \quad (26)$$

$$\frac{3}{(1+\bar{r}_1)^2}\int_{-1}^{\bar{r}_1} \bar{\theta}(1+s)^2\mathrm{d}s = \left[\sigma_{\mathrm{th}} + \bar{\theta}(\bar{r}_2)\right](1+\bar{r}_2)$$

$$\times\left[\frac{1}{2} - 2\left(\frac{1+\bar{r}_2}{1+\bar{r}_1}\right)\right] + \int_{\bar{r}_1}^{\bar{r}_2} \bar{\theta}\mathrm{d}s = 0. \quad (27)$$

It is important that the system of Eqns (26) and (27) admits the existence of a crack of only a finite size. A crack of a minimal possible length arises at the exact equality of the maximum stress in the locally heated region to the critical stress σ_{th}. Under such conditions, at the moment of damage, $\theta(t) = \theta_{\mathrm{cr}}$, and, as the numerical analysis of the system of Eqns (26) and (27) shows, the crack size is $r_2 - r_1 \simeq 1.59R$.

In accordance with the fracture mechanics theory [10], a crack is characterised by the energy

$$E_{\mathrm{m}} = 2\pi(r_2^2 - r_1^2)\gamma \simeq 39R^2\gamma, \quad (28)$$

where γ is the surface energy density. For a damage to form, the mechanical energy stored in the deformation field must exceed the energy determined by relation (28). This implies that the condition for achieving a laser damage of a transparent solid through the crack formation mechanism is

$$k\vartheta E_{\mathrm{p}} \geqslant E_{\mathrm{m}}, \quad (29)$$

where E_{p} is the laser pulse energy and k is the factor characterising the fraction of the absorbed energy. In addition, as it follows from the laser damage theory [11], the radiation intensity must exceed the threshold intensity I_{th}:

$$I \geqslant I_{\mathrm{th}}. \quad (30)$$

For long laser pulses, the fulfilment of the condition (30) involves the validity of the requirement (29), i.e., the absorbed energy is sufficient for crack formation. As the pulse duration decreases (with a laser radiation intensity being constant), the absorbed energy decreases, and, as follows from (29), in the range

$$\tau_p < 39R^2\gamma/k\vartheta W_p \equiv \tau_p^* \qquad (31)$$

(where W_p is the laser-pulse radiation power), the crack formation becomes impossible.

It is obvious that an increase in the incident radiation intensity (for a constant pulse duration) should again lead to the production of cracks. However, a necessary condition for the accomplishment of this process is the absorption of an additional energy at the first stage of the damage process (during the formation of a highly nonequilibrium state). This can be impossible, for example, because of the screening of the incident radiation by the produced plasma, or due to some nonlinear process (self-defocusing of radiation by nonequilibrium carriers, nonlinear scattering, etc.). This means formally that the k value in (29) decreases with increasing laser intensity, i.e., a saturation occurs.

5. Discussion

The results obtained in this study show that the mechanical damage process is identical for both the intrinsic mechanism of laser-pulse energy absorption and the absorption caused by inclusions. The insensitivity of mechanical damage to the energy absorption mechanism is associated with a low damage-formation rate. In the case of short pulses ($\tau_p \leqslant 10^{-8}$ s), a crack forms after the termination of a laser pulse. A change in the damage character with shortening the laser pulse duration is related to energy limitations during the crack formation.

Probable specific features in the laser-radiation interaction with matter and their effect on the damage process can be related only to the stage of absorption of the laser radiation energy. The effect that should be primarily noted here is the screening of laser radiation by a plasma produced due to the interaction. This effect evidently accounts for a rise of the damage threshold for a quartz surface irradiated by femtosecond pulses observed in paper [2]. There is no doubt that the nonresonance interaction of laser radiation with a transparent solid may undergo more substantial changes in the case of ultrashort pulses. This is associated primarily with a much more significant role of nonlinear effects at a laser radiation intensity close to the threshold one and also with the spectral width of femtosecond pulses.

Since $\tau \sim 10^{-7}$ s, inequality (17) is always valid for pulses of duration $\tau_p \ll \tau$ considered in this study. The limitation imposed by (17) is important for the laser damage of transparent solids by long laser pulses. If the condition (17) is not satisfied, cracks do not develop in a locally heated region despite the fact that the temperature exceeds θ_{cr}. This evidently implies that, as a result of an exposure of a transparent solid to laser radiation, a melt appears in it. However, this problem requires a special study.

A numerical estimate of τ_p^* for the experimental conditions of paper [1] is of interest. According to [1], when fused silica is damaged, the crack formation is observed for pulse durations of up to 20 ps. The value of τ_p^* is calculated from (31). In the case of a damage caused by a photoionisation thermal explosion of an absorbing inclusion, the size of the damaged region is $R \sim \mu^{-1} \sim 3 \times 10^{-6}$ m (μ is the absorption coefficient for UV radiation at the boundary of the transparent region of the material under study) [11]. According to [10], the surface energy is assumed to be $Ea/100$ (a is the value on the order of the interatomic spacing). For fused silica, $E = 6 \times 10^{10}$ N m^{-2} [12] and $a \simeq 4 \times 10^{-10}$ m. According to [1], for a pulse duration of 10 ps, the threshold energy density of laser radiation is 5 J cm^{-2} at a focal spot diameter of 5×10^{-4} m, yielding $W_p = 10^9$ W. Taking into account the values of the material constants for silica [13], the coupling coefficient is $\vartheta \approx 5 \times 10^{-5}$. Finally, we will assume that the fraction k of the absorbed energy is $(R/R_0)^2 \sim 3.4 \times 10^{-5}$ (R_0 is the laser beam radius). Substituting the above numerical values into (31) results in the estimate for $\tau_p \simeq 50$ ps, which agrees well with the experimental data [1].

For laser pulse durations at which condition (30) is valid and (29) is not, a crack cannot be formed. In this case, the absorbed energy will lead to the formation of defects (of the type of F centers) in the bulk of a transparent solid or to an ablation process under the surface irradiation. Irreversible changes of this type will accumulate in the material under multiple irradiation.

6. Conclusions

The theory developed above explains qualitatively a transition from the crack formation to ablation observed upon irradiation by ultrashort laser pulses. The crack formation process upon laser damage is independent of the laser-energy absorption mechanism. Upon irradiation by long (nanosecond) laser pulses, the damage process in a transparent solid occurs via the crack formation mechanism due to local thermoelastic stresses, whereas upon irradiation by ultrashort (femtosecond) pulses, a solid can be damaged through the ablation and defect-formation mechanisms without the formation of cracks.

The formulated crack-formation criterion upon local laser heating, the calculated minimum crack size, and the minimum energy required for its formation make it possiblle to determine the conditions for implementing these types of laser damage in transparent solids. The theory developed above consistently explains the change in the damage morphology: a transition from the crack formation to ablation with decreasing pulse duration.

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