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The influence of bulk absorption of substance on the threshold of destruction by the intensive pulse of electromagnetic radiation

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A problem of interaction of a laser pulse radiation with a solid surface is considered. The thermal action of radiation on the surface layers of irradiated materials for the different types of absorption coefficient is analyzed, namely for the unlimited, almost zero, and finite absorption coefficients, and for the absorption that is strongly depending on the intensity of radiation flux. The relations determining the thresholds of destruction in dependence on the intensity and the duration of action of the flux are received. The properties of the irradiated material are also taken into account. The analysis of the obtained threshold relations shows that the magnitude of the absorption coefficient of the material considerably influences the conditions at which the irreversible local phase modifications occur.

Рассмотрена задача взаимодействия импульсного лазерного излучения с поверхностью твердого вещества. Проанализировано тепловое воздействие излучения на поверхностные слои облучаемых материалов для различных видов коэффициента поглощения: бесконечного, конечного и коэффициента поглощения, который зависит от интенсивности излучения. В работе получены соотношения для определения порогов возникновения разрушения поверхности в зависимости от интенсивности и длительности воздействия потока. Эти пороговые соотношения учитывают также свойства облучаемого материала. Анализ полученных пороговых соотношений показывает, что величина коэффициента поглощения материала существенно влияет на условия, при которых наступают необратимые локальные фазовые изменения поверхности в зоне действия излучения.

1. Introduction

An action of laser radiation on a surface of solid causes the certain changes which are mainly characterized by temperature and pressure [1-3]. When modeling the interaction of radiation with substance a continuum hydrodynamic model [4, 5] is mostly used. One of the main issues is a definition of threshold values of flux and the duration of pulse electromagnetic radiation that distinguishes an absence of destruction of the surface from the process when the surface destruction and a burning of corrosive torch are already possible.

In [6, 7] the general problem of processing of a solid surface under the influence of powerful laser radiation has been formulated. Two separate problems are generally considered. The first is a problem that describes the processes of destruction of the surface [7-9]. The second is a problem that describes the processes preceding to the destruction of the surface namely the warming up of the surface. This is subject of our interest, because it is connected with the definition of related thresholds. As shown in [6], this problem is based mainly on the heat equation. In one-dimensional space it has the form

$$\rho C_{\upsilon}\frac{\partial T}{\partial t}=\lambda\frac{\partial^2 T}{\partial z^2}-\vartheta\left(\tau-t\right)\left(1-L_d\right)\frac{\partial q}{\partial z}. \qquad (1)$$

Relevant initial and two boundary conditions have the form

$$T\left(0,z\right)=T_{in},\quad T\left(t,\infty\right)=T_{in},\quad \frac{\partial T}{\partial z}\left(t,0\right)=-\frac{L_d}{\lambda}q_s\vartheta\left(\tau-t\right). \qquad (2)$$

Here $T=T\left(t,z\right)$ is the material temperature as a function of time and coordinate z, τ is the duration of laser pulse on the surface, $\vartheta\left(\tau-t\right)$ is the Heaviside step function whose value is zero for negative argument and one for positive argument, q is the heat flux inside solid phase, q_s is defined through the input (surface) heat flux, λ is the thermal conductivity of material, ρ is the mass density, C_{υ} is mass-specific heat capacity, T_{in} is the initial temperature of the material before irradiation, L_d $(0\le L_d\le 1)$ is the coefficient of overall dissipative losses associated with the inhomogeneity of the surface layer material. The case $L_d\sim 1$ means that almost all radiation does not penetrate the surface, on which the flux of energy influences (the case of metals and non-transparent material). The case $L_d\to 0$ corresponds to a situation where the flux almost does not bear losses when passing through the surface material. Due to the availability of this factor, the equation (1) with the boundary conditions (2) considers all possible options for the interaction of radiation with the surface (in the framework of the used one-dimensional model).

When it comes to irradiation of semiconductors transparent for the given frequency range and dielectrics with intense radiation of the visible and near-visible ranges, and metals with the intense far ultraviolet radiation and the soft X-ray, the conditions can be realized under which the absorption coefficient is a function of the flux q, i.e. $k=k(q)$. Dependence of the radiation flux on the depth of its penetration z into the material is defined by the Lambert–Beer law with the dependence of the absorption coefficient $k(q)$ on the radiation flux q of general form:

$$\frac{dq}{dz}=-q\,k(q). \qquad (3)$$

Below we use the dimensionless flux value [10] $x=q/q_s$ $(0<x\le 1)$, where q_s is the value of the flux on the surface of material. By applying the direct and inverse Laplace transform in time to the problem (1), (2), we obtain the solution, which determines the surface temperature change with time [6]:

$$\begin{aligned}T_s(t)=T_{in}+&\tfrac{2q_s}{(\pi\lambda\rho C_{\upsilon})^{1/2}}\left\{t^{1/2}\left[L_d+(1-L_d)\cdot\int_0^1 e^{-\frac{\rho c(B(u))^2}{4\lambda\,t}}\,du\right]-\right.\\&\left.-\tfrac{(\pi\rho C_{\upsilon})^{1/2}}{2\lambda^{1/2}}(1-L_d)\cdot\int_0^1 B(u)\mathrm{erfc}\left(\tfrac{(\rho c/\lambda)^{1/2}}{2t^{1/2}}B(u)\right)du\right\}-\\-\vartheta\left(t-\tau\right)&\tfrac{2q_s}{(\pi\lambda\rho C_{\upsilon})^{1/2}}\left\{(t-\tau)^{1/2}\left[L_d+(1-L_d)\cdot\int_0^1 e^{-\frac{\rho c(B(u))^2}{4\lambda\,(t-\tau)}}\,du\right]-\right.\\&\left.-\tfrac{(\pi\rho C_{\upsilon})^{1/2}}{2\lambda^{1/2}}(1-L_d)\cdot\int_0^1 B(u)\mathrm{erfc}\left(\tfrac{(\rho c/\lambda)^{1/2}}{2(t-\tau)^{1/2}}B(u)\right)d\,u\right\}.\end{aligned} \qquad (4)$$

Here $\mathrm{erfc}(x)=\frac{2}{\sqrt{\pi}}\int_x^{\infty}e^{-t^2}dt$ is complementary error function and

$$B(u)=\int_u^1\frac{dx}{xk(x)}. \qquad (5)$$

The solution (4) is the general solution for any dependence of absorption coefficient of solid matter from the value of flux.

2. Thresholds of destruction of the material in case of the constant absorption coefficient

When the absorption coefficient is constant and has sufficiently small value ($k(x) = k_0 \to 0$), the solution (4) reduces to the form [6]:

$$T_s^0(t) = T_{in} + \frac{2q_s L_d}{(\pi\lambda\rho C_\upsilon)^{1/2}} \left(t^{1/2} - \vartheta\,(t-\tau)\,(t-\tau)^{1/2}\right). \tag{6}$$

It is interesting to note that another limiting case $k(x) = k_0 \to \infty$ can be obtained from (6) by replacing $T_s^0(t)$ with $T_s^\infty(t)$ on the left-hand side of (6) and by substituting $L_d = 1$ on the right-hand side of (6). This case fully coincides with the solution derived in [11]. Therefore we consider these two situations simultaneously, temporarily discarding the upper index on the temperature, but keeping the value L_d in the formula (6).

Having analyzed the dependence (6), it is possible to notice that the maximum value $T_s\,(t)$ is reached at $t = \tau$, unless the destruction of surface does not occur. Hence:

$$T_{\max}\,(q_s) \equiv T_s\,(\tau) = T_{in} + \frac{2q_s L_d}{\sqrt{\pi\rho C_\upsilon\lambda}}\sqrt{\tau}. \tag{7}$$

The threshold flux can be obtained from some boundary condition when the destruction has not yet occurred but the maximum temperature $T_{\max}\,(q_s)$ at the moment of the termination of impulse $t = \tau$ reaches the interface phase of "solid – gas". The condition $T_{\max}\,(q_s^*) = T_{cr}\,(q_s^*)$ is the condition determining the threshold intensity q_s^*. Here $T_{cr}\,(q_s^*)$ is the critical temperature, which depends on the flux due to dependence from the pressure (according to the phase diagrams of substances). Using the relation (7) the threshold for q_s^* can be obtained:

$$(q_s^*)^2\,\tau = \frac{\pi\rho C_\upsilon\lambda}{4L_d^2}\left(T_{cr}\,(q_s^*) - T_{in}\right)^2. \tag{8}$$

Hence, when the energy flux satisfies condition $q_s < q_s^*$, the destruction does not occur, but as soon as $q_s > q_s^*$ the destruction of the material surface happens.

If the temperature T_{cr} is not dependent on the flux q_s, the threshold value $(q_s^*)^2\,\tau$ for each specific material and the initial temperature T_{in} would be a constant. But, as seen from (8), the temperature $T_{cr}\,(q_s^*)$ is a function of the intensity q_s^*, and usually it increases with the increase of q_s^*, so the condition (8) is not reduced to a simple "law"of invariance of product $(q_s^*)^2\,\tau$ for a particular "substance-radiation" pair. Thus, the threshold value of flux q_s^*, under which the radiation begins to destruct the surface, for the limiting values of absorption coefficient, $k(x) = k_0 \to 0$ and $k(x) = k_0 \to \infty$, takes the next form:

$$q_s^* = \frac{\sqrt{\pi\rho C_\upsilon\lambda}}{2\sqrt{\tau}L_d}\left(T_{cr}\,(q_s^*) - T_{in}\right). \tag{9}$$

Note that $L_d = 1$ if $k(x) = k_0 \to \infty$.

Now consider the case when the absorption coefficient is a finite quantity, that is $k(x) = k_0$ and $0 < k_0 < \infty$. It is possible to show [8] that the following expression for the dynamics of surface temperature can be obtained from (4):

$$\begin{gathered} T_s^{k_0}(t) = T_{in} + \tfrac{q_s}{\lambda k_0}\left((\alpha t)^{1/2}\,\pi^{-1/2} + (1-L_d)\cdot\left[e^{\alpha t/4}\mathrm{erfc}\left((\alpha t)^{1/2}/2\right) - 1\right]\right) - \\ -\vartheta\,(t-\tau)\,\tfrac{q_s}{\lambda k_0}\left((\alpha\,(t-\tau))^{1/2}\,\pi^{-1/2} + (1-L_d)\cdot\left[e^{\alpha(t-\tau)/4}\mathrm{erfc}\left((\alpha\,(t-\tau))^{1/2}/2\right) - 1\right]\right). \end{gathered} \tag{10}$$

Here the designation $\alpha \equiv 4k_0^2\lambda/(\rho C_\upsilon)$ is used. At $t \le \tau$ only the first two terms remain. In this case, the threshold of radiation flux is defined by the equality:

$$\overset{*}{q_s^{k_0}} = \frac{\lambda k_0\sqrt{\pi}}{\sqrt{\pi}(1-L_d)\left(e^{\frac{\alpha\tau}{4}}\,\mathrm{erfc}\,(\sqrt{\alpha\tau}/2) - 1\right) + \sqrt{\alpha\tau}}\left(T_{cr}\left(\overset{*}{q_s^{k_0}}\right) - T_{in}\right). \tag{11}$$

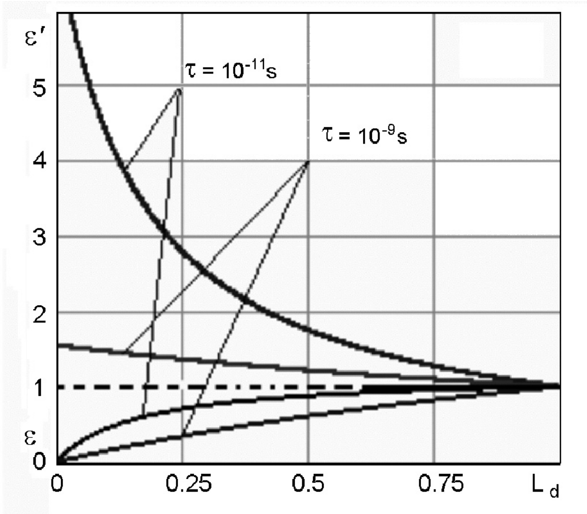

Fig. 1. The dependence of the ratios of thresholds ε and ε' from the factor of overall dissipative losses L_d.

For comparison with the previous case under consideration one can consider the flux ratio of (11) to (9):

$$\varepsilon \equiv \frac{\overset{*}{q}{}_s^{k_0}}{\overset{*}{q}_s} \equiv \frac{\sqrt{\alpha\tau}L_d}{\sqrt{\pi}(1-L_d)\left(e^{\frac{\alpha\tau}{4}}\operatorname{erfc}\left(\sqrt{\alpha\tau}/2\right)-1\right)+\sqrt{\alpha\tau}}\frac{\left(T_{cr}\left(\overset{*}{q}{}_s^{k_0}\right)-T_{in}\right)}{\left(T_{cr}\left(q_s^*\right)-T_{in}\right)} \tag{12}$$

Similar expression for the situation $k(x) = k_0 \to \infty$ (further denoted it by ε') differs from (12) only by the factor L_d being absent in the numerator. In the approximation of the independence of temperature from the flux, the ratios of the thresholds ε, ε' can be represented graphically (Fig. 1). The two lower and the two upper curves in this figure correspond to the ratio ε and ε', respectively. The dependences of ε and ε' from the factor L_d of overall dissipative losses are presented for the different durations of stimulated laser radiation. The estimations are fulfilled for silicon. The analysis of results shows that both approximations (when the bulk absorption coefficients equal to infinity or zero) differ from the case when the absorption coefficient is finite (in Fig. 1 — the dotted line that corresponds to $\varepsilon = 1$). The differences are minimal for materials with the large surface losses ($L_d \to 1$). With the reduction of the overall dissipative losses, the errors in determining the threshold of thermal destruction in the approximation (9) increase.

3. Determination of the threshold of destruction of the material when the absorption coefficient depends on radiation flux

Approximations of the absorption coefficient from the previous section are relevant for metals ($k(x) = k_0 \to \infty$) or the materials of semiconductor-dielectric nature ($k(x) = k_0$) for the cases of transparent ($k_0 \to 0$) and translucent ($k_0 > 0$) materials. The common feature of all these situations was that the absorption coefficient was constant ($k(x) = k_0$). Hence the so-called optically inactive materials were considered. In this section, the response to intense flux of electromagnetic radiation is taken into account, mostly for materials of nonmetal or mixed nature.

When the intensity of the beam interacting with the material is large, the absorption coefficient becomes a function of light intensity. Typically, the dependence $k(q)$ is based on the so-called effective two-level model for atomic system [12]. With the dimensionless flux value $x = q/q_s$ [10] it can be written as follows

$$k(x) = \frac{k_0}{1+(\omega-\Omega)^2\tau_t^2+\xi x}. \tag{13}$$

Here $\xi \equiv q_s/q_E < 1$ actually determines the degree of nonlinearity of the absorption coefficient $k(x)$. The magnitude $q_E \equiv cE_0^2/(8\pi)$ formally corresponds to the energy flux associated with electrostatic resistance of material, $k_0 \equiv |\beta|/(c\tau_l)$ is the permanent part of the absorption coefficient, which depends only on the characteristics of the material and the fundamental constants, the magnitude $\beta = 4\pi\Omega\hbar\gamma^e/E_0^2$ has negative value as it includes the equilibrium value of inverse population γ^e, which is negative by definition, and $\vec{E}_0$ is the material electrical breakdown field. Here τ_l is the longitudinal relaxation time of inverse population which is determined by transitions between the levels caused by the inelastic processes (namely spontaneous emission, inelastic collisions) in the absence of external field, τ_t is the transverse relaxation time (the relaxation time of polarizability), which is defined not only by the inelastic processes but also by the elastic processes which change phase states, Ω is the eigenfrequency of material absorption, ω is the frequency of stimulating radiation, and c is the velocity of light.

To determine the surface temperature of substance with the absorption coefficient (13), we will use the general solution of the heat equation (4), where the function $B(u)$ is defined by (5) and (13):

$$B(u) = \frac{1}{k_0}\left(-\ln(u)\left(1 + (\omega-\Omega)^2\tau_t^2\right) + \xi(1-u)\right). \tag{14}$$

Here $B(u)$ is a monotonically decreasing function in $(0,1]$. It has a logarithmic singularity at zero and goes to zero in the neighborhood of $u = 1$. In the general solution of the heat equation (4) the function $B(u)$ appears in the integrals of the form: $\int_0^1 e^{-\alpha B^2(u)}du$ and $\int_0^1 B(u)\,\mathrm{erfc}(\alpha B(u))\,du$. Since the functions $e^{-\alpha B^2(u)}$ and $B(u)\,\mathrm{erfc}(\alpha B(u)) \sim \frac{e^{-\alpha^2 B^2(u)}}{\alpha\sqrt{\pi}}$ exponentially go to zero in the vicinity of $u = 0$ (see (14)), then taking into account that the vicinity of $u = 1$ makes the main contribution in the integrals on u in (4), one can replace the lower limit of the integrals by some $\delta > 0$ and replace $\ln(u)$ with $(u-1)$ or vice versa in the expression (14) in the vicinity of $u = 1$, for example, using the following simple convenient form:

$$B(u) = -\frac{1}{k_0}\left(1 + (\omega-\Omega)^2\tau_t^2 + \xi\right)\ln(u). \tag{15}$$

Since the maximum temperature has been shown earlier to be determined by the moment of the termination of the pulse, we consider only the first two terms of the solution (4), which are not equals to zero for $t \le \tau$, and describe the processes during the period of the action of the pulse. As a result of substitution (15) in the equation (4), after integration, for $t \le \tau$ we will receive:

$$\begin{aligned}\Delta_T = \left[1 + (\omega-\Omega)^2\tau_t^2 + \xi\right]\cdot\Bigg(&\frac{\sqrt{\alpha t}}{\sqrt{\pi}\left[1+(\omega-\Omega)^2\tau_t^2+\xi\right]} + \\ &+ (1-L_d)\left(\mathrm{erfc}\left(\frac{\sqrt{\alpha t}}{2\left[1+(\omega-\Omega)^2\tau_t^2+\xi\right]}\right)\exp\left(\frac{\alpha t}{4\left[1+(\omega-\Omega)^2\tau_t^2+\xi\right]^2}\right) - 1\right)\Bigg).\end{aligned} \tag{16}$$

Here $\Delta_T \equiv (T_s(t) - T_{in})\frac{\lambda k_0}{q_s}$ is the dimensionless temperature. An important feature of dependence (16) is that it simultaneously takes into account both the response of the material on the radiation intensity (the optical nonlinearity, which is expressed as dependence on ξ) and the influence of the radiation frequency on the temperature near the absorption frequency. Graphic rendering of these effects is shown in Fig. 2.

As seen from Fig.2, the dependence curve $\Delta_T(\omega)$ in the resonance region for smaller values ξ passes higher. This means that in presence of optical nonlinearity for any values of the absorption coefficient ($\xi > 0$) the surface is warmed weaker than in absence of this nonlinearity. The greater the nonlinearity of absorption, the stronger the effect is (i.e., the smaller warming up is). So neglecting the effect of nonlinear absorption can lead to significant errors in evaluating the energy threshold of the material destruction. Using (16) it is also possible to find the threshold of the radiation flux $\overset{*}{q}{}_s^n$ at which the nondestructive processing of the material becomes destructive one. Assuming $t = \tau$, it is found:

$$\overset{*}{q}{}_s^n = \frac{\sqrt{\pi}\lambda k_0\left(T_{cr}\left(\overset{*}{q}{}_s^n\right) - T_{in}\right)}{\sqrt{\pi}(1-L_d)\cdot\Sigma\cdot\left(\mathrm{erfc}\left(\frac{\sqrt{\alpha\tau}}{2\cdot\Sigma}\right)\exp\left(\frac{\alpha\tau}{4\cdot\Sigma^2}\right) - 1\right) + \sqrt{\alpha\tau}}. \tag{17}$$

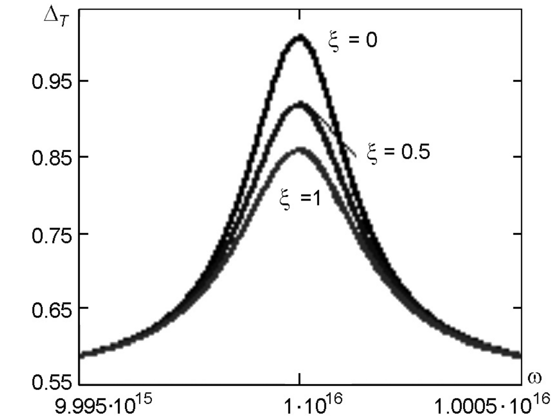

Fig. 2. The temperature of heating surface by radiation at the moment of the termination of action of the pulse ($\tau = 10^{-12}s$) in the resonance area for the different values of nonlinearity parameter ξ.

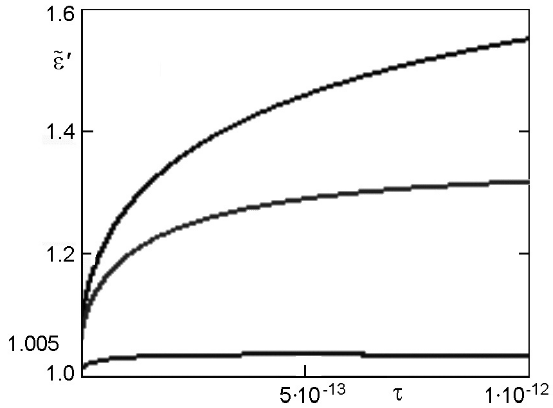

Fig. 3. The ratio of the thresholds of destruction $\tilde{\varepsilon}' \equiv \overset{*}{q}{}_s^n \Big/ \overset{*}{q}{}_s^{k_0}$ depending on the pulse duration τ.

Here the designation $\Sigma \equiv 1 + (\omega - \Omega)^2 \tau_t^2 + \xi$ is used. In (17), unlike the previous cases of the constant absorption coefficient, the situation is complicated by the fact that the nonlinearity parameter $\xi \equiv q_s/q_E$ is directly proportional to the radiation intensity q_s. This complicates both the direct determination and the qualitative forecasting of influence of the material and the radiation parameters on the value of the threshold flux.

To compare (11) and (17) (the absence and the presence of optical nonlinearity) let's consider ratio $\tilde{\varepsilon}' \equiv \overset{*}{q}{}_s^n \Big/ \overset{*}{q}{}_s^{k_0}$. The analysis of behavior of $\tilde{\varepsilon}'$ as a function of τ is shown in Fig. 3. The parameter of nonlinearity was assumed to be $\xi \sim 0,2$ that is the typical value of the ratios of the fluxes used to the electrostatic stability of the material. Its dependence on the threshold flux was also not taken into account. Since the value $\tilde{\varepsilon}' = 1$ corresponds to the absence of optical nonlinearity, one can see that neglecting of nonlinear effects in absorption can lead to significant errors in determining the energy threshold of material destruction. This happens because of a reduction of the absorption coefficient.

4. Conclusions

The paper analyzes the influence of bulk absorption on the threshold of the material destruction with the intense fluxes of electromagnetic radiation. The relation determining the thresholds of destruction in dependence on the heat flux is obtained for the absorption coefficient of different materials. The ratios of threshold characteristics were analyzed for the different values of the absorption coefficient, namely for the unlimited (metals), almost zero (transparent semiconductors or dielectrics), finite (semi-transparent semiconductor and dielectrics) absorption and absorption that strongly depends on the intensity of radiation flux (so-called nonlinear materials). The results obtained confirm that as absorption coefficient of material decreases, regardless of the nature of this decrease, it is necessary to increase the threshold characteristics of the energy flux to achieve the material destruction. Ignoring this can lead to significant errors in the question of forecasting the effects of intense electromagnetic pulses.

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Вплив коефіцієнта об'ємного поглинання матеріалу на поріг його руйнування інтенсивним імпульсним електромагнітним випромінюванням

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Розглянуто задачу взаємодії імпульсного лазерного випромінювання з поверхнею твердої речовини. Проаналізовано тепловий вплив випромінювання на поверхневі шари матеріалів, які опромінюються, для різних видів коефіцієнта поглинання: нескінченного, скінченного та коефіцієнта поглинання, що залежить від інтенсивності випромінювання. У роботі отримано співвідношення для визначення порогів виникнення руйнування поверхні твердого тіла залежно від інтенсивності й тривалості дії зовнішнього впливу. Вказані співвідношення враховують, окрім характеристик випромінювання, також властивості матеріалу, який опромінюється. Проведений аналіз показує, що величина коефіцієнта поглинання матеріалу істотно впливає на умови виникнення необоротних локальних фазових змін поверхні у зоні дії лазерного випромінювання.