Influence of changes in the phase state of the surface and external factors of laser irradiation on the nanocraters formation

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Introduction

Under the influence of powerful laser irradiation, a micro explosion occurs on the solid surface with the formation of a nanocrater and luminous plasma. From the start of the laser action process, the surface actively heated in the local area of the irradiated substance. When the light pressure on the surface and its temperature take critical values, a local phase transition occurs. Phase changes cause the substance ablation and are accompanied by a glow. The substance removed from the surface is a plasma with a complex structure. Later on the flowed from the surface solid and liquid particles (aerosol) affect the degree of laser exposure. To assess the consequences of such an influence, an analytical study of this process was carried out in the work.

Analytical solution of the gas phase dynamics problem in the one-dimensional approximation

A system describing such processes consists of two equations.
equation of the dynamics of crater formation:

$$\Sigma_\theta = \Pi^\beta \sqrt{1+\Sigma_X^2+\Sigma_Y^2}, \qquad (1)$$

which depends on the surface pressure Π as an external factor, and
the equation for this pressure:

$$\Pi_\theta = \left(-1+\left(\Lambda+\frac{1}{\Sigma_\theta}\right)e_q\vartheta(\tau-t)\right)\Pi^{\beta+\eta} - \Pi^{\beta+1}, \qquad (2)$$

which depends on the crater form function Σ as an external factor. The parameter e_q determines the fraction of the flow incident on the surface of the substance q_s relative to the original flow q_{in} and has a complex structure. Σ_θ and Π_θ denote the partial derivatives of dimensionless functions over dimensionless time θ. We denote $N \equiv \sqrt{1+\Sigma_X^2+\Sigma_Y^2}$.
Assume that the width of the stimulating pulse is much larger than the depth of the crater, which is formed under the action of this pulse, and the pulse itself has no transverse structure. This allows us to neglect the coordinate dependence in (1): $N=1$. The parameter e_q will also lose its dependence on coordinates $e_q = e_q(\theta,\Pi,\Sigma)$. The equation of the dynamics of near-surface pressure in this approximation depends only on time. Therefore, equation (2) can be considered as a normal differential equation.
The ideal gas model is used here. To estimate, we can take into account the possibility of deviation from the ideality due to the polytropicity index κ, which is equal to 5/3 for an ideal monoatomic gas (point molecules), and when deviating from monoatomicity (non-point molecules) tends to 1. It was assumed that the aerosol formed near the surface has a complex drops-cluster structure. Therefore $\kappa \to 1$. So far as $\beta = (\kappa+1)/2\kappa$; $\eta = 1/\kappa$, the equation for the pressure can be written as follows:

$$\frac{d\Pi}{d\theta} = \left(-2+\Lambda e_q\vartheta(\tau-t)\right)\Pi^2 + e_q\vartheta(\tau-t)\Pi. \qquad (3)$$

The given equation contains stepwise Heaviside function from time $\vartheta(\tau-t)$, so equation (3) is two separate equations, each of which is responsible for a part of the process as a function of the time, namely: $t<\tau$ (dimensionless $\theta<\theta_\tau$) - the period when the pulse has not yet ended and its action still stimulates the destruction of the surface; $t>\tau$ (dimensionless $\theta>\theta_\tau$) - the period when the action of the pulse ceases.
For this case, approximate piece-wise continuous solutions were obtained during the time of the pulse and after its termination.

$$\Pi(\theta)=\begin{cases}\left(\left(\Pi_{in}^{-1}-2/e_q+\Lambda\right)\exp(-e_q\theta)-\Lambda+2/e_q\right)^{-1}, & \theta\le\theta_\tau;\\ \left(2(\theta-\theta_\tau)+\dfrac{\left(\Pi_{in}^{-1}-2/e_q+\Lambda\right)\exp(-e_q\theta_\tau)-\Lambda+2/e_q}{1-e_q\Pi_q\left(\left(\Pi_{in}^{-1}-2/e_q+\Lambda\right)\exp(-e_q\theta_\tau)-\Lambda+2/e_q\right)}\right)^{-1}, & \theta>\theta_\tau;\end{cases}$$

Influence of radiation absorption on pressure dynamics during pulse action

The obtained solutions include two dimensionless parameters Λ and e_q, which are the characteristics of the interaction of radiation with ablative substance.
Based on these solutions, averaged expressions for pressure and crater function were obtained. Analysis of their behavior is carried out for various values of the parameters Λ and e_q.
The quantity Λ is directly proportional to the absorption coefficient of radiation. The parameter e_q depends exponentially on Λ. Both parameters affect the value of the maximum pressure near the surface at the time of active laser exposure.
The dependence presented in Figure 1 indicates that the effect of the radiation flux on the substance will be stronger when the absorption capacity of the gas (plasma) evaporated from the irradiated substance is minimal. A value of $e_q = 1$ means that the flux does not suffer any losses on the way to the substance, and this is possible only with the propagation of the laser pulse in vacuum. These results are valid if we consider the value of e_q constant over time. But the increase in pressure and depth of the crater leads to a decrease in this parameter over time. That is, over time, the pressure in the near-surface area will decrease.
The dependence of the average pressure on θ_τ was also investigated, at different values of the parameter Λ, which characterizes the interaction of radiation with the gaseous medium. Λ is related to the absorption coefficient of this medium.
InIn fig. 2 the value of $\Lambda = 10^{-10}$ corresponds to the real absorption coefficient $k \sim 10^2 sm^{-1}$, $\Lambda = 10^{-15}$ – the absorption coefficient $k \sim 10^{-3} sm^{-1}$, and $\Lambda = 10^{-18} - k \sim 10^{-6} sm^{-1}$. Accordingly, the radiation flux begins to be absorbed at times $t \sim 10^{-15} s$ when $k \sim 10^2 sm^{-1}$, $t \sim 10^{-7} s$ when $k \sim 10^{-3} sm^{-1}$ and $t \sim 10^{-7} s$ when $k \sim 10^{-6} sm^{-1}$.
It can be seen from Fig. 2 that the pressure increases rapidly at the beginning and reaches its maximum value already at $t \sim 10^{-13} s$, and then begins to decrease, and the higher the value, the faster the pressure begins to decrease exponentially. This pressure behavior is due to the fact that over time, the corrosive torch formed by the radiation takes up more volume by increasing its length. This reduces the amount of flow that reaches the surface of the solid. Mathematically, this fact tracks the influence of the factor e_q, which depends on the value of the parameter Λ and takes into account the loss of radiation flux intensity on the way to the target.

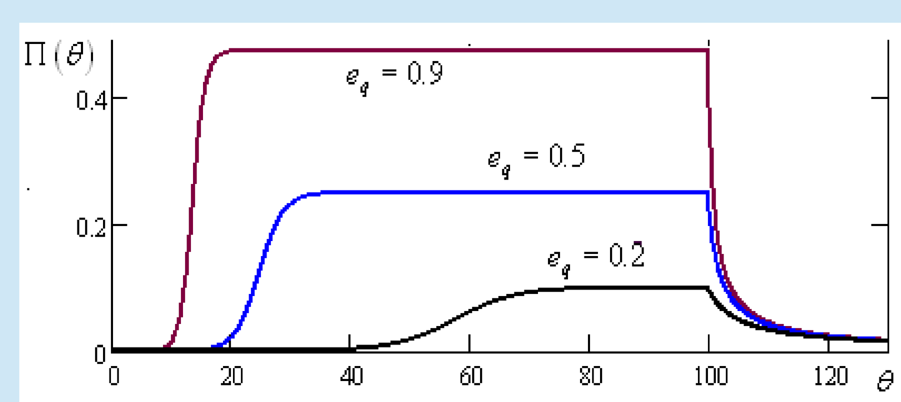

Fig.1 Qualitative form of the dependence of the gas pressure Π on the time near the surface for different values of the parameter e_q

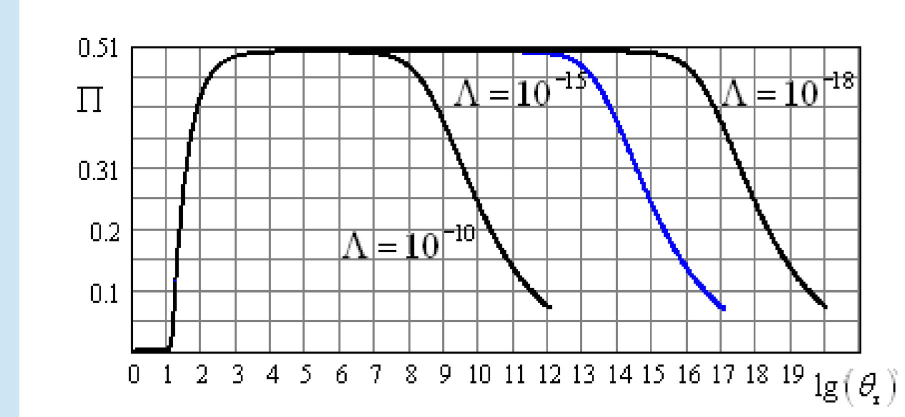

Fig. 2 Dependence of pressure on the value of θ_τ on a logarithmic scale for different possible (estimated) values of Λ.

Influence of resonant absorption of radiation by a gas on the flame dynamics

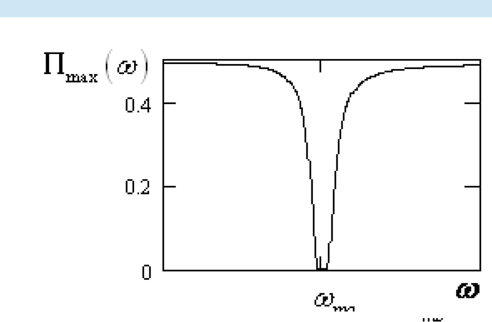

Fig. 3 Qualitative type of dependence of maximum pressure on frequency ω.

Also Λ depends on the frequency of the radiation and the frequency characteristics of the irradiated physical system. In the paper, the influence of the frequency parameter $h(\omega)$ to the absorption coefficient is studied. It is obvious that the pressure can reach its maximum value during the action of the pulse, if its duration is not too short.
The graphical dependency $\Pi_{max}(\omega)$ is shown in Fig. 3. It is seen that at the point $\omega = \omega_{m0}$ the pressure formally becomes zero. In fact, its value does not reach zero due to the presence of other, nonresonant terms, which were rejected when obtaining an explicit expression for the absorption coefficient k as a function of the frequency ω.
The purely resonant case ($\omega = \omega_{m0}$) requires a separate study, so due to the formula obtained in this work, we can trace only the tendency of the maximum pressure Π_{max} to change depending on the frequency at $\omega \to \omega_{m0}$.

The influence of this parameter to the maximum pressure in the process under consideration is analyzed. It is shown that in the case of resonance, aerosol can to put up significant resistance to the laser action and practically stops the nanostructures formation on the substance surface.
Numerical studies show that the dependence $\Pi(\Lambda)$ does not change qualitatively with increasing value of θ_τ. Let us note, based on numerical calculations, that the pressure Π is approximately dependent on the product $\Lambda\theta_\tau$. In dimensional units , this product is determined for the specific conditions of the experiment pressure and depends on the product $q_{in}^3\tau$. The additional dependence on θ_τ is significant in the region of only small values of pulse lengths.