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INTERACTION OF LASER RADIATION WITH MATTER. LASER PLASMA

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Efficiency of ablation loading and the limiting destruction depth of material irradiated by a high-power laser pulse

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Abstract. **The problems of calculating the energy of a substance encompassed by a shock wave (the ablation loading efficiency) and determining the limiting destruction depth of a solid irradiated by a plasma-producing laser beam of intensity varying in a broad range from 10^8 to 10^{14} W cm^{-2} are analytically solved. The limiting destruction depth of material is calculated. This depth is a total thickness of the substance layers evaporated and melted during the laser pulse and of a melted substance layer behind the front of a shock wave decaying in a target after the pulse end. For laser pulses with intensities above $\sim 10^{11} - 10^{12}$ W cm^{-2} and duration 20 – 100 ns, the material destruction depth caused by the action of the decaying shock wave substantially exceeds the depth of evaporation and melting of material during irradiation by the laser pulse.**

Keywords: *shock wave, ablation loading, melting and evaporation of matter.*

1. Interaction

The theoretical dependences of the melting and evaporation rates of substances on the parameters of a laser pulse and physical characteristics of materials varying in a broad range are important for physical studies and technological applications related to the action of high-power laser radiation on the substance. These dependences are determined from numerical calculations of the interaction of laser radiation with the substance, which are performed using mathematical programs developed recently.

However, such programs, as a rule, are intended for the solution of certain problems. The physicomathematical models of these programs include the description of the physics of processes calculated for rather narrow ranges of variation of parameters of the laser pulse and characteristics of materials. Therefore, to obtain the universal dependences of the evaporation and melting rates of a substance on the laser-pulse parameters, analytical models should be used, which can adequately describe the general properties of the process, provided a certain simplification of the physics of interaction of laser radiation with the substance is used.

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In this paper, we develop the analytical theory of the propagation of a shock wave in a solid and of the ablation destruction of a semi-infinite material layer irradiated by a plasma-producing laser pulse, whose intensity varies over the entire range corresponding to the hydrodynamic interaction regime, from 10^8 to 10^{14} W cm^{-2}. We study the ablation loading efficiency of the target material-the fraction of the absorbed laser energy, which is contained at the instant of the laser pulse termination in the target material encompassed by a shock wave propagating deep in the target. We solve the problem of the material destruction caused by the shock wave decaying in the material after the end of the laser pulse. The possibility of such 'delayed' destruction of the material was found in Ref. [1] based on the analysis of experimental results and calculations of a shock wave in the short impact approximation. The analytic dependences of the depth and time of the material destruction on the laser pulse parameters and physical constants of the material are obtained.

2. General picture of physical processes of propagation of a shock wave and destruction of material irradiated by a laser pulse

Upon the hydrodynamic interaction of laser radiation with a substance, a laser plasma is produced, and the laser energy is absorbed in the substance via the hydrodynamic mechanism of energy transfer. The range of the laser-pulse parameters corresponding to this regime is determined by the following conditions: the energy transfer related to the electron heat conduction, intrinsic plasma radiation, and fast electrons is negligible compared to the energy transfer caused by the hydrodynamic motion of the substance.

Analysis of the role of various mechanisms of energy transfer in a laser plasma for different parameters of a laser pulse can be found, for example, in book [2]. The first condition is satisfied for laser pulses of moderate intensities $I \leqslant 10^{14}$ W cm^{-2} with not very short durations $\tau \geqslant 0.1$ ns. The second condition is in fact the condition of the dominating role of the inverse bremsstrahlung of laser radiation without generation of fast neutrons. This condition is satisfied when the parameter $I\lambda^2$ (λ is the laser radiation wavelength) is bounded above: $I\lambda^2 \leqslant 10^{14}$ W μm^2 cm^{-2}.

In this paper, we restrict ourselves to the case of interaction of laser radiation with the matter when the energy of intrinsic radiation of a plasma is far smaller than the matter energy, which certainly provides the condition of a small role of radiant energy transfer. Such a formulation of the problem corresponds to the interaction of a laser pulse with materials of light and heavy elements, including heavy metals, at the relatively low radiation intensity, which does not exceed 5×10^{12} W cm^{-2} when the temperature of the plasma being produced does not exceed 100 eV. At higher intensities $5 \times 10^{12} \leqslant I \leqslant 10^{14}$ W cm^{-2}, the approximation of low conversion of laser radiation to the intrinsic radiation of a plasma is valid for light-element materials, including light metals, such as beryllium or aluminium.

The destruction of a material irradiated by a high-power laser pulse occurs due to phase transitions of two types: evaporation and melting. The dynamics of the phase transitions during the action of the laser pulse and after its termination differ in some features. Consider these features in the case of a constant intensity of the laser pulse, when the material is evaporated from the surface being irradiated. Under the action of pressure of the evaporated part of the target (corona), a shock wave propagates deep in the target. If the pressure inside the shock wave exceeds the pressure corresponding to the yield strength, the material melts behind the shock-wave front. In this case, as shown below, the shock-wave velocity substantially exceeds the evaporation-wave velocity, and melting occurs during the entire pulse duration.

After the laser pulse end, a decaying shock wave and the following unloading wave propagate from the free surface of the target deep in the target. The initial pressure amplitude in the shock wave is determined by the efficiency of ablation loading. The outflow of the material from the free surface will result in the additional (relative to the energy transfer to new portions of a solid) decay of the shock wave. However, as follows from the solution of the problem on the propagation of a shock wave after a short impact of the material surface [3], the influence of the unloading wave on the decay rate of a cylindrical and, especially spherical shock wave, is weak. For example, according to a self-similar solution of the problem on a point explosion in an infinite medium, the pressure behind the wave front decreases with time as $p \sim t^{-6/5}$, whereas the pressure in the shock wave decreases in time due to the gas outflow from the free surface much slower, as $p \sim t^{-1/2}$. Taking into account this circumstance and the fact that in the problem under study the wave front is separated from the free surface at the initial moment by the distance equal to the penetration depth of the shock wave during the laser pulse, the influence of the unloading wave on the dynamics of the decaying shock wave propagating deep in the matter can be neglected.

Therefore, the depth of the material destruction caused by high-power laser irradiation can be approximately determined in the following way. If the pressure amplitude of the shock wave during the laser pulse proves to be lower than the pressure corresponding to the yield strength of the matter, the destruction of the matter ends with the laser pulse termination. In this case, the destruction depth is equal to the thickness of the matter layer evaporated during the laser pulse. If the shock-wave amplitude exceeds the pressure corresponding to the yield strength, the destruction depth is equal to a sum of the thickness of a matter layer evaporated during the laser pulse action, the penetration depth of the shock wave during the laser pulse action, and the penetration depth of the shock wave decaying after the laser pulse end until its amplitude decreases to the pressure corresponding to the yield strength of the matter.

3. Ablation loading of matter irradiated by a laser pulse

In the hydrodynamic regime of the action of a laser pulse on matter, the laser radiation energy absorbed by the target is contained in the form of thermal and kinetic energy of the matter. In this case, the absorbed energy can be divided into two parts. The first part is the energy of the evaporated flow of the matter (laser plasma corona) expanding towards the laser beam and the second one is the energy of the dense part of the matter compressed by the shock wave, which propagates deep in the target under the action of the corona pressure. Let us calculate these energies.

Consider the problem in the following formulation. Let a laser beam of radius R_{L} be normally incident on a plane surface of a semi-infinite layer of matter with the density ρ_0. The laser radiation intensity I is constant during the laser pulse duration τ. We assume that laser radiation is absorbed near the surface of the expanding plasma with the density that is close to the critical plasma density (in g cm^{-3}):

$$\rho_{\mathrm{c}} \approx 1.83 \times 10^{-3} \frac{\mu}{Z\lambda^2}, \tag{1}$$

where μ and Z are the atomic weight and charge of ions in the plasma produced, respectively; λ is measured hereafter in micrometers.

The convenient and adequate method for the description of the state of the laser plasma corona in the case of the hydrodynamic action of the laser beam is the stationary approximation [4]. For moderate laser power densities, not exceeding 10^{14} W cm^{-2}, the stationary positions of the critical-density surface subjected to laser irradiation and of the Jouguet surface, on which the hydrodynamic velocity of matter is equal to the isothermal sound velocity, coincide and are close to the position of the surface of the non-evaporated part of the target [4]. This means that we can replace the region between the surface where the laser energy is absorbed and the surface of evaporation by a hydrodynamic discontinuity, which propagates deep in the target with the velocity of the evaporation-wave front.

The flux of absorbed laser energy of density I_{a} arrives at the target through the hydrodynamic discontinuity from the side of a low-density part of the plasma. Because the region of the energy release is close to the target boundary, the mass and energy of the evaporated target material can be found from the relations for plane fluxes of matter and energy in the hydrodynamic discontinuity. The density of the energy flux of the evaporated target material [5] flowing through the discontinuity is

$$\begin{gathered} I_{\mathrm{e}} = \rho u \left(\varepsilon + \frac{p}{\rho} + \frac{u^2}{2} \right) \approx \frac{3\gamma_{\mathrm{c}} - 1}{2(\gamma_{\mathrm{c}} - 1)} \rho_{\mathrm{c}} u_{\mathrm{c}}^3, \\ u_{\mathrm{c}} = c \equiv \left(\frac{p_{\mathrm{c}}}{\rho_{\mathrm{c}}} \right)^{1/2}, \end{gathered} \tag{2}$$

where ε, p, ρ, u are the specific internal energy, pressure, density, and velocity of matter, respectively; $p_{\mathrm{c}} = \rho_{\mathrm{c}} c^2$ and u_{c} are the pressure and velocity of matter at the critical-density point; c is the isothermal velocity of sound at the critical-density point; γ_{c} is the adiabatic constant of the evaporated material. The velocity of the front of the evaporation wave propagating deep in the target can be determined from the continuity relation for the matter flowing through the discontinuity:

$$V_e = \frac{\rho_c}{\rho_0} c. \quad (3)$$

The second component of the absorbed laser energy contained in the target material behind the shock-wave front can be determined from the relations for the material parameters on the shock-wave front under the condition that pressure p_s behind the wave front is uniform and is equal to that in the region of laser radiation absorption at the evaporation boundary. The pressure at the evaporation boundary is equal to a sum of the thermal and reactive components, i.e., $p_s = 2\rho_c c^2$. The shock-wave velocity in a solid with the pressure amplitude exceeding the pressure corresponding to the yield strength of the material is rather high. The velocity of the shock wave induced by a laser pulse of intensity $10^{12} - 10^{14}$ W cm^{-2} in various metals amounts to $(0.5-2)\times 10^6$ cm s^{-1}. However, even at such a high velocity, the shock wave propagates deep in the target during the action of a nanosecond laser pulse only to the depth not exceeding several tens of micrometers. For the laser pulse energy no less than 10 J and the above specified laser pulse intensity and duration, this distance is far smaller than the laser-beam radius, which is several hundreds of micrometers. Therefore, we can assume with high accuracy that the laser energy transfer to the non-evaporated part of the target occurs at the stage of a plane shock wave.

Taking into account that the mass of matter encompassed of the shock wave is determined by the relative velocity of the shock wave and the evaporation wave and using the relations for the matter parameters at the front of the plane shock wave, we can easily obtain the expression for the flux density I_s of the absorbed laser energy, which is transformed to the energy of the non-evaporated part of the target:

$$I_s = \left[1 - \frac{(\gamma_s + 1)V_e}{(\gamma_s - 1)V_s}\right] \frac{2}{(\gamma_s + 1)} V_s p_s, \quad (4)$$

where γ_s is the adiabatic constant of the dense material of the non-evaporated part of the target; and

$$V_s = c(\gamma_s + 1)^{1/2} \left(\frac{\rho_c}{\rho_0}\right)^{1/2} \quad (5)$$

is the shock-wave velocity. By comparing (5) and (3) and taking into account that $\rho_c \ll \rho_0$ we can easily see that the evaporation-wave velocity is much lower than that of the shock wave:

$$\frac{V_e}{V_s} = \frac{1}{(\gamma_s + 1)^{1/2}} \left(\frac{\rho_c}{\rho_0}\right)^{1/2} \ll 1.$$

By substituting (5) into (4) and using the relation $p_s = 2\rho_c c^2$, we obtain for the flux I_s in the case of a semi-infinite medium the expression

$$I_s \approx \frac{4}{(\gamma_s + 1)^{1/2}} \left(\frac{\rho_c}{\rho_0}\right)^{1/2} \rho_c c^3.$$

By equating the total density of energy fluxes $I_e + I_s$ to the flux density I_a of absorbed laser energy, we obtain the expressions

$$c = \left[\frac{3\gamma_c - 1}{2(\gamma_c - 1)} + \frac{4}{(\gamma_s + 1)^{1/2}} \left(\frac{\rho_c}{\rho_0}\right)^{1/2}\right]^{-1/3} \left(\frac{I_a}{\rho_c}\right)^{1/3}, \quad (6)$$

$$p_c = \left[\frac{3\gamma_c - 1}{2(\gamma_c - 1)} + \frac{4}{(\gamma_s + 1)^{1/2}} \left(\frac{\rho_c}{\rho_0}\right)^{1/2}\right]^{-2/3} \rho_c^{1/3} I_a^{2/3}. \quad (7)$$

for the velocity of sound and pressure at the critical-density point. Now, using (6) and (7), we find from (4) the expression for the fraction σ of absorbed energy of the laser pulse which is imparted to the non-evaporated part of the target:

$$\sigma \equiv \frac{I_s}{I_a} = \left\{\frac{(\gamma_s + 1)^{1/2}}{4} \left[\frac{3\gamma_c - 1}{2(\gamma_c - 1)}\right] \left(\frac{\rho_0}{\rho_c}\right)^{1/2} + 1\right\}^{-1}.$$

Because this fraction of the absorbed laser energy is contained in the shock wave, it is reasonable to call σ the efficiency of ablation loading of matter. By using the inequality $\rho_c \ll \rho_0$, again, we obtain

$$\sigma \approx \frac{4}{(\gamma_s + 1)^{1/2}} \frac{2(\gamma_c - 1)}{3\gamma_c - 1} \left(\frac{\rho_c}{\rho_0}\right)^{1/2}. \quad (8)$$

The efficiency of ablation loading of material increases with decreasing material density and with increasing critical plasma density, i.e., with decreasing wavelength of laser radiation (see expression (1)). The calculation by formula (8) shows that the ablation loading efficiency for solids is several percent. Indeed, the constant γ_c of the evaporated part of the target can be assumed equal to its value for an ideal gas $\gamma_c = 5/3$. According to [3], we will take $\gamma_s = 3$ for estimates in the case of metals. Then, using expression (1) for the critical density ρ_c of a plasma, expression (8) for the ablation loading efficiency upon irradiation of metals by a laser pulse can be written in the form

$$\sigma_m \approx 2.8 \times 10^{-2} \left(\frac{\mu}{Z\rho_0}\right)^{1/2} \frac{1}{\lambda}; \quad (9)$$

Hereafter, ρ_0 is measured in g cm^{-3}.

The ablation loading efficiency increases with decreasing material density and laser wavelength, but only weakly depends on the laser pulse intensity (via the ionisation degree $Z(I)$ of the material). For example, the ablation loading efficiency upon irradiation by the first harmonic of a neodymium laser is 3 % – 4 %, 4 % – 5 %, and 2 % – 3 % for beryllium, aluminium, and copper, respectively. These estimates are based on the fact that at laser-pulse intensities $I = 10^{12} - 10^{14}$ W cm^{-2}, the ionisation of the beryllium laser plasma corona is almost complete ($Z = 3 - 4$); for aluminium, $Z \approx 4 - 5$ at $I = 10^{12}$ W cm^{-2} and $Z \approx 8 - 10$ at $I = 10^{14}$ W cm^{-2}; and for copper, $Z \approx 5 - 6$ at $I = 10^{12}$ W cm^{-2}. The ablation loading efficiency for plastics is $2 - 3$ times higher and amounts to 6 % – 8 %.

The ablation loading efficiency represents the efficiency of energy transfer from a high-power laser pulse to the target in the case when the target thickness exceeds the distance of propagation of the shock wave during the action of the laser pulse. One of the important trends in the physics of interaction of laser radiation with matter is the acceleration of the target as a whole under the action of the laser pulse. It is known (see, for example, [2]) that the maximum degree of conversion of the laser pulse energy to the kinetic energy of the target, the so-called coefficient of hydrodynamic transfer, is achieved after evaporation of approximately half the target mass and amounts to several tens percent. Because, as shown above, the shock-wave velocity is a few tens times greater than that of the evaporation wave, large coefficients of hydrodynamic transfer are achieved upon pulsed laser irradiation of a relatively thin target, through which the shock wave passes for a time that is much shorter than the laser pulse duration.

Thus, the ablation loading efficiency and the coefficient of hydrodynamic transfer determine the energy imparted from the laser pulse to the target in two limiting cases: the first quantity is applied to thick material layers, when the target thickness greatly exceeds the penetration depth of the shock wave, and the second one – to thin layers, through which the shock wave passes for a time that is much shorter than the laser pulse duration.

Note that the method for calculation of the ablation loading efficiency developed in this paper can be used for determining the efficiency of energy transfer from the laser pulse to a material layer of an arbitrary thickness because the acceleration of a thin target as a whole results from the successive action of shock waves and unloading waves of the layer material.

4. Evaporation and melting of material during the laser pulse action

Let us discuss the result of ablation action on matter during the laser pulse. Because the energy of ablation loading represents a small fraction of the total laser-pulse energy absorbed by matter, we can quite exactly calculate the parameters of plasma in the evaporated part of the target by assuming that all the absorbed energy is contained in the laser plasma corona:

$$c = \left[\frac{2(\gamma_c - 1)}{3\gamma_c - 1}\right]^{1/3}\left(\frac{I_a}{\rho_c}\right)^{1/3}, \tag{10}$$

$$p_c = \left[\frac{2(\gamma_c - 1)}{3\gamma_c - 1}\right]^{2/3}\rho_c^{1/3} I_a^{2/3}. \tag{11}$$

In this case, expressions (5) and (3) for velocities of the shock wave and the evaporation wave are simplified:

$$V_s = (\gamma_s + 1)^{1/2}\left[\frac{2(\gamma_c - 1)}{3\gamma_c - 1}\right]^{1/3}\left(\frac{\rho_c}{\rho_0}\right)^{1/2}\left(\frac{I_a}{\rho_c}\right)^{1/3}, \tag{12}$$

$$V_e = \frac{1}{(\gamma_s + 1)^{1/2}}\left(\frac{\rho_c}{\rho_0}\right)^{1/2} V_s. \tag{13}$$

Velocities (12) and (13) determine the penetration depth of the shock wave in the dense part of the target $L_s = V_s\tau$ and the thickness of the evaporated layer $L_e = V_e\tau$ to the end of the laser pulse. For metals ($\gamma_s = 3$), these quantities (in centimetres) are

$$L_s \approx 10^2\left(\frac{\mu}{Z}\right)^{1/6}\frac{I_a^{1/3}\tau}{\lambda^{1/3}\rho_0^{1/2}}, \tag{14}$$

$$L_e \approx 2.1\left(\frac{\mu}{Z}\right)^{2/3}\frac{I_a^{1/3}\tau}{\lambda^{4/3}\rho_0}; \tag{15}$$

Hereafter, I_a is measured in W cm^{-2} and τ in seconds.

The penetration depth of the shock wave in targets made of Be, Al, and Cu to the end of the laser pulse of duration, for example, 1 ns at the intensity of the absorbed energy $I_a = 10^{12}$ W cm^{-2} was 5–9 μm, while for $I_a = 10^{14}$ W cm^{-2}, it was 20–40 μm. The thickness of the evaporated layer was considerably smaller, approximately by a factor of $(\rho_0/\rho_c)^{1/2}$, than the penetration depth of the shock wave. For $I_a = 10^{12}$ W cm^{-2}, the evaporation depth was 0.1–0.3 μm, while for $I_a = 10^{14}$ W cm^{-2}, it was 0.6–0.8 μm.

Taking into account (13), the expression for the evaporation rate $\dot{m}_e$ (in g cm^{-2} s^{-1}) of material irradiated by a laser pulse has the form

$$\dot{m}_e \equiv V_e\rho_0 = \left[\frac{2(\gamma_c - 1)}{3\gamma_c - 1}\right]^{1/3} I_a^{1/3}\rho_c^{2/3} \approx 2.1 I_a^{1/3}\lambda^{-4/3}\left(\frac{\mu}{Z}\right)^{2/3}.$$

Note that this expression is consistent with the results obtained in earlier theoretical papers [5, 6] and with experimental data (see, for example, [7]).

Using the expression for the ablation loading efficiency derived above, we will find the condition of material melting during the laser pulse action. Because the elastic component of the internal energy is approximately three times greater than the thermal component on the shock adiabat of metals at pressures close to the pressure corresponding to the yield strength, the condition of melting consists in the four-fold excess of the internal energy of matter behind the shock-wave front over the melting heat:

$$\sigma I_a\tau > 4\varepsilon L_s\rho_0, \tag{16}$$

where ε is the specific melting heat.

By inserting expression (8) for the ablation loading efficiency and expression (14) for the penetration depth of the shock wave into (16), we obtain the condition

$$I_a > (\gamma_s + 1)^{3/2}\left[\frac{3\gamma_c - 1}{2(\gamma_c - 1)}\right]\rho_0^{3/2}\frac{\varepsilon^{3/2}}{\rho_c^{1/2}}. \tag{17}$$

for the laser pulse intensity, which corresponds to the melting of material caused by the hydrodynamic action of the laser pulse of constant intensity.

For metals, condition (17) takes the form

$$I_a > 1.7\times 10^6(\varepsilon\rho_0)^{3/2}\lambda\left(\frac{Z}{\mu}\right)^{1/2}; \tag{18}$$

Hereafter, ε is measured in J g^{-1}.

For targets made of Be ($\varepsilon = 1.4\times 10^3$ J g^{-1}, $\rho_0 = 1.84$ g cm^{-3}), Al ($\varepsilon = 4\times 10^2$ J g^{-1}, $\rho_0 = 2.7$ g cm^{-3}), and Cu ($\varepsilon = 10^2$ J g^{-1}, $\rho_0 = 8.9$ g cm^{-3}), the intensities of the laser pulse at which melting of these metals occurs behind the shock-wave front are 2.2×10^{11}, 4.3×10^{10}, and 3.8×10^{10} W cm^{-2}, respectively.

5. Destruction of material under the action of a decaying shock wave

Thus, provided conditions (16) or (18) are satisfied, melting of the material continues behind the front of the decaying shock wave after the end of the laser pulse. Note that the minimum intensity of the laser pulse corresponding to the 'decaying' destruction of material increases linearly with increasing laser wavelength. In addition, it increases with increasing specific melting heat and density of material.

As a criterion for a significant role of the material destruction in the decaying shock wave, we will take more than threefold excess of the total depth of the melting region over the penetration depth of the shock wave during the action of the laser pulse. Because, as shown above, upon irradiation of material by nanosecond laser pulses, the shock wave propagates in the hydrodynamic regime during the laser pulse action by the distance of several tens of micrometers, which is significantly smaller than the radius of the focal spot, we can estimate the laser pulse intensity corresponding to a significant role of the 'decaying' destruction of material in the plane decaying wave approximation. It is obvious that this intensity exceeds the threshold intensity of 'decaying' destruction by a factor of $3^{3/2}$. By using the results of calculations of the threshold intensity performed at the end of the preceding section, we can easily show that the laser pulse intensity at which the role of 'decaying' destruction of various metals proves to be significant lies within $10^{11} - 10^{12}$ W cm^{-2}.

Let us calculate the depth of the material destruction for the case of a large depth of the 'decaying' destruction, which considerably exceeds the penetration depth of the shock wave during the laser pulse. The depth L_d and time t_d of the destructive action of the shock wave on matter are determined from relations

$$4\varepsilon M = \sigma I_a \tau, \quad t_d \approx \frac{3}{2}\frac{L_d}{V_s}, \tag{19}$$

$$M = L_d\left(1 + \frac{L_d}{4R_L}\right)^2 \rho_0, \tag{20}$$

where M is the limiting mass of the destructed matter; V_s is the initial velocity of the decaying shock wave described by expression (12).

The expression (20) for the mass of material encompassed by the shock wave was obtained with taking into account the possible non-one-dimensional decay of the shock wave when it propagates by the distance comparable with the radius of the laser beam or greater.

By using the relation for the ablation loading efficiency (9), we obtain the expression for the limiting destruction depth produced in metals upon the ablation action of the laser beam:

$$L_d\left(1 + \frac{L_d}{4R_L}\right)^2 = 7 \times 10^{-3}\frac{I_a \tau}{\varepsilon \rho_0^{3/2} \lambda}\left(\frac{\mu}{Z}\right)^{1/2}; \tag{21}$$

Here, L_d and R_L are measured in centimetres.

Comparison of expressions (14) and (21) gives the following upper limit for the laser pulse duration (in seconds) that provides the excess of the limiting destruction depth of the target over the melting depth during the laser pulse action:

$$\tau \leqslant 3.2 \times 10^{-4}\frac{R_L}{\varepsilon^{1/2}}.$$

In the case of the beryllium target, this limit corresponds to the maximum pulse duration equal to 85 ns for $R_L = 100$ μm and to 8.5 ns for $R_L = 10$ μm. For the aluminium target, these durations are 160 and 16 ns, respectively.

Fig. 1 shows the results of calculations of the evaporation (15) and melting (14) lengths of the target during the action of the laser pulse and of the limiting length of the target destruction (19) caused by the decaying shock wave propagating in the target after the end of the laser pulse. The calculations were performed for a flat target irradiated by 1-ns, 1.06-μm pulses of the first harmonic of a neodymium laser at the laser beam radius $R_L = 100$ μm and various pulse intensities (energies).

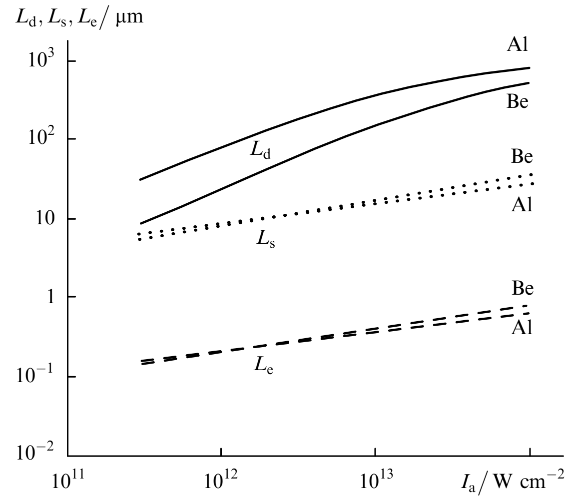

Figure 1. Limiting destruction depth L_d, melting depth L_s, and evaporation depth L_e of aluminium and beryllium targets during the laser pulse action.

These results show that the limiting destruction depth of the material significantly exceeds its evaporation and melting depths during the action of the laser pulse. Thus, for the laser radiation intensity $I = 10^{12}$ W cm^{-2}, the limiting destruction depth of the beryllium target is 25 μm (during the decay time of the shock wave equal to 4.5 ns), whereas the evaporation and melting depths (during the laser pulse action) are 0.2 and 8 μm, respectively. As the laser intensity increases, the difference between the former depth and two latter depths becomes even greater. For $I = 10^{14}$ W cm^{-2}, the limiting destruction depth of the beryllium target is already 530 μm (for the decay time equal to 22 ns), whereas the evaporation and melting depths (during the laser pulse action) are 0.8 and 37 μm, respectively.

In addition, we also present the results of calculations of the limiting destruction depth for some other materials. For the above parameters of the laser beam, the limiting destruction depth of the copper target at the laser pulse intensity $I = 10^{12}$ W cm^{-2} is 43 μm (during the decay time of the shock wave equal to 12 ns), while this depth for plastic at $I = 10^{14}$ W cm^{-2} is 3000 μm (during the decay time of 100 ns).

Thus, upon irradiation of a target by a high-power laser pulse with the intensity exceeding $10^{11} - 10^{12}$ W cm^{-2} and duration 20 – 100 ns, the destruction depth of the target material considerably (tens times) exceeds the penetration depth of the shock wave during the laser pulse. This is explained by the destructive action of the shock wave propagating and decaying in the target material after the end of the laser pulse. The limiting destruction depth of materials increases with increasing intensity and duration of the laser pulse and decreasing laser wavelength and material density. Our results explain large destruction depths of materials observed in many experiments (see, for example, [1]), which correspond to their formation times that substantially exceed the laser pulse duration.

6. Conclusions

Based on the theory of ablation action of a plasma-producing laser beam on a solid developed in this paper, we showed that, for laser pulses with the intensity above $\sim 10^{11} - 10^{12}$ W cm^{-2} and duration to $20-100$ ns, the depth of material destruction caused by the decaying shock wave substantially exceeds the evaporation and melting depths of material during the laser pulse action.

This theory can be used for calculations of the propagation of the first shock wave and shock-wave induced variations in the state of the fusion target material (foot step physics [8]); calculations of the shock-wave parameters, in particular, after the laser pulse termination; to study the equations of state of matter; as well as for calculations of the laser-induced destruction of materials in studies devoted to the technological machining of materials.

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