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# DYNAMICS OF SUBLIMATION AND INITIAL EROSION PLASMA FORMATION UNDER THE ACTION OF QUASICONTINUOUS LASER RADIATION ON METALS*

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*Onset times of sublimation and plasma production as well as of pressure on surfaces under the action of quasicontinuous Nd-laser radiation with a power density up to 10 MW/cm$^2$ on metals are investigated experimentally. The results on sublimation onset time and dynamics are compared with a thermophysical action model that accounts for phase boundaries of melting and sublimation as well as for the temperature dependence of thermophysical characteristics of metals and the time dependence of the power density of laser radiation.*

The aim of the present study is to compare experimental results on the action of real laser pulses on metals with a thermophysical action model [2] that is widely used at moderate power densities of laser radiation (LR). The comparison usually made does not take into account the time dependence of the LR power density $q(t)$ or the distribution of $q(t)$ over the irradiated spot. In the present investigation a quasicontinuous regime of lasing with good homogeneity of the power density distribution over a large irradiated spot was used, which justified the use of a one-dimensional thermal model in numerical modeling of the experiment. The theoretical investigation was reduced to solving a thermal problem with two phase fronts (melting and sublimation) present with account for differences in the thermophysical characteristics of metals in the solid and liquid phase as well as an exact description of the experimental $q(t)$ dependence.

The dependences of sublimation and plasma production onset times as well as of pressure at the target surface on the power density $q$ for LR action on Al and Bi in atmospheres at NTP have been investigated experimentally. Here $q$ denotes the LR power density at the maximum of the laser pulse. An experimental setup based on a GOS 1001 laser with outside hemispherical resonator that provided generation of quasicontinuous pulses of energy up to 900 J and duration of about 1.25 msec was used. The LR pulse energy was varied with neutral light filters installed in the path of the laser beam. In this case $q$ was varied from 0.1 to 10 MW/cm$^2$. The leading edge duration of the laser pulse was about 300 $\mu$sec. Intensity pulsations at the quasistationary lasing stage did not exceed 10% of the mean level. The pulsations could reach 50% of the mean level at the initial stage. Sublimation onset time was determined from the onset of flare emission, the onset of a drop in the reflection coefficient, and the pressure pulse onset determined by a piezodetector. The error of the piezodetector locking to the beginning of lasing was not worse than 10%. The onset time of plasma production was determined from the onset of bright flare emission detected by SFR as well as by a ZhFR-2 camera within spectral bands selected with light filters, which correspond to intense spectral lines of atoms and molecules of the target material. A more detailed description of the methods is given in [3, 4]. Experimental values of sublimation onset time under LR action on a Bi target measured by various methods are presented in Fig. 1.

* The main results were presented at the 7th All-Union Conference on Interaction of Optical Radiation with Matter [1].

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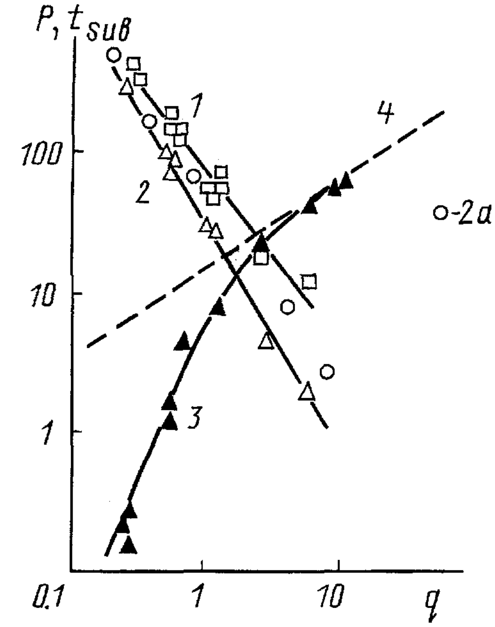


Fig. 1. Dependences of sublimation onset times (1, 2, 2a) and of the maximum pressure at the target (3) on the LR power density. The dashed line corresponds to the dependence $P = 13q^{2/3}$. Sublimation onset was determined: 1) from the onset of flare emission; 2) from the pressure rise at the target; 2a) from the drop in the specular reflection coefficient. $P$, bar; $t_{\rm sub}$, $\mu\cdot$sec; $q$, MW/cm$^2$.

Pressure measurements were used both for determination of sublimation onset time and for study of the dependence of the pressure on the LR power density. The experimental values of the maximum pressure reached at the Bi target surface for values of the LR power density within the range under investigation are also shown in Fig. 1. At first, the pressure grows rapidly with the LR power density approximately proportionally to $q^{2,3}$. Then, at the beginning of plasma production at LR power densities of $q > 2$ MW/cm$^2$ the rise in pressure slows down abruptly to the dependence $P \sim q^{2/3}$. In this case no distinctly pronounced linear dependence of $P$ on $q$, which corresponds to the developed sublimation regime, is observed. Moreover, at the beginning of plasma production the dependence of the pressure at the target on the LR power density closely follows the law $P = 13q^{2/3}$, which is typical of "pushing-out"-type regimes with developed surface screening [5]. It should be noted that the pressure rise at the low LR power density can hardly be explained solely by influence of radial expulsion of melt from the irradiation zone, which should lead, as is shown in [6], to the law $P \sim q^4$.

The numerical solution of the one-dimensional problem of heating-up and sublimation of a metal target by LR was carried out within the framework of the thermophysical action model. The target heating dynamics in the process of laser action (LA) is described by a heat conduction equation. In the one-dimensional case for a target that occupies the half-space $x > 0$ a temperature distribution arises in the material of the target with the absorption coefficient $A$ due to absorption of the heat flow $Aq$ at the surface $(x = 0)$. This temperature distribution is described by the heat conduction equation

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(a\frac{\partial T}{\partial x}\right) \qquad (1)$$

with the boundary condition at the surface (condensed phase/gas phase interface)

$$-\chi\frac{\partial T}{\partial x}\Big|_{x=0} = Aq \qquad (2)$$

and $(-\chi \partial T/\partial x)|_{x=\infty} = 0$ deep inside the target ($\chi$ is the thermal conductivity) and with the initial temperature distribution:

$$T(x, t=0) = T_0, \quad 0 \le x \le \infty. \tag{3}$$

holds in the experiments.

A one-dimensional treatment of the problem is reasonable in this case since the well-known condition $r_{sp}^2/\tau > a$, where $r_{sp}$ is the focussing spot radius ( $\approx 1.75 - 2$ mm) and $\tau$ is the laser pulse duration.

In the process of action the melting temperature $T_{liq}$ is achieved at the surface at the time $t = t_{liq}$ and the melting wave starts to propagate inward from the surface with the velocity $v_{liq}$, which is determined by the following condition at the melting front:

$$\rho \lambda_{liq} v_{liq} = \chi_{liq} \frac{\partial T}{\partial x}\Big|_{liq} - \chi_s \frac{\partial T}{\partial x}\Big|_s, \quad T(x = x_{liq}, t) = T_{liq}, \tag{4}$$

where $\rho$ and $\lambda_{liq}$ are the density and the specific heat of melting; $v_{liq}$ is the phase boundary velocity; the subscripts liq and s denote liquid and solid phase, respectively.

It should be noted that in the majority of problems of thermal action with concentrated energy fluxes sublimation is a powerful factor that constrains the temperature rise. We restrict our attention to the case where the temperature of the target surface is less than the critical one. Then, to account for sublimation one should replace condition (2) with the following condition at the sublimation front:

$$-\chi_{liq} \frac{\partial T}{\partial x}\Big|_{x=x+\int_0^t v_{sub} dt'} = q(t) A - \rho v_{sub} \Delta H, \tag{5}$$

where $v_{sub}$ is the propagation velocity of the sublimation front; $\Delta H$ if the difference in the enthalpies of vapor and condensed matter.

The main difficulty in exact accounting for the sublimation process is connected with treating the gasdynamic flow of sublimated matter and setting boundary conditions at the front of the sublimation wave. However, in most cases for engineering calculations it is possible to restrict oneself to specifying the velocity $v_{sub}$ of sublimation front propagation as a function of the surface temperature $T_0$ without any consideration of hydrodynamic flow:

$$v_{sub} = v_0 \exp\left(-\frac{T_{sub}}{T_0}\right), \tag{6}$$

where $v_0$ is velocity of sound in the solid state; $T_{sub}$ is the sublimation temperature of the target material.

It should be noted that (6) describes well not only the case of sublimation in vacuum but also the influence of sublimation on the heating dynamics in cases where the pressure of the saturated vapor of the target material exceeds by far the pressure of the surrounding atmosphere. However, the applicability of this description has natural restrictions in cases where the erosion plasma flare screens the target surface substantially. Therefore the complete solution of the problem of determination of plasma production thresholds and LA dynamics should include simultaneous solution of thermal and gasdynamic problems. In the present paper a comparison of theory with experimental data is carried out only for the sublimation onset time in cases where the influence of the erosion plasma flare on the heating dynamics is not substantial.

The thermal problem was solved by the factorization method with account for differences in the thermophysical coefficients of the solid state and the liquid and explicit melting boundary separation. The time dependence of the flux density $q(t)$ was specified according to experimental data. The coefficient of LR absorption by the surface was assumed to be independent of the temperature. Calculations were carried out using an

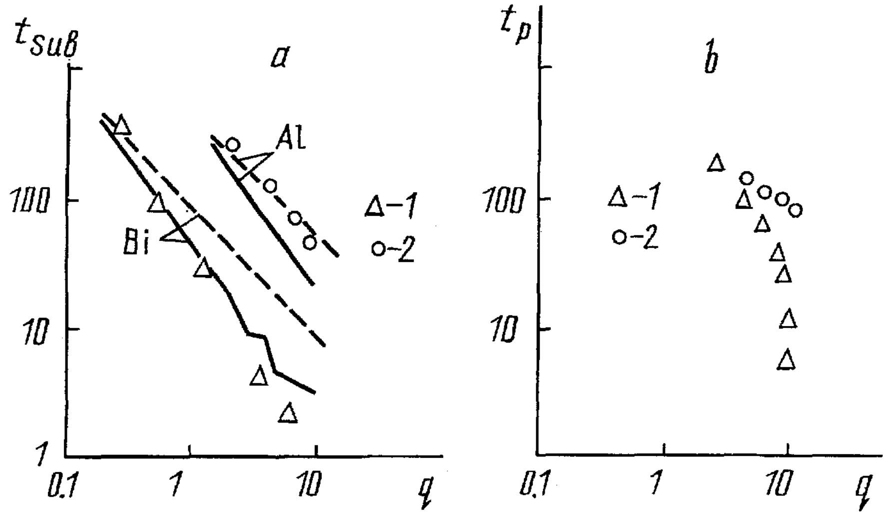


Fig. 2. Dependences of sublimation (a) and plasma production (b) onset times on the LR power density for Al and Bi targets. Experimental points: 1) Bi, 2) Al. $t_p$, $\mu\cdot$sec.

experimental pulse shape according to the mean level and periodic oscillations that describe an actual $q(t)$ dependence.

Dependences of sublimation onset time $t_{sub}$ on $q$ for Al and Bi targets at a saturated vapor pressure of $P$ = 1 atm are shown in Fig. 2a. (The saturated vapor pressure was determined in the calculations as a function of the surface temperature using approximation formulas.) Dashed lines show theoretical dependences for a smoothed representation of $q(t)$ according to the mean value. Solid lines show the same dependences in the case when the time structure of $q(t)$ is taken into account. Experimental data on the sublimation onset determined for Bi with various methods are close to each other, as it is clear from Fig. 1. Therefore, only general $q$-dependence of the experimentally obtained sublimation onset for Bi is shown in Fig. 2a. The experimental results agree closely with the results of calculations for values of $q$ for which sublimation starts at times $t_{sub} \geq 20\,\mu$sec, when LR intensity fluctuations already have no effect. Notice the nonmonotonic course of $t_{sub}(q)$ if intensity fluctuations are taken into account in the case of a Bi target for $q \gtrsim 2$ MW/cm$^2$ when the sublimation starts at the first peaks of lasing. Therefore, one needs exact information on time dependence of intensity and its distribution over the irradiated spot. Calculations have shown that the fraction of energy expended for melting by the moment of sublimation onset comprises about 20% for an Al target and about 50% for a Bi target. Therefore, taking into account melting front dynamics and differences in the thermophysical characteristics of molten and solid metal can affect the determination of the sublimation onset time from theoretical estimates and calculations substantially. The energy input into the target decreases with increase in $q$ as $\varepsilon \sim q^{-0.5}$ by the onset of sublimation, while its absolute value depends strongly on the time shape of the laser pulse.

Figure 2b shows experimental dependences of sublimation onset times $t_p$ for Al and Bi targets. A close connection of plasma production inside the erosion plasma flare with target surface sublimation is evident from the presented dependences $t_{sub}(q)$ and $t_p(q)$. Notice that in the case of an Al target the plasma production delay in relation to sublimation onset is short, while in the case of a Bi target this delay is considerable. Only at $q \gtrsim 10$ MW/cm$^2$ is a sharp decrease in plasma production onset time observed, its value approaching the value of the sublimation onset time.

In conclusion, in the present paper the applicability of a thermal model to the action on metals by LR of moderate intensity is demonstrated experimentally. The model accounts for the phase boundaries of melting and sublimation, the temperature dependence of thermophysical properties of metals, and an exact description of the experimental $q(t)$ dependence. Good correspondence between the theory and experimental data on the onset time and dynamics of sublimation is obtained. Still, the experimental dependence of the pressure at the target surface on the LR power density does not correspond to predictions of the thermal model since the latter does not account for the dynamics and screening properties of the laser erosion flare. The boundaries of existence of the sublimation regime (without plasma production) and plasma production regime of LA on Al and Bi are determined experimentally.

## NOTATION

LR, laser radiation; LA, laser action; $q$, power density of a laser pulse at its maximum; $q(t)$, instantaneous value of the laser radiation power density; $P$, pressure at the target surface; $A$, absorption coefficient of the target material for laser radiation; $x$, space coordinate; $t$, time; $a$, thermal diffusivity; $\chi$, thermoconductivity coefficient; $\chi_{liq}$, $\chi_s$, thermoconductivity of the liquid and solid state, respectively; $T$, temperature; $T_0$, temperature at a surface; $T_{liq}$, $T_{sub}$, melting and sublimation temperature, respectively; $t_{liq}$, onset time of surface melting; $v_{liq}$, velocity of a melting wave; $v_{sub}$, velocity of a sublimation wave; $\rho$, matter density; $\lambda_{liq}$, specific heat of melting; $\Delta H$, enthalpy difference of vapor and condensed matter; $v_0$, velocity of sound in a solid; $t_{sub}$, $t_p$, onset time of sublimation and plasma production, respectively; $\varepsilon$, energy input into the target by the moment of sublimation onset. Subscripts: 0, initial value of a parameter; sp, focussing spot; liq, liquid; s, solid; sub, sublimation; p, plasma.

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