increases with increasing beam density more slowly than in (2).

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FLUSHING OUT THE LIQUID PHASE - A NEW MECHANISM OF PRODUCING A CRATER IN PLANAR FULLY DEVELOPED EVAPORATION OF A METALLIC TARGET BY A LASER BEAM

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We examine a new physical mechanism of crater development in a metal acted upon by laser radiation, wherein the liquid metal is ejected from the irradiated region by the reaction vapor-pressure gradient. The mechanism in question is decisive at not too high a radiation intensity. The obtained estimates agree with the experimental data.

In the case of fully developed metal evaporation by a laser beam, the entire energy of the radiation absorbed in the surface metal layer goes over into the work required to evaporate the material from this layer. The simplest to interpret are experiments in which the depth h of the crater produced by the radiation in the target is small in comparison with its diameter d, which is determined by the dimension of the irradiated area on the target surface. In this case we can neglect effects on the edges of the shallow crater and assume approximately that the evaporation is planar and one-dimensional. The conditions under which such a process can be observed are given by the inequalities [1]

$$d > ut > \sqrt{\chi t} > 1/\alpha. \qquad (1)$$

Here α is the metal absorption coefficient, χ is the temperature conductivity, t is time of action of the laser beam, and u is the velocity of the evaporation front and is determined from energy considerations.

$$I(1-R) = \rho\lambda u. \qquad (2)$$

In Eq. (2), ρ is the density of the condensed phase, R is the reflection coefficient, and I is the beam intensity. According to (1) and (2), the crater depth $h = ut$ is determined by the mass of the removed vapor and depends linearly on the intensity, $h \propto I$.

It was shown in [2] that the metal disintegrates via a liquid-vapor phase transition, unlike in [1], where a solid-vapor transition was considered. This difference is fundamental and leads to new effects, one of which is discussed in the present paper.

We have observed experimentally a new mechanism of crater formation, in which the liquid phase is flushed out from a shallow planar crater by a vapor-pressure gradient directed along the metal surface. The experiments and the calculations shown that, at not too high light intensities, this process makes a larger contribution to the depth of the crater than the removal of the vapor.

If we denote by T_L the characteristic liquid flushing-out time, defined as the time necessary to move the liquid over the target surface to a distance d/2, then the rate of advance of the disintegration front is $u_L \approx \Delta\ell/t_L$, where $\Delta\ell$ is the thickness of the liquid layer near the phase separation boundary (the high-temperature front), and is usually estimated at $\Delta\ell \approx \chi/u$ [2]. However, if $u_L >$ u, then $\Delta\ell \approx \chi/u_L$, and consequently $u_L \approx \sqrt{\chi/t_L}$. The time t_L can be estimated from the relation $t_l \approx \sqrt{d/a}$, where a is the acceleration along the crater surface, acquired by the liquid under the influence of the vapor pressure gradient; in the developed-evaporation regime, this gradient is given by $\nabla P \approx 2P/d = 2\pi\rho v_z(u/d)$ [2]. Here v_z is the vapor-velocity component in a direction perpendicular to the metal surface (the value of v_z in the interval of I corresponding to the developed operation can be assumed to be approximately constant [2]). The acceleration a is determined by the equation $\rho a = \nabla P$. As a result we get $t_L \approx d/(2\pi v_z u)^{1/2}$, and accordingly, the values of u_L of the crater depth h_L

$$h_L = u_L t \approx (\chi/d)^{1/2}(2\pi v_z u)^{1/4} t . \tag{3}$$

In the case of planar one-dimensional evaporation, the conditions for observing the flushing out of the liquid take, in analogy with (1), the form

$$d > u_L t > ut > \sqrt{\chi t} . \tag{4}$$

According to (2) - (4), the flushing-out of the liquid predominates in the crater formation over the escape of matter in gaseous form at not too high intensities, I < I*, where

$$I^* \approx [\lambda\rho/(1-R)](\chi/d)^{2/3}(2\pi v_z)^{1/3} . \tag{5}$$

When I > I*, the crater is produced principally as a result of escape of vapor. The value of I* should exceed the threshold of developed evaporation, for only in this case can the vapor press against the liquid layer and cause it to be flushed out. We obtain accordingly from (4) and (5) the limitation on the experimental conditions for the existence of the discussed flushing-out effect:

$$t(4\pi^2 v_z^2 \chi/d^4)^{1/3} > 1. \tag{6}$$

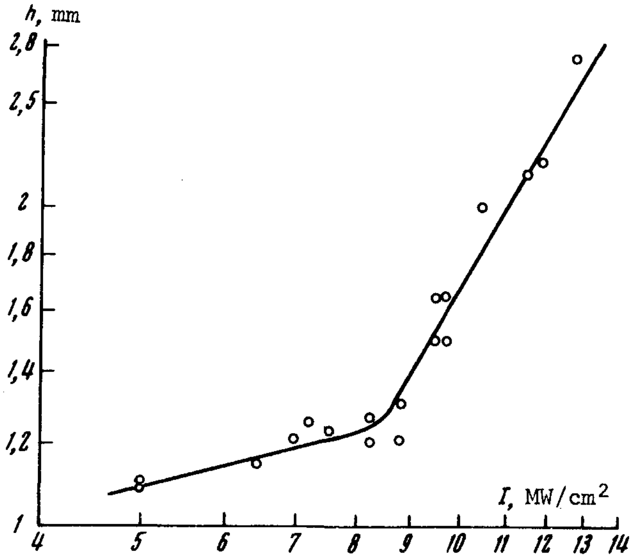
Thus, the effect is possible if the action time t is sufficiently long and the irradiation-zone dimension d is not too large.

We have neglected in this analysis the energy lost to melting, to heating the metal, and to flushing out the liquid, in comparison with the loss to evaporation. Since these energy losses per atom are lower by not less than one order of magnitude than the heat of evaporation, the derived relations are suitable for estimates if the mass of removed liquid exceeds by even one order of magnitude the mass of the ejected vapor; this accuracy is sufficient to discuss the experimental results that are cited below.

We measured in the experiments the depth of the crater in aluminum targets irradiated by millisecond laser pulses. The measurement results are shown in the figure. According to calculations [2], the aluminum surface temperature in the interval $I \approx (0.5 - 1.3) \times 10^7$ W/cm^2 ranges from 3600 to 4000°K (the critical temperature of aluminum is $T_{cr} \approx 4700$°K). Accordingly, $\chi = (0.36$ cm^2/sec)

[3] and $v_c = 4.6 \times 10^4$ cm/sec. The values of t and d in the experiments were t = 0.8 msec and d = 0.8 cm. In this case $t(4\pi^2 v_z^2 \chi/d^4)^{1/3} \simeq 4.4$, so that the experimental conditions satisfy the inequality (6).

The qualitative character of the observed h(I) dependence corresponds to the presented theoretical description. It is seen from the figure that at $I < 0.9 \times 10^7$ W/cm^2 the depth of the crater increases slowly with intensity, $h \propto I^{1/4}$, which agrees with the theoretical relation (3) describing the formation of the crater as a result of flushing out the liquid. At $I > 0.9 \times 10^7$ W/cm^2, the h(I) dependence is stronger, namely $h \propto I^{1.5}$. This part of the curve corresponds to formation of the crater through vapor ejection[1)]. The deviation from the theoretical relation $h \propto I$ that results from (2) may be due to a certain lowering of the reflection coefficient R in this intensity interval.



Depth h of crater in aluminum, averaged over the cross section, vs. the intensity I of the incident laser radiation.

There is also a satisfactory qualitative agreement between the foregoing calculations and experiment. According to (5), the value of I* (at $\lambda = 1.15 \times 10^4$ J/g, $\rho = 2.7$ g/cm^3, R = 0.74), with allowance for the screening of the target by the plasma flare (the optical thickness of which is close to unity [2]), amounts to $I^* \simeq 1.3 \times 10^7$ W/cm^2, whereas experiment yields $I^* \simeq 0.9 \times 10^7$ W/cm^2. The calculated depth of the crater at this point is equal to $h^* = (\chi/d)^{2/3}(2\pi v_z)^{1/3} t \simeq 1.4$ mm, which differs little from the experimental value $h^* \simeq 1.3$ mm.

The flushing-out mechanism considered in the present paper takes place under conditions of planar developed evaporation and differs in principle from the mechanism of ejection of liquid from the walls of a deep crater with h >> d [1], observed under conditions of sharp focusing of light by the target.

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1) The character of the plot in the figure is also confirmed qualitatively by data obtained by photographing the evaporation process. At the start of the intensity interval corresponding to developed evaporation one observes, besides the glow of the plasma flare, also a large number of bright tracks due to liquid-metal drops. With increasing I, the tracks disappear and only the flare can be seen.