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PRIORITY OF FACTORS CONTRIBUTING TO VOLUME VAPOR FORMATION IN LASER TARGETS

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A time distribution of drops in a flame is obtained based on experimental data on laser probing of lead and silicon erosion flames and calculations according to the Mie scattering theory. Results obtained under the action of neodymium laser pulses of different shape on the metal are compared. Some special features of particle formation that depend on the space-time nonuniformity of the laser radiation, the amount of dissolved gases in the metal, different impurities, and structural heterogeneities are established.

Destruction products formed under the action of laser radiation of moderate intensity (10^5-10^8 W/cm^2) on metals consist of vapors, plasma, and a liquid-drop phase [1-3]. Formation of liquid drops of the target material occurs in two stages [4, 5]. In the first stage of laser action the mechanism of formation of particles as a result of volume vapor formation prevails, and in the second one larger particles form [7] by the hydrodynamic mechanism [6]. The present work concerns factors that facilitate the process of volume vapor formation.

In [8] various reasons for the appearance of volume vapor formation are discussed: space-time nonuniformity of the laser radiation, gases dissolved in the metal, different impurities, and structural heterogeneities. It is of interest to reveal the degree of influence of each factor. For this purpose we conducted experiments on the action of pulses of neodymium laser radiation on lead targets. We produced the targets by melting lead: in one case in air and in another case in vacuum, striving for a substantial decrease in the gas content in the lead of vacuum melting.

Furthermore, the action was produced with different pulses of the neodymium laser. In one case a rectangular pulse with a duration of 400-450 μsec was cut from a millisecond pulse of the laser, lasing in the regime of free generation, with a mechanical gate. This pulse had 100% amplitude modulation by spikes of microsecond duration, having a rather random space-time distribution. In another case use was made of a smooth rectangular pulse produced using the mechanical gate from a pulse of the neodymium laser with a confocal resonator [9, 10]. In our case this pulse has a space-time nonuniformity of no worse than 3%. The basic method of investigating the erosion flame that forms under the action of plasma-forming neodymium laser radiation on the target was that of laser probing using an auxiliary ruby laser. The ruby laser lased in a regular-pulse regime and had a power density not exceeding 10^4 W/cm^2 in the probing zone so as not to disturb the parameters of the probed medium. Probing was performed at a distance of 1.5 mm from the target surface perpendicularly to the erosion flame axis. The target was placed in the center of an integrating sphere, because of which it was possible to control the time dependence of the transmission $K_{tr}(t)$, absorption $K_{abs}(t)$, and scattering $K_{scatt}(t)$ coefficients in the experiment. The procedure for this experiment is described in detail in [11].

From the ratio of the scattering and absorption coefficients of the probing radiation, measured experimentally, and using the dependence of this ratio on the diameter of the scattering particles, calculated theoretically by the Mie formulas, we determined the dimensions of the liquid lead drops as a function of time (see [5]).

Experiments with the lead targets were performed with a power density of the neodymium laser of $6.5 \cdot 10^5$ W/cm^2. The diameter of the spot illuminated on the target amounted to 0.9 cm. Under these experimental

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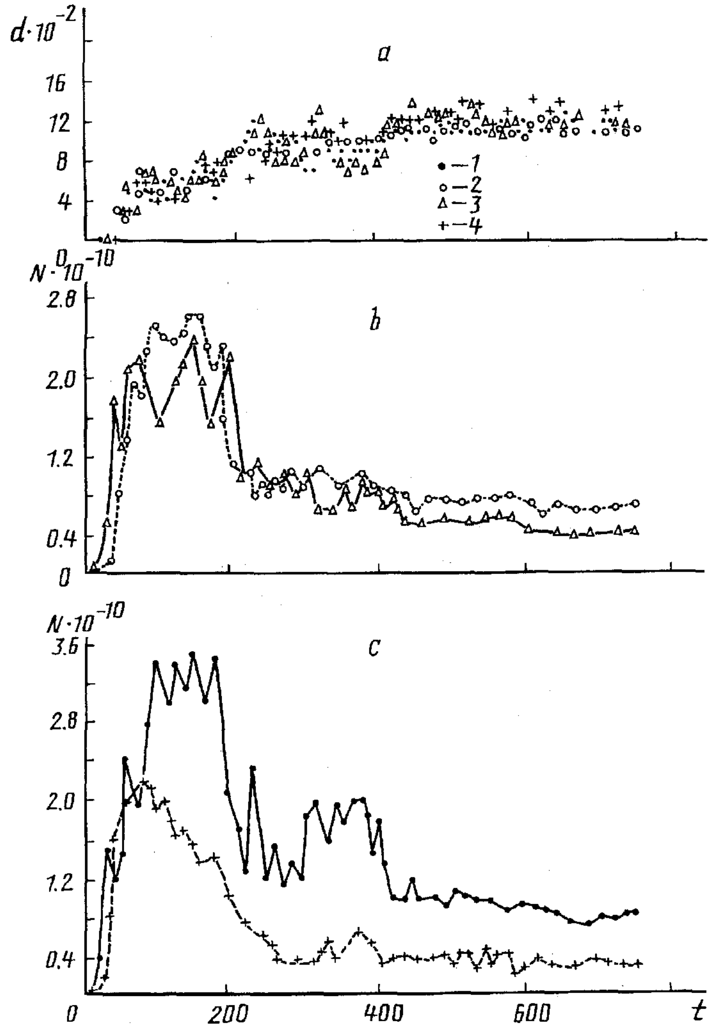

Fig. 1. Time variation of the particle dimensions (a) and concentration (b, c) under the action of a rectangular laser pulse with 100% random modulation (1) and of smooth one (2) on an air-melted lead target; of a rectangular laser pulse with 100% random modulation (3) and a smooth one (4) on a vacuum-melted lead target. d, μm; N, cm^{-3}; t, μsec

conditions we succeeded in dividing, in space and time, the liquid-drop phase particles that form because of vapor formation and by the hydrodynamic mechanism. Results of the experiments are given in Fig. 1.

Figure 1a shows that different conditions of the action, namely, the gas content in the target material and the space-time nonuniformity of the acting laser radiation, affect the dimensions of the target material particles only slightly. Their dimensions are determined by the thermophysical properties of lead. An increase in the particle dimensions with time is probably associated with an increase in the melt thickness due to heat conduction [12]. However, the particle concentration depends largely on the experimental conditions. The minimum number of particles form under the action of a smooth laser pulse on the vacuum-melted lead target. The maximum particle concentration is observed under the action of a laser pulse with 100% modulation on the target of air-melted lead (see Fig. 1c).

The concentrations of particles formed under the action of the smooth laser pulse on the air-melted lead and the modulated laser pulse on the vacuum-melted lead are fairly close although in the former case the curve lies somewhat higher (see Fig. 1b).

By analyzing Fig. 1b and c it can be inferred that the space-time nonuniformity and gases dissolved in the metal facilitate substantially the process of volume vapor formation, due to which a finely divided liquid phase appears. The influence of these two factors is comparable.

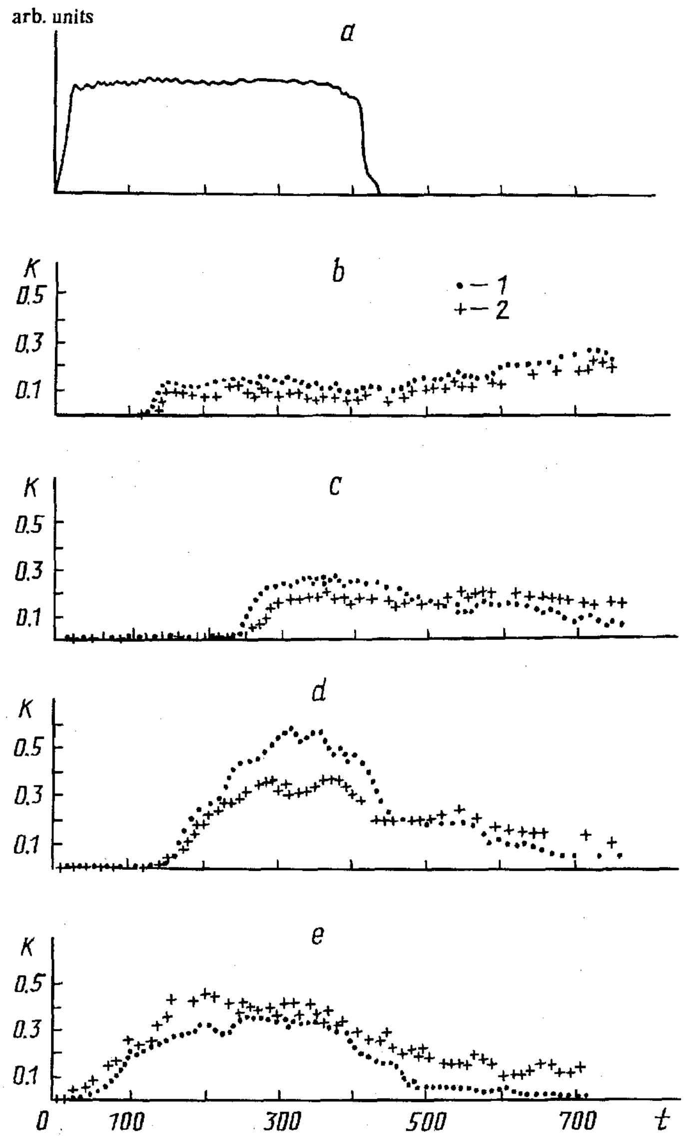

Fig. 2. Time shape of the acting laser pulse (a) and time variation of the absorption (1) and scattering (2) coefficients of the probing radiation for targets of polycrystalline silicon (b), single-crystal silicon (c, d), and single-crystal silicon with inclusions of an abrasive material (e); b, c, e) power density of the acting radiation $4.3 \cdot 10^6$ W/cm^2; d) $6.8 \cdot 10^6$ W/cm^2.

In [13] under the action of neodymium laser radiation in the free generation regime on metals with different contents of gases it is shown that the latter have a substantial effect on formation of the liquid-drop phase. In [14] it is shown that under the action of a quasistationary laser pulse on metal targets liquid-drop phase formation is affected both by gases dissolved in the metals and by space-time nonuniformity of the laser radiation. To be correct it is pertinent to note that under the conditions of these experiments the liquid-drop phase of the target material forms as a result of two processes at once: volume vapor formation and hydrodynamic vapor formation. The latter may turn out to be more substantial. In the results of the present work, however, the role of the hydrodynamic mechanism of formation of rather large drops is reduced to a minimum. In [8, 15] it is noted that volume vapor formation on different inclusions and artificial sites is also of importance in the destruction dynamics of metals. In [3, 11] experiments were performed concerning the action of neodymium laser pulse radiation on targets of molybdenum and copper produced by the powder metallurgy method. It is shown that inclusions of molybdenum grains in copper act as artificial sites and facilitate the process of volume vapor formation. However, perceptible results are obtained only upon adding 20% molybdenum to the copper. These inclusions are rather rare in real metals (except for exotic alloys and composite materials). Therefore, volume vapor formation in them will be facilitated mainly because of the gas content and the space-time nonuniformity of the laser radiation.

Under experimental conditions made such that the above-described factors that contribute to volume vapor formation are absent or reduced to a minimum, facilitation of the volume vapor formation may occur on heterogeneities associated with the polycrystalline structure of the metal (structural heterogeneities). Of interest are comparative experiments on the action of laser radiation on a polycrystal of a metal and a single-crystal. However, there were no metal single-crystals at the authors' disposal, and therefore experiments were performed with targets of high-purity polycrystalline and single-crystal silicon. As is well known [16], under the action of powerful laser radiation semiconductor materials are metallized in times of $10^{-10}-10^{-9}$ sec and act as a metal subsequently.

The action was produced with a neodymium laser pulse close in shape to a rectangular one. The space-time nonuniformity of this laser pulse did not exceed 3%. Figure 2a gives the time form of the acting laser radiation.

Experiments with different power densities of the acting radiation have shown that destruction of both polycrystalline and single-crystal silicon begins with a power density of $4 \cdot 10^5$ W/cm^2, the destruction products being transparent to the probing radiation, i.e., liquid drops do not form. The particles in polysilicon begin to appear in the erosion flame with a power density of the acting radiation of $2.7 \cdot 10^6$ W/cm^2, and in monosilicon with $4.2 \cdot 10^6$ W/cm^2. It is noted that in this case formation of a finely divided liquid-drop phase occurs more suddenly and intensely. This is quite evident from the time variation of the absorption and scattering coefficients of the probing radiation (Fig. 2b and c) that are obtained under the action of the same power density of neodymium laser radiation $4.3 \cdot 10^6$ W/cm^2. In this case formation of the liquid-drop phase occurs appreciably later on the monosilicon target. It can be assumed that the main factor leading to formation of the liquid-drop phase in polysilicon is volume vapor formation, which is facilitated by structural heterogeneities that lead to local superheating. There are no such structural heterogeneities in the monosilicon target; however, the liquid-drop phase also appears in this case, though with an appreciable time delay. It may appear due to instability of the evaporation front [17–19] or explosion of a metastable liquid [19].

The behavior of the absorption and scattering coefficients in probing the erosion flame of the monosilicon target suggests a more sudden and intense discharge of the liquid-drop phase, which makes the hypothesis of explosion of a metastable liquid more appealing in the present case. This is particularly evident when the power density of the acting laser radiation is increased (Fig. 2d).

To compare the influence of different conditions for the formation of the liquid-drop phase of the silicon target, we give results of experiments on the action of laser radiation on a target of monosilicon contaminated with relatively large particles of an abrasive material (Fig. 2e). In the present case it is evident that various impurities and inclusions have a more substantial effect on the process of volume vapor formation than structural heterogeneities.

Thus, the investigations performed enable us to infer that for real metals formation of an erosion flame with a finely divided liquid-drop phase of the target material by volume vapor formation is facilitated primarily on account of gases dissolved in the metal and space-time nonuniformity of the laser radiation. The effect of these two factors is comparable. The presence of various inclusions and artificial sites in the metal is next in importance. In the absence of these three factors it is structural heterogeneities that contribute to the process of volume vapor formation. And, finally, with all these factors being absent, formation of the liquid drop phase, hindered as it is, is also realized with increasing power density. This may occur both because of an unstable evaporation front and on account of explosion of a metastable liquid. To elucidate the latter, additional rather difficult complex experiments that include modern theoretical calculations must be performed.

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