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START OF CONDENSATION IN EROSIONAL JETS OF METALS SUBJECTED TO HIGHLY INTENSE SUBMICROSECOND LASER ACTION

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Using the technique of laser probing, the time dependences of the transparency factor, integral glow, and of the scattered component of probing radiation for erosional laser jets of metals exposed to intense submicrosecond laser pulses have been determined. Based on the results of laser probing, a conclusion on the condensation nature of the process of formation of a liquid-droplet phase of the target-material under the given conditions of laser action has been drawn.

Keywords: *laser erosion of metals, submicrosecond pulses of optical radiation, condensed phase of the target material.*

Introduction. Hystorically one of the first applications of laser radiation fluxes was the treatment of metals. For these purposes use was usually made of high-energy (10–1000 J) long (from 100 μs to a continuous operation) optical pulses that on focusing into characteristic spots of about 1 mm correspond to the range of moderate power density (10^5–10^8 W/cm^2). Due to this, a basic array of experimental information was accumulated precisely for this regime of laser action [1–4].

As early as 10 to 15 years ago the study of the processes proceeding in the interaction of shorter (<1 μs) laser pulses with metal targets was hindered considerably, because of the lack of fast analog-to-digital converters (ADC) and the insufficient computational power of personal computers. Due to these factors, there is no single theoretical-experimental model of the interaction of submicrosecond laser pulses of high power density (10^8–10^{10} W/cm^2) with metals.

At the present time, the appearance of mass-produced laser facilities that can generate laser pulses of length 10–100 ns in the frequency regime is responsible for the increasing practical interest to the treating of metals by pulses of high power density. The present work is devoted to the investigation of the processes proceeding in the first microseconds of the existence of erosional laser jets (ELJ) during erosion of metals exposed to submicrosecond pulses of high power density.

Experiment. For the study of the dynamics of the ELJ of metals with a high time resolution an experimental laser facility was employed the basic diagram of which is presented in Fig. 1. Functionally the facility can be divided into several blocks: a block generating acting pulses, a block generating probing pulses, and a block for recording the components of probing radiation and synchronization.

The block generating the acting radiation consists of a standard laser setup of GOS 1001 operating in the regime of Q-switching of the resonator quality with the aid of a rotating prism of total internal reflection. The characteristic temporal form of the acting radiation pulse is shown in Fig. 2a, its duration is 100 ns and its energy is 2–3 J, which on focusing into a spot of diameter 1 mm makes it possible to obtain a power density of 1–2 GW/cm^2.

The probing radiation generation block consists of a ruby laser functioning in the regime of quasistationary generation attainable with the aid of a confocal resonator and of a considerable excess of gain over losses. A fragment of the temporal form of the probing pulse is presented in Fig. 2b. The peak power density of probing radiation attains 10^4 W/cm^2. The order of this quantity is determined, on the one hand, by the undesirability of disturbance of the test medium by the probing pulse and, on the other hand, by the requirement of an intensity sufficient for recording the scattered component.

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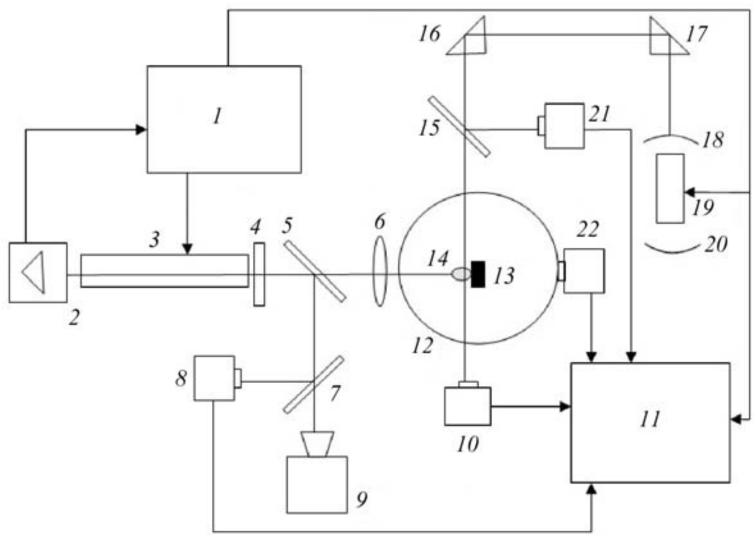

Fig. 1. Basic diagram of the experimental setup for studying the processes proceeding in erosional laser jets: 1) synchronization system; 2) rotating prism of total internal reflection with the possibility of generation of a synchronizing pulse; 3) neodymium laser; 4) semitransparent mirror (for 1064 nm); 5, 7, 15) branching, plane-parallel quartz plates; 6) mobile lens; 8, 10, 21, 22) photodetectors; 9) calorimeter; 11) computer with an ADC block; 12) integrating sphere; 13) target; 14) erosional laser jet; 16, 17) rotating prisms; 18–20) ruby laser with a confocal resonator.

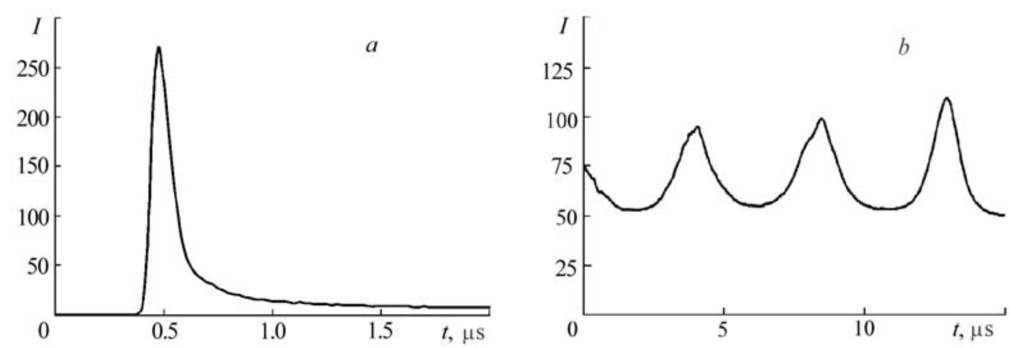

Fig. 2. Temporal form of laser pulses: a) acting; b) probing.

The block of recording the probing radiation components includes FhD-21 KP photodiodes combined with a PC by means of fast ADC40M/10-2 making it possible to attain the time resolution of up to 25 ns.

To ensure the coordinated operation of all the constituent parts of the setup, a multichannel generator of delayed G200P pulses producing synchronization pulses with a different delay in time for each of the blocks was applied.

With the aid of the setup described it is possible to carry out investigation with a high time resolution of the dynamics of the following characteristics:

a) the spectrum-integral glow of erosional laser jets (with account for the spectral sensitivity of a photodetector);

b) the transparency of the jet for probing radiation at a varying distance from the target surface;

c) the probing radiation component scattered by the jet (by applying an integrating sphere) at a variable distance from the target surafce.

As metal targets we selected lead, zinc, silver, copper, and nickel that differ considerably in optical and thermophysical characteristics, which allows one to speak of the laws governing the processes of laser erosion as a whole for metals [5].

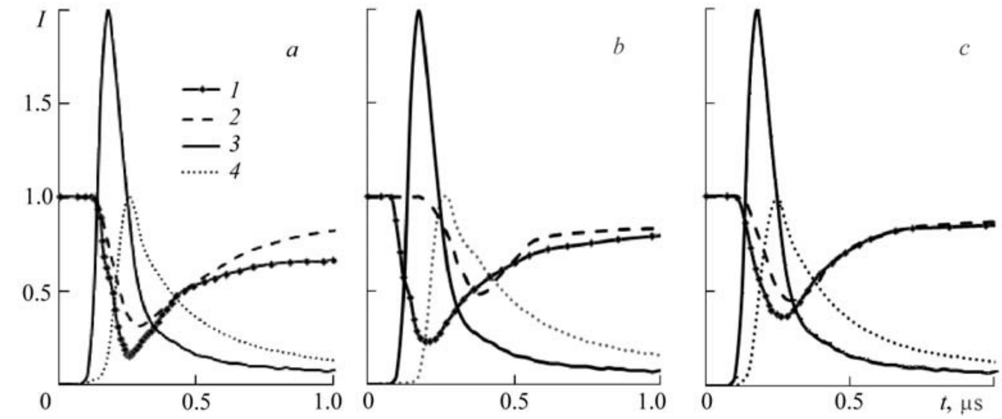

Fig. 3. Temporal forms: 1, 2) of the jet transparency for the probing radiation at a height of 1 and 2 mm, respectively; 3) of the acting pulse; 4) of the integral luminosity of the jet for zinc (a), lead (b), and silver (c). The power density of the acting pulse is 2 GW/cm^2.

TABLE 1. Estimation of the Initial Velocity of the Moving Forward Front of ELJ

Metal	Time interval between the minima of transmission at heights of 1 and 2 mm, ns	Estimated value of the initial velocity of the plasma formation, km/s
Silver	100	10
Zinc	50	20
Lead	150	7
Copper	125	8
Nickel	75	13

The character of the destruction of metal targets exposed to laser pulses of high power density (10^8–10^{10} W/cm^2) differ considerably from the case of moderate power density [1]. The differences reveal themselves already from the very start of laser action when a part of the energy of the acting pulse in the surface zone of the metal target is absorbed. At a sufficient steepness of the intensity front of the acting pulse the processes of plasma formation proceed much faster. In this case, it is precisely the hydrodynamic motion of plasma that determines the character of the interaction of radiation with targets [2]. In a number of research works [6, 7] it is shown that the formation of the erosional laser jets at the indicated parameters of laser action proceed under the conditions of the absence of the liquid phase (melt) in the zone of action: a solid body-vapor phase transition occurs in a microlayer determined by the shape of the evaporation front.

The results of the study of the temporal form of the integral luminosity of the ELJ on exposure to submicrosecond (100 ns) pulses with a power density of 10^8–10^9 W/cm^2 of different types of metal targets show that the luminescence of a plasma formation attains its maximum already at the decay of the acting pulse intensity being behind the maximum of acting radiation by 70–100 ns depending on the type of the metal (see Fig. 3).

In this case, radiation of the entire forward front of the acting pulse freely arrives at the target surface. It should be noted that the initially high reflection coefficient at the wavelength of the laser pulse (for metals 0.8–0.99) upon intense action decrease rapidly, and the integral dose of the absorbing radiation may attain 30–50% of the total amount of energy that reached the target surface [8, 9].

In investigation of the temporal form of transparency (reciprocal of extinction) of the ELJ at a height of 1 mm (Fig. 3) an analogous trend is seen: in 30–50 ns after the maximum of the acting pulse intensity the losses of the probing radiation attain their highest value. This means that in about 50 ns after the start of the action (the indicated time interval is commensurable with the duration of the front of the increase in the acting radiation intensity) plasma formation occurs as well as its motion in the direction perpendicular to the target surface.

In the process of its evolution the plasma (in the given case ELJ) begins to actively absorb radiation at the rear front of the acting pulse, and this leads to a rapid increase in the plasma parameters and in its opacity, as indi-

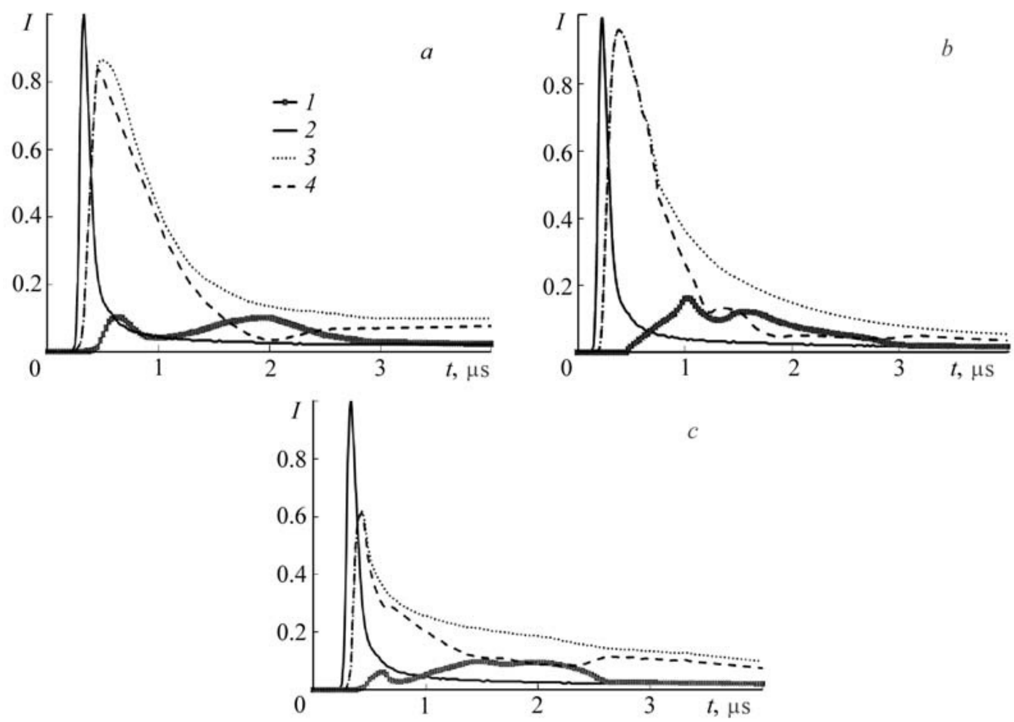

Fig. 4. Temporal forms: 1) of the probing radiation losses in the ELJ on scattering; 2) of the acting pulse; 3) of general losses of the probing radiation in the ELJ; 4) of the losses of probing radiation on absorption in the ELJ for zinc (a), plumbum (b), and silver (c).

cated by the increase in the integral luminosity of the jet and in the losses of probing radiation. The indicated trends exist at the expense of the effect of the reverse bremsstrahlung of optical radiation (both acting and probing ones) in a plasma on free charge carriers [10]. As a rule, the maximum of the ELJ luminescence falls within 120–150 ns after the start of the effect. In a comparable interval of time after the start of the effect (80–100 ns) the losses of the probing radiation attain their maximum at a height of 1 mm from the target surface.

From the difference of the instants of time (delay) in the attainment of the maximum of transmission of probing radiation at heights of 1 and 2 mm from the target surface it is possible to evaluate the initial velocity of the motion of a plasma formation for each type of the metal. This value is equal to 7–20 km/s depending on the type of the target (see Table 1).

As is seen from the form of integral luminescence of ELJ for different metals (see Fig. 3), the tendency of a decrease in this parameter is somewhat delayed as compared to the delay in the intensity of a laser pulse. Whereas in 500 ns after the start of the action the intensity of the laser radiation is at a level of about 10% of the maximum level, the integral liminescence attains such a value only after 2 μs after the start of action. This corresponds to a rather slow cooling of the ELJ at the expense of adiabatic spreading of plasma.

To determine the temporal structure of the plasma formation for the ELJ of metals, the time dependence of the scattering of probing radiation at different distances from the target surface (1 and 2 mm) was recorded in addition to the temporal form of extinction. This made it possible to divide the radiation losses due to absorption and scattering caused by different physical processes. It is seen from Fig. 4a that indeed in the first 350 ns after the start of action on a lead target all the losses of the probing radiation in the ELJ are determined by the absorption in a plasma (at the expense of the effect of the reverse bremsstrahlung absorption on charge carriers). Thereafter in the structure of extinction of the probing radiation a scattered component appears; it increases noticeably, forming a clear maximum somewhat 500 ns after the start of the action. After this, a nonmonotonic decrease in the value of this parameter is observed. Figure 4b and c demonstrates the similar dynamics of the considered parameters for other types of metal targets.

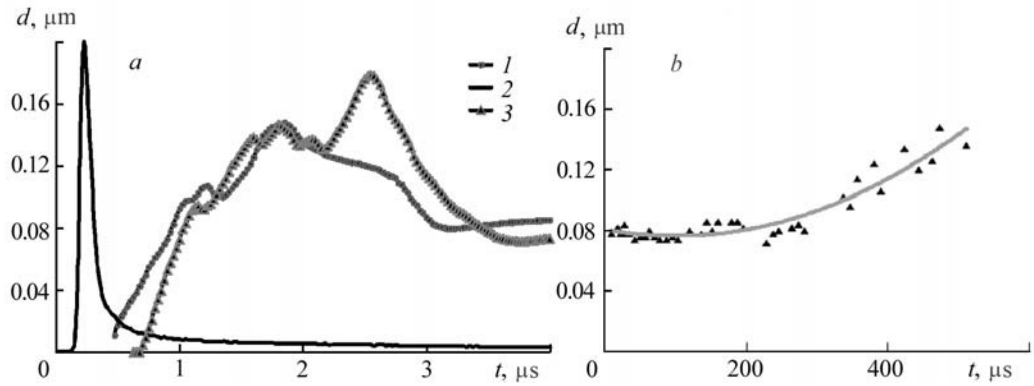

Fig. 5. Dynamics of the sizes of particles of the condensed phase of lead with a high (a) and low (b) time resolution: 1, 3) dynamics of the sizes of particles for heights of 1 and 2 mm, respectively; 2) the temporal form of the acting pulse.

Such a form of the temporal dependence of the scattered component can be explained by the start of the process of condensation in the ELJ. Indeed, two competing processes made a contribution to the scattering of the probing radiation: the increasing scattering on local inhomogeneities of the cooling plasma (on the density fluctuations) [11] and the adiabatic expansion of the plasma, which decreases scattering by decreasing the amount of the target material in the zone of probing. For lead the indicated local inhomogeneities manifest optical properties similar to the presence of metal quasiparticles with characteristic dimensions of 100–150 nm (Fig. 5a) in the zone of probing.

Approximately in 3 μs after the start of exposure the ELJ plasma "cools off" enough, and the expansion practically ceases. From this moment, a stable drop formation begins at the expense of condensation processes, as indicated by the appearance of stable absorption processes prevailing over scattering. The estimation of the diameter of particles in the interval 3 μs after the start of the effect (Fig. 5a), corresponds to about 80 nm, which is in good agreement with the result of laser probing of similar ELJ of lead in wider temporal intervals with a worse temporal resolution (Fig. 5b) described in [12]. The results of investigations of the dynamics of the scattered component and of the probing radiation extinction at a height of 2 mm from the target surface show that all the trends described are displaced in time by 200–300 ns (relative to a height of probing 1 mm from the target surface), which can also characterize the rate of the processes described.

Discussion of Results. Based on the investigated trends of the laser erosion of metals by submicrosecond (100 ns) highly intense radiation pulses the conclusion can be drawn that about 50 ns after the start of laser action (a time comparable with the duration of the front of increase in the acting pulse) an intensely luminescent plasma is formed in the surface area of the target. The laser jet propagates normally to the target surface, absorbing practically all the enegry of the rear part of the front of the acting laser pulse due to the reverse bremsstrahlung effect and, as a consequence, it is heated considerably. The characteristic velocity of propagation of the plasma formation is equal first to 7–20 km/s depending on the type of the metal target.

After the decay in the laser action intensity a rather slow cooling of the jet begins predominantly at the expense of the adiabatic scattering of the plasma, which can be judged by the certain delay in the decrease in the jet luminosity relative to the rear front of the acting pulse. In this case, in the structure of the extinction of probing radiation a scattered component appears indicating the formation, inside the flare, of local plasma homogeneities that at this moment determine the trasmission of the probing radiation by the jet.

Thereafter, 2–2.5 μs from the start of action, the processes of absorption of probing radiation begin to prevail again over scattering at a sufficiently low level of losses in the jet, which indicates the beginning of fine-disperse droplet formation at the expense of plasma cloud condensation. The results of the previous investigations [12] show that this process persists long enought (~300–400 μs) after the exposure and leads to the appearance of nanosized particles of the processed metal in the surface region of the target.

Conclusions. The results of the investigations carried out show that the application of highly intense submicrosecond laser pulses for treating metals is promising only for small durations (50–100 ns). Otherwise the main part of the acting pulse density does not reach the target surface and is spent to increase the parameters of the plasma formed. The procedure of the condensation processes appearing in the ELJ under the given conditions of the effect makes laser erosion attractive from the viewpoint of realizing highly productive processes of formation of nanosized metal particles.

NOTATION

d, effective size of particles, μm; I, relative intensity of radiation, dimensionless; t, time, μs.

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