

INFLUENCE OF AN EXTERNAL ELECTRIC FIELD ON PARTICLE GENERATION DURING LASER-PLASMA TREATING OF METALS

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Abstract. Evolution of plasma torch at the surface of some metals (Cu, Al, Sn, Pb) induced by varying external electric field of different polarity from 0 to 10^6 V/m⁻¹ in the course of laser processing with the mean radiation flux density $\sim 10^6$ W/cm⁻² is studied. A size of the target material droplets, carried out from the irradiated zone, becomes several times less, as the field strength amplitude grows, independently of the field polarity.

Keywords: fast holographic filming, laser radiation, strip projection method

1. Introduction

Technological applications of lasers generate new problems, which solution requires investigation of processes taking place under the action of light fluxes on the surface of solids. Such studies are of particular importance for choosing the most efficient regimes of laser processing of materials, including laser pattern cutting, perforation, welding of materials, modifying their surface properties, and laser film deposition, as well as for developing new control methods for laser technological processes. In addition, such studies are of separate scientific interest. It is urgent to study the surface relief of a solid in the course of exposing it to pulsed laser radiation under different external conditions, particularly, in the presence of external electric fields. The processes that occur in a steam-plasma cloud arising near the surface of irradiated material are also of great interest since they affect the material processing. The aim of the present paper is to study the influence of electric fields of different strength (from 0 to 10^6 V/m⁻¹) on the spatial and temporal evolution of the laser plasma arising under the action of millisecond laser pulses at the surface of different metals (copper, aluminum, tin, lead). The formation mechanism of the surface relief is also the subject of investigation.

2. Experimental equipment

The radiation of GOR-100M ruby laser ($\lambda = 0.694$ mm) operating in the free oscillation regime, pulse duration ~ 1.2 mc, passed through the focusing system and was directed through the hole in the first electrode onto a sample that served as the second electrode and was mounted in air at pressure of 10^5 Pa. The radiation spot diameter on the sample with sharp edges was varied in the course of the experiments from 1 to 2 mm. From the front face of the glass wedge a part (4 %) of laser radiation was directed into the IMO-2N energy meter, whose entrance window was located in the focal plane of the lens. The energy of the laser pulses varied from 5 to 60 J. FEK-14 coaxial photo-detector, which signal was coupled to the S8-13 oscilloscope, was used to record the temporal shape of the laser pulse. The voltage was applied to the electrodes from the source, built on the basis of the UN 9/27-13 voltage

multiplier of the TVS-110 unit. The source allowed the voltage variation within 25 kV and its stabilization in the course of the experiment.

To study the spatial and temporal evolution of the laser plasma torch in the course of laser radiation action on the sample, we used the method of high-speed holographic motion-picture recording [1]. The sample was placed in one of the arms of Mach–Zehnder interferometer, which was illuminated with the radiation of the ruby laser ($\lambda = 0.694 \mu\text{m}$) operating in the free oscillation regime. The pulse duration of the radiation amounted to 400 ns. The transverse mode selection in the probing laser was accomplished using the aperture, placed in the cavity, and the longitudinal mode selection was provided by the Fabry–Perot cavity standard used as the output mirror. The probing radiation after the collimator was a parallel light beam with the diameter up to 3 cm, which allowed observation of the steam-plasma cloud development. The interferometer was attached to the SFR-1M high-speed recording camera, in which the film plane was conjugate with the meridian section of the laser beam, acting on the sample, by means of the objective.

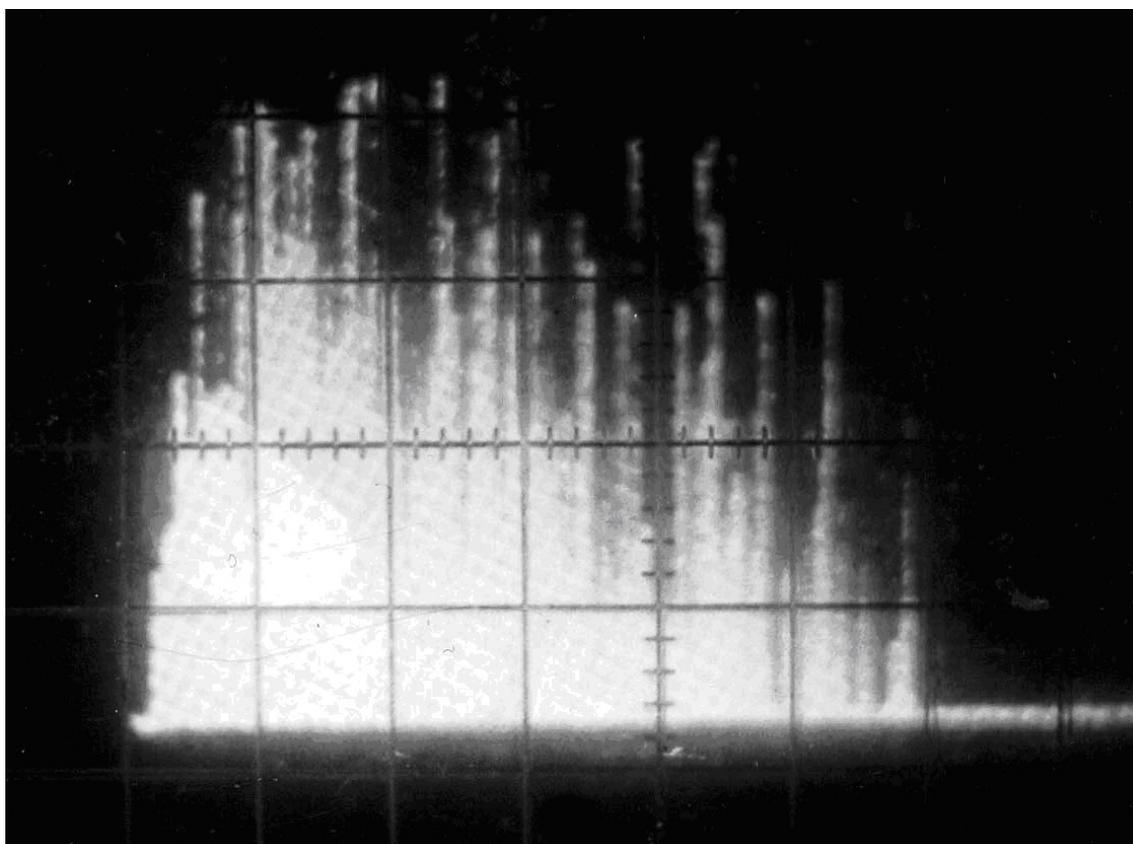


Fig. 1. Radiation pulse oscillogram produced by GOR-100M laser. The scanning rate is 200 m/s div^{-1}

The high-speed camera operated in the time magnifier regime. The described setup allowed recording time-resolved holograms of the laser plasma torch. Separate holographic frames provided temporal resolution no worse than 0.8 ns (the single frame exposure time) and the spatial resolution in the object field $\sim 50 \text{ mm}$. The diffraction efficiency of the holograms allowed one to reconstruct and record interference and shadow pictures of the studied process under the stationary conditions.

3. Results and discussion

The interferograms reconstructed from the holograms recorded at different instants in the course of high-speed holographic motion-picture shooting clearly illustrates both the initial stage of the laser plume development and the plasma flow around the electrode at different directions of the external electric field strength vector. The data on the distribution of concentration of free electrons in the plasma of an evaporated metal at different instants, obtained by processing the interferograms [2], show that although the energy distribution over the laser radiation focusing spot is not uniform, the lines of equal concentration are practically smooth, which is an evidence of relatively uniform ionization of the eroded substance steams. It is essential that, despite a substantial increase in the plasma formation over time, the mean electron concentration in the plume remains practically unchanged and even slightly grows, which may be associated both with a constant increase in the mass of emitted substance and with secondary ionization of plasma by the laser radiation. Note, that the presence of an external electric field weakly affects the concentration of electrons in the laser plasma plume.

When either positive or negative potential is applied to the sample, many small droplets appear on its surface after the laser action (Fig. 2). In particular, at the laser pulse energy 20 J, the focusing spot diameter 2 mm, and the electric field strength 10^6 V/cm, we observed ejection of droplets having the mean characteristic size less than 0.1 mm to the distance up to 2 cm from the crater centrum. The maximal characteristic size of drops was ~ 0.4 mm. In the absence of the external electric field the mean size of the droplets was ~ 0.4 mm. The droplets were seen at the distance up to ~ 1 cm from the crater centrum.

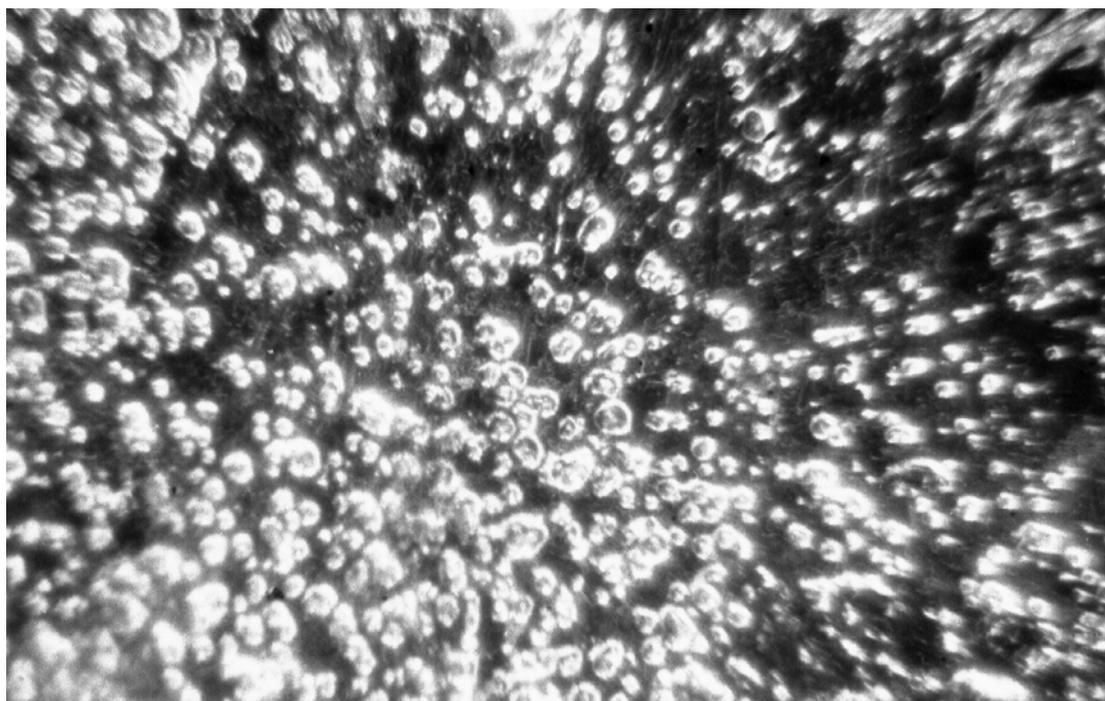


Fig. 2. Photograph of the microscopic surface relief of the crater outer zone

In accordance with the results presented above, the process dynamics on the surface of a sample, placed in an external electric field with the strength from 0 to 10^6 V/m and subject to the action of the pulsed laser radiation with the parameters mentioned above, is thought to be as follows. The primary plasma formation and the initial stage of the laser plume development, in principle, do not differ from those observed in the absence of the external electric field. The metal is melted and evaporated. As a result of local formation of steam and

plasma, the erosion plume begins to form with the fine-dispersed liquid-drop phase. Note, that the bulk evaporation is promoted by the gases, diluted in the metal, and by the spatiotemporal non-uniformity of the laser radiation. At a radiation flux density $10^6 - 10^7$ W/cm² the bulk evaporation is typical of all metals used in the experiments [3]. Obviously, the presence of the external electric field affects (increases or decreases depending on the direction of the field strength vector) the motion velocity of the plasma front and causes some distortion of the plasma cloud shape. It is essential that the mentioned differences (at the considered parameters of laser radiation) are observed only at the initial stage of the laser plume development, because after the steam-plasma cloud reaches the electrode an electric breakdown (short-circuit) occurs, and the external field in the interelectrode gap disappears.

Consider now the motion of the molten metal droplets in the steam-plasma cloud. In our opinion, the significant difference in the droplet sizes observed on the surface of the irradiated sample in the presence of the external electric field (independent of the direction of the field strength vector) and in the absence of the field, is a manifestation of the following mechanism of droplet formation. It is known that at the surface of a liquid (including a liquid metal) the formation of gravity-capillary waves [4] is possible under the action of various perturbations. Undoubtedly, the examples of such perturbations are the spatially non-uniform evaporation of the target material due to non-uniform heating caused by non-uniform energy distribution over the focusing spot, the non-uniform primary plasma formation [5] caused by roughness of the irradiated sample surface, and, in the first place, the slop of the molten metal initiated by each spike of laser radiation, acting on the exposed sample [6].

Using the method presented in [4], one can show that at insignificant thickness of the molten metal layer (confirmed by the view of the 'outer' (directed) zone of the crater, particularly, the absence of fillets of significant height at the crater edge) the dispersion equation for the gravity-capillary waves takes the form

$$\omega^2 = \frac{\alpha k^3}{\rho} + g k - \frac{k E_0 E'}{4\pi\rho\xi'} \Big|_{z=0}, \quad (1)$$

where α is the surface tension coefficient of the molten metal; ρ is the metal density; g is the free fall acceleration; k is the magnitude of the wave vector of the gravity-capillary wave; E_0 is the electric field strength at the surface $z=0$ of the molten metal (the z axis is perpendicular to the surface of the irradiated sample, directed towards the laser radiation source and parallel to the vector \vec{E}_0); $E' = -\partial\varphi'/\partial z$ is the perturbation of the electric field in the space surrounding the molten metal; ξ' is the small displacement of the liquid surface in the z axis direction in the gravity-capillary wave.

Because for the uniform field E_0 , the potential is $\varphi = -E_0 \cdot z$ (the potential at the metal surface is considered to be zero), the displacement of the mentioned surface by the small quantity ξ' leads to a small distortion of the potential:

$$\varphi' \Big|_{z=0} = E_0 \cdot \xi'. \quad (2)$$

In our case the maximal concentration of electrons in the plasma formation does not exceed $\sim 10^{18}$ cm⁻³, which corresponds to the change in the dielectric constant of the medium ε by approximately 10^{-5} . Therefore, near the metal surface $\varepsilon \cong 1$ and with the boundary condition (2) taken into account

$$\varphi' = E_0 \xi' e^{-kz}.$$

In this case, the dispersion equation for gravity-capillary waves takes the form

$$\omega^2 = \frac{\alpha k^3}{\rho} + g k - \frac{k^2 E_0^2}{4\pi\rho}.$$

Since the frequency of the gravity-capillary waves ω is determined by the temporal characteristics of the abovementioned perturbations and, therefore, does not depend on the electric field strength E_0 , the growth of the magnitude E_0 (independent of the direction of the vector \vec{E}_0) should cause the increase in the magnitude of the wave vector $k = \frac{2\pi}{\Lambda}$ and the decrease in the wavelength Λ of the gravity-capillary wave. If we assume that the droplets are 'torn away' by the plasma flow from the 'tops' of the gravity-capillary wave and, therefore, their characteristic size is proportional to Λ , then it becomes clear why in the presence of the external electric field (of any direction) the observed mean size of the droplets becomes essentially reduced.

The escaped droplets possess the charge of the same sign as the sample. That is why the droplets begin to move with acceleration towards the second electrode. However, since the maximal initial velocity of the outgoing droplets under the analogous conditions [7] is ~ 45 m/s, i.e., an order of magnitude smaller than the velocity of steam-plasma cloud spreading, the droplets do not reach the electrode before the breakdown in the interelectrode gap. In what follows (in the absence of the external electric field) the droplets move under the action of the same forces as in Ref. [7] and, therefore, in the way, described in Ref. [7]. In this case, having acquired at the stage of accelerated motion in the electric field the velocity, exceeding the initial one, the droplets may fly to a greater distance along the surface of the irradiated sample than in the absence of the electric field, which is observed in the experiment. Moreover, having moved to a greater distance from the sample surface and, therefore, being affected by the plasma for longer time before returning to the surface, the droplets can be split into finer parts than in the absence of the external field.

It should be noted that the droplets in the erosion plume may appear not only due to the molten pool surface instability, but also due to the condensation of the steams of the erosion products. Moreover, since the droplets produced in the course of condensation of steams may be charged, they, similar to those carried out from the molten pool, in the electric field may be removed from the crater to a greater distance than in the absence of the electric field. However, this mechanism of plasma formation is dominating under somewhat different conditions of laser radiation acting on the material, namely, at significantly greater mean radiation flux density ($10^8 - 10^9$ W/cm²) and smaller exposure duration (single pulses of laser radiation were used with the duration 100 – 200 ns and with less smooth temporary shape). In the case of such a regime of laser metal processing, one observes the screening of the irradiated sample by the plasma cloud, which is possible only at the concentration of the ablated material steam essentially exceeding 10^{18} cm⁻³. In this case, one observes intense formation of droplets with the dimension ~ 200 nm and smaller, and this process is most active at the late stages of laser radiation action on the material (at decreasing intensity of laser action) and even after its termination. At smaller radiation flux density, characteristic of the experiment considered in the present paper ($\sim 10^{18}$ cm⁻³), the condensation of droplets from the steam of ablation products is expected to be less intense. Therefore, the essential contribution of the condensation mechanism to the formation of drops (having the size 0.1 – 0.4 mm, see Figs. 1 and 2), especially at early stages of the process, i.e., before filling the entire interelectrode gap by the plasma cloud, seems to be hardly probable.

4. Conclusion

Under the action of laser radiation with the mean radiation flux density $\sim 10^6$ W/cm⁻² at the surface of some metals (Cu, Al, Sn, Pb) in the external electric field with different polarity and the strength up to 10^6 V/m, the characteristic size of the target substance droplets, carried out of the irradiated zone, decreases by several times with increasing external electric field strength. Probably, this is due to a change in the wavelength of the gravity-capillary wave,

excited on the molten metal surface. The observed effect offers the possibility to control the size of the metallic droplets in the course of laser deposition of thin films.

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