

Droplets generation conducting during laser-plasma treating of metals in electric field

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Evolution of plasma plume generation on the surface of metal irradiated by laser beam with the mean radiation flux density $\sim 10^6$ W/cm² in the external electric field with different polarity and field strength from 0 to 10^6 V/m was experimentally investigated. It is shown that the mean size of metal droplets carried out from the irradiated zone of target becomes materially (in several times) smaller when of the external electric field strength amplitude grow, independently to its polarity. 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. Electric breakdown leads to the spasmodic increase of electron density and temperature of plasma and to effective absorption of laser radiation by plasma torch (shielding of the target). In consequence of shielding droplets generation happens only during electric field existence. This explains decrease by several times of the characteristic size of the target substance droplets in spite of short duration of electric field existence.

Keywords: pulse laser radiation, electric field, plasma formation, electric breakdown, shielding of target.

Introduction

In the publication [1] was shown that under the action of laser radiation with the mean radiation flux density $\sim 10^6$ W/cm² at the surface of some metals (Cu, Al, Sn, Pb, In) in the external electric field with different polarity and the strength up to 10^6 V/m the mean size of the target substance droplets carried out of the irradiated zone decreases by several times with increasing external electric field strength in spite of short duration of electric field existence. The aim of the present work is to study the influence of electric fields of different strength (from 0 to 10^6 V/m) on the spatial and temporal evolution of the laser plasma arising under the action of millisecond laser pulses at the surface of metals and to explain the mentioned effect.

Experimental equipment and experimental results

Figure 1 schematically presents the used in the study experimental setup. To treat a metal sample we used operating in the free oscillation regime GOR-100M laser (wavelength $\lambda = 0.694$ μ m, pulse duration ~ 1.2 ms). Its radiation with the help of the focusing system (2) was directed through the hole in the first electrode onto the target (3) serving as the second electrode. Diameter of the hole was equal to 1 cm. The electric voltage applied to the electrodes from the source created on the basis of the UN 9/27-13 multiplier of the TVS-110 unit. The voltage varied from -25 kV to $+25$ kV in different experiments.

The optical stop (4) allowed us to form on the surface of irradiated target the radiation spot with sharp edges. Its diameter in the course of experiments was varied from 1 to 2 mm. A part (4 %) of laser radiation from the front face of the glass wedge (5) was directed into the IMO-2N energy meter (6). The entrance window of IMO-2N was located in the focal plane of the lens (7). Energy of the laser pulse varied from 10 to 60 J.

To record the temporal shape of the laser pulse we used coaxial photo-detector FEK-14 (8). The signal from FEK-14 was coupled to the S8-13 oscilloscope.

High-speed holographic cinematography method [2] was used to study the temporal and spatial evolution of the plasma plume near the sample treated by laser radiation.

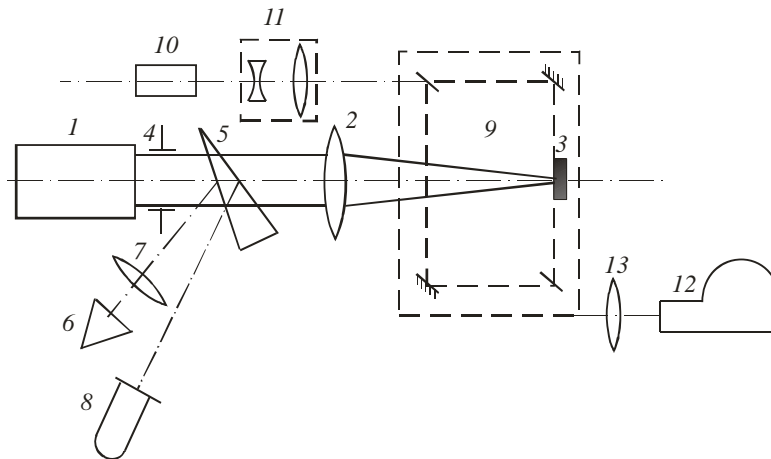


Fig 1. – Schematic diagram of the experimental plant.

The target (3) was placed in one of the arms of a Mach – Zehnder interferometer (9). Interferometer was illuminated with the radiation of operating in the free oscillation regime ruby laser (10). The duration of radiation pulse was 400 mc. The transverse modes of probing laser were selected with the placed in the cavity optical stop. The longitudinal mode selection was provided by the used as the output mirror Fabry–Perot standard.

With the help of the collimator (11) we obtained a parallel light beam of the probing radiation with the diameter up to 3 cm. Such size of the observation field allowed to observe the plasma cloud development.

The interferometer was conjugated by the high-speed recording camera SFR-1M (12), in which the plane of the film was attended with the meridian section of the treating the sample laser beam by means of the objective (13). SFR-1M operated in the time magnifier regime. This apparatus allowed us to record the time-resolved holograms of the focused image of the laser plasma plume. Separate holographic stills had temporal resolution $0.8 \mu\text{s}$ (the single still exposure time) and the spatial resolution in the object field $\sim 50 \mu\text{m}$.

After laser treating of the target (3) many small droplets appear on its surface of irradiated target independently either positive or negative potential was applied to the electrode (3). For instance, after treating a spot of led target with the diameter of 2 mm by laser pulse with energy 20 J and using electric field having strength 10^6 V/cm one observed ejection of droplets with the mean size less than $\sim 0.1 \text{ mm}$. The maximal size of the droplets was 0.4 mm. The droplets were observed up to the distance of 2 cm from the crater centre. It is essential that without external electric field the mean size of the droplets was $\sim 0.4 \text{ mm}$, and droplets were seen at the distance up to 1 cm from the crater centre.

It is material that despite a considerable temporal increase of the plasma formation size the mean concentration of electrons in the plume remains practically stable and slightly grows. This may be caused both by the constant increase of the of emitted metal mass and with secondary ionization of the neutral atoms in plasma plume by laser radiation.

Presence of an external electric field weakly affects the concentration of electrons in the laser plasma plume. Maximal transverse size of the plasma plume for negative voltage on the led sample was 2 cm. In the absence of the external electric field maximal transverse size of the plasma plume was 1.5 cm. After reaching the second electrode

respectively in 56, 64, and 72 μs plasma plume practically does not grow in the transverse dimension.

At the first stage of the laser plume development dynamics of plasma formation, in principle, do not differ from those observed in the absence of the external electric field. The metal of the irradiated target melts and evaporates. As a result of local erosion plasma formation, the plasma plume with a material dispersed liquid-drop phase begins to form. Note, that the bulk evaporation is promoted by the gases, diluted in the metal and by the spatiotemporal non-uniformity of the laser radiation. Bulk evaporation is typical for all metals used in our experiments if they were treated by laser radiation with flux density $10^6 - 10^7 \text{ W/cm}^2$. Obviously, the presence of the external electric field affects (increases or decreases depending on the direction of the field strength vector) the velocity of motion of the plasma front and causes some distortion of the plasma cloud shape.

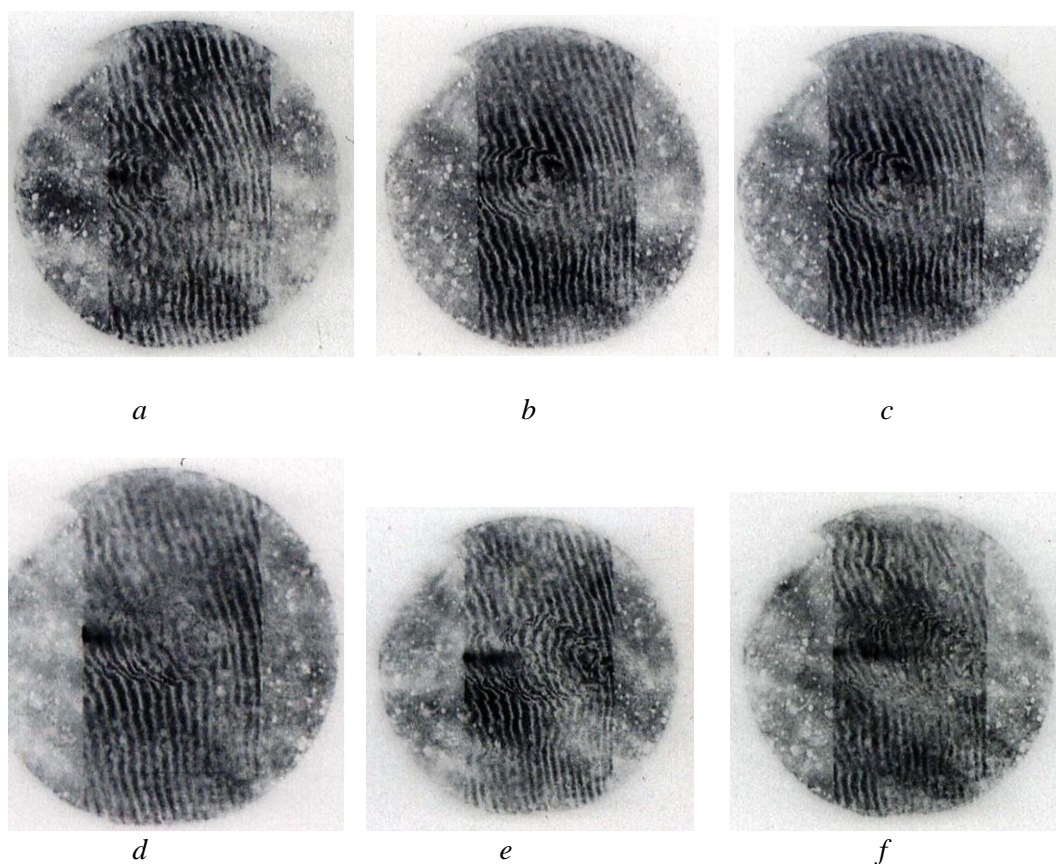


Fig. 2. – Interferograms of laser plasma plumes after electric breakdown at the positive target potential. Interferograms were obtained 90 (a), 150 (b), 270 (c), 360 (d), 450 (e), 510 (f) μs after start of laser treating of led sample.

It is material that even when the plasma front reaches the second electrode, its velocity not only does not decrease (which is typical for late stages of the laser plasma plume evolution [2]), but even increases. This effect was observed in the presence of the external electric field of any orientation. Already was mentioned that this phenomenon can be explained by the permanent and material increase of the mass of the metal carried out during laser treating of the irradiated sample as well by the secondary ionization of plasma by laser radiation. The maximal expansion velocity of the plasma plume front was 350 m/s

for the negative voltage at the target (3), 310 m/s without external electric field and 270 m/s for the positive voltage applied to the electrode (3).

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.

The interferograms presented at fig. 2 show that electric breakdown leads to the spasmodic increase of electron density of plasma. In the hole of the second electrode forms a plasma bubble there the interference fringes are not separated. This means that refraction in the plasma bubble differs not less than 10^{-3} from the initial (non-varied) air. In our case it can be only if electron density in this area is not less 10^{20} cm^{-3} , and this means full ionization of plasma in the plume. This leads to the effective absorption of laser radiation by plasma torch and to the shielding of the target.

The interferograms show also that the plasma bubble moves supersonically from the second electrode toward the laser beam direction. This means a light-detonation wave generation that is typical for such value of electron density. It is to be mentioned that not only electron density but plasma temperature in the light-detonation wave increases in several times versus to the temperature in the plasma cloud near the irradiated target.

In consequence of shielding droplets generation happens only during electric field existence. This explains decrease by several times of the characteristic size of the target substance droplets in spite of short duration of electric field existence.

Conclusion

The studies performed have shown that evolution of plasma plume generation on the surface of metal (Cu, Al, Sn, Pb, In) irradiated by laser beam with the mean radiation flux density $\sim 10^6 \text{ W/cm}^2$ in the external electric field with different polarity and field strength from 0 to 10^6 V/m was experimentally investigated.

It is shown that the mean size of metal droplets carried out from the irradiated zone of target becomes materially (in several times) smaller when of the external electric field strength amplitude grow, independently to its polarity. It is also shown that the change in the evolution of parameters plasma plume formed on the surface of metals (Cu, Al, Sn, Pb, In) treated by laser radiation at early stages is quantitative rather than qualitative.

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 inter-electrode gap disappears. Electric breakdown leads to the spasmodic increase of electron density and temperature of plasma and to effective absorption of laser radiation by plasma torch (shielding of the target). In consequence of shielding droplets generation happens only during electric field existence. This explains decrease by several times of the characteristic size of the target substance droplets in spite of short duration of electric field existence.

References

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