Dynamics of liquid metal surface under impact of XeCl laser pulses

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Processes on liquid metal surfaces under impact of XeCl laser pulses with energy of 50 mJ are studied. Relaxation times for melt surfaces of Gallium, as well as alloys of Wood's metals and Gallium–Indium are determined. Minimal relaxation time (about 4 ms) was found for Ga and Ga–In alloys. Qualitative description of the processes based on the assumption of the capillary wave formation on the fusion surface, was suggested. The choice of the liquid metal with minimal surface relaxation time was suggested based on the description.

Introduction

At present, laser-plasma engines (LPE) for correction of microsatellite orbits, based on matter evaporation under the influence of laser radiation, are being intensively developed.[1] Recently, the first LPE prototypes have already been constructed.[2,3] The targets in the form of rotating metal disks or moving tape with some evaporating matter were used as evaporants. The service life of such LPE is quite low because of rapid destruction of the target. A promising approach to the increase of the service life and reliability of LPE is the use of targets made of ready fusible liquid metals (LM). In this case, after laser pulse impact the liquid layer relaxes due to forces of surface tension. The time of LM relaxation is an important parameter, which determines the LPE maximal working frequency.

Note that dynamics of LM surface under the laser impact is poorly studied yet. Only in one work[4] the time of relaxation of liquid tin and bismuth after the influence of ArF laser is reported to be 0.3–1 sec.

In this paper we consider the processes on the surface of different liquid metals irradiated by the XeCl laser.

1. Instrumentation

LM drops were placed on the surface of a nickel plate in a chamber at a pressure of 0.01–500 Torr. In these experiments we used Gallium ($t_{melt} = 29.8$°C, $\rho = 5.904$ g/cm^3), Ga–In alloy ($t_{melt} = 16$°C, $\rho = 6.235$ g/cm^3) and Wood alloy ($t_{melt} = 65.5$°C, $\rho = 9.72$ g/cm^3). The temperature during the experiment was constant. The radiation of XeCl laser with pulse energy of 50 mJ was focused on the target surface with a lens and the rotating mirror. The ablation region in the lens focus consisted of two contacting squares with a size of $d = 0.4 \times 0.4$ mm. Radiation power density was ~1 GW/cm^2. The state of target surface was determined through rapid photographing with the use of high-rate SensisCam CCD-camera, installed above the target. The target surface was photographed every 100 μs with a 0.5–1 μs exposure.

The dynamics of laser plasma luminosity on the surface of LM was measured in different spectral ranges by the PEC-22 SPU vacuum diode placed at the side of the target. Electric signals were recorded by TDS-3034 digital oscilloscope.

2. Results and discussion

Typical oscillograms of laser pulse and plasma luminosity on the surface of liquid and heavy metals are presented in Fig. 1. An intensive peak of laser radiation reflected from metal surface was detected during several nanoseconds after the start of irradiation.

The reflected signal fell abruptly after the start of the erosive torch luminosity. The intensity of reflected signal decreased significantly during the irradiation of smelt surface. Besides, when irradiating LM, the delay time of the start of plasma luminosity decreased by 2–3 ns. This fact indicates the decrease of threshold of ablation and plasma formation on the LM surface.

The acceleration of optic breakdown development on the melt surface can be caused either by the decrease of laser pulse reflected energy or by the decreased energy consumption for metal surface heating up to the melting temperature and the heat penetration inside the target. The LM ablation threshold is mainly influenced by the decrease of heat loss,[5,6] because the radiation reflection from the metal surface is constant during the melting. However, metal vapor, appeared near the target surface, can strongly absorb the incident and reflected laser radiation.[7] When ablating LM, the vapor is generated faster, possibly leading to the decrease of reflection from the target surface.

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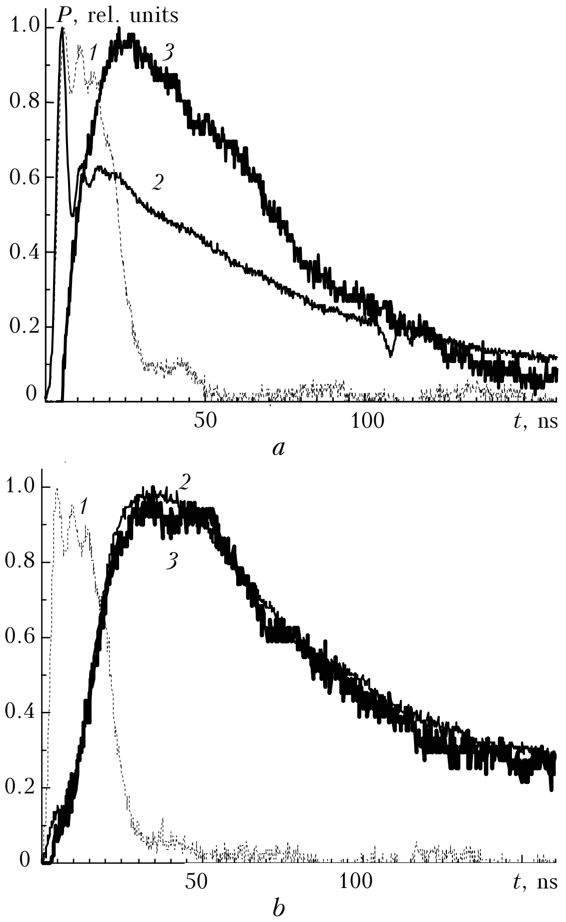

Fig. 1. The oscillograms of laser pulse (*1*) and plasma luminosity pulses on the surface of heavy (*a*) and liquid (*b*) Wood alloy at 200–600 (*2*) and 340–600 nm (*3*) wavelengths in the neon atmosphere at a pressure of 370 Torr.

Changes on the liquid gallium surface started in 2 or 3 μs after the irradiation beginning (like in Refs. 4 and 8), which was followed by the growth of crater of almost hemispherical form during 600 μs. Small ledges on the crater ridge can be seen, which have no time to turn into drops. In 600 μs the maximal crater size was about two millimeters in diameter. Then the liquid from the crater edges starts to drain inside, making a convexity, which gradually grew, filling the whole crater in 2–2.5 ms. After that, decaying waves of small amplitude run several times on the drop surface. The surface was completely relaxed in ~ 4 ms (Fig. 2).

In case of Ga–In alloy, the time of oscillation damping on the drop surface increased approximately by 0.5 ms. With the increase of melt temperature the relaxation time also increased. In case of Wood alloy, the process of liquid surface relaxation took ~ 10 ms.

The processes, which take place after the laser pulse impact on the LM surface can be qualitatively described in assumption of generation of surface capillary waves. The speed of a capillary wave propagation V_k is[9]

$$V_k = \sqrt{\frac{2\pi\sigma}{\rho\lambda}\tanh\left(\frac{2\pi H}{\lambda}\right)},$$

where λ is a typical size of disturbance on the LM surface, formed under the impact of the laser pulse; σ is the surface tension; ρ is the fluid density; $\tanh(2\pi H/\lambda)$ is the hyperbolic tangent; H is the fluid depth.

It is seen that the time of surface relaxation is determined by the surface tension and the density of the liquid metal used. In case of Ga ($\sigma = 0.705$ N/m), the typical size of the crater is $\lambda \approx 2.5$ mm (Fig. 2) and the speed of capillary wave propagation V is 0.5 m/sec. Consequently, the surface relaxation time is about 5 ms, which well agrees with the experimental data. The density of Wood alloy is by 1.5 times higher than of pure gallium, and its surface tension is two times lower.[10]

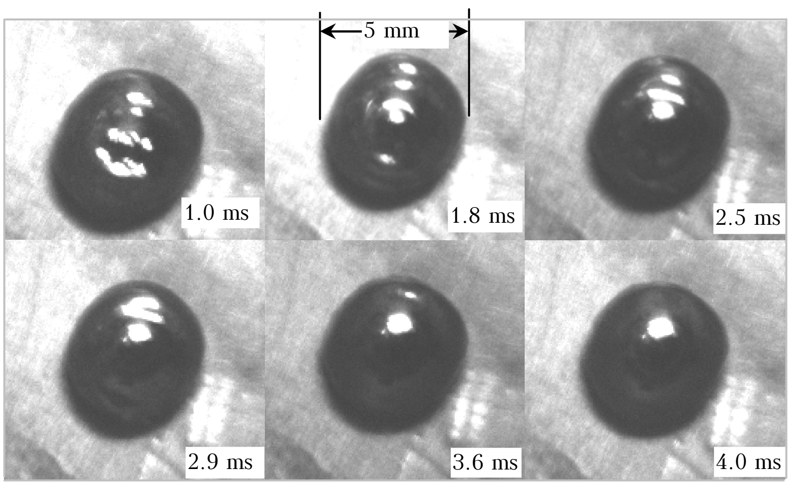

Fig. 2. Dynamics of relaxation of the liquid gallium drop surface. Exposure time of each frame is 1 μs, the interframe times are: 1; 1.8; 2.5; 2.9; 3.6; and 4 ms after the irradiation. The beam incidence is normal to the picture. The ablation region is in the drop center.

Therefore, the capillary wave propagation speed on the surface of Wood alloy decreases by 1.74 orders of magnitude and the surface relaxation time increases. In the experiment, the time of Wood alloy surface relaxation was about two times longer than of gallium.

The typical size of the crater strongly depends on the melt metal viscosity.[8] Therefore, to minimize the crater size, liquid metal with high viscosity should be used. As the viscosity decreases with the temperature increase, the temperature of liquid metal should be maintained close to the melting point.

Based on the above discussion, the requirements to the choice of LM for the use in LPE can be formulated. LM should have a high viscosity and maximal value of the σ/ρ parameter. These criteria show lithium to be one of the best materials.

Conclusion

The processes occurring on LM surface under the impact of XeCl laser pulse with energy of 50 mJ have been investigated. Relaxation rates of a series of liquid metals have been determined. Minimal surface relaxation time (about 4 ms) was found for liquid gallium and its alloy with indium.

A qualitative description of the processes on the surface of LM, assuming formation of capillary waves on the alloy surface, is proposed. The description allows the conclusion that LM with minimal surface relaxation time is to be chosen.

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