Evolution of steam and plasma plume generation on pulse laser action on the surface of metal in water

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Abstract. Evolution of steam and gas plume generation on the surface of the irradiated metal was investigated experimentally. It is shown that on using GOR-100M operating in free oscillating regime the form of a crater developed on being in water the irradiated target surface differs in essence from the topography of the crater developed on processing by laser pulse with the same parameters of the analogical target surrounded by air on normal pressure (10⁵ Pa). It is pointed that the substantial difference of the forms of crater surfaces developed as a result of processing of the identical targets by laser pulses with the identical parameters of the identical targets being in water or air determines by principally different character of plasma and steam and gas mixture flow in the mentioned cases.

1. Introduction
The main opinions about the mechanisms of the destruction of solids surrounded with gas during their treatment by laser beams with the radiation flux density varied 10⁵ to 10⁶ W·sm⁻² are constructed now. The aim of this work is the investigation of processes running near a metal target mounted in water during its treatment by pulse laser radiation with the radiation flux density ~ 10⁶ W·sm⁻².

2. Experimental equipment and experimental results
The scheme of the experimental setup used in the study is presented in figure 1. The radiation of the GOR-100M ruby laser (l) (λ = 0.694 μm) operating in the free oscillation regime (pulse duration ~ 1.2 ms) passed through the focusing system (2) and was directed onto the sample (3) that was mounted in water. 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 (5) a part (4%) of laser radiation was directed into the IMO-2N energy meter (6), whose entrance window was located in the focal plane of the lens (7). The energy of the laser pulses varied from 5 to 60 J. The FEK-14 coaxial photodetector (8), the signal from which was coupled to the S8-13 oscilloscope, was used to record the temporal shape of the laser pulse. 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 (3) was placed in one of the arms of a Mach-Zehnder interferometer (9), which was illuminated with the radiation of the ruby laser (10) (λ = 0.694 μm) operating in the free oscillation regime. The pulse duration of the radiation amounted to 400 ms. 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 (11) 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 (12), in which the plane of the film was conjugate with the meridian section of the laser beam, acting on the sample, by means of the objective (13). The high-speed camera operated in the time magnifier regime. The described setup allowed recording of time-resolved holograms of the focused image of the laser plasma torch. Separate holographic frames provided temporal resolution no worse than 0.8 μs (the single frame exposure time) and the spatial resolution in the object field ~ 50 μm. The diffraction efficiency of the holograms allowed one to reconstruct and record interference and shadow pictures of the studied process under the stationary conditions.

The experimental results have shown that topography of crater obtained on laser treating of lead sample in water (figure 2) differs considerable from the form of crater obtained on laser treating of the same sample in air under normal conditions (pressure ~ 10^5 Pa, figure 3).

![Figure 1. Schematic diagram of the experimental setup.](image)

**Figure 1.** Schematic diagram of the experimental setup.

To study the surface shape of the crater that appears on the plate, we used the fringe projection method [2], which in the present case appeared to be more efficient than holographic methods of surface relief imaging and the stereophotogrammetric method, since, already at the stage of fringe projecting, it allowed obtaining a picture with controllable sensitivity of measurements and sufficiently good visibility of (relative fringe displacement) was set by changing the period of the projected fringes, and the good visibility was provided by changing the angle of illumination of the
studied surface till removing the light flares from the crater surface. The present method is thoroughly described and successfully used in [3]. The crater surface obtained in water after treating of lead sample by laser pulses is foamed, macroscopic alveolus is practically absent (figure 2). Crater obtained in air after treating of lead sample by laser pulse has an alveolus with a plane surface (figure 3). The crater topography is determined by distribution of light energy density over the transverse cross-section of the laser beam [4].

Figure 3. Photographs of craters obtained in air after treating of lead sample by laser pulse with energy 40 J.

Figure 4. Shadow pictures of steam and plasma bubble obtained 10 μs (a), 50 μs (b), 500 μs (c), 1200 μs (d), 2000 μs (e), 3000 (f) μs after start of laser treating of lead sample.

The shadow pictures obtained using the described method in different time moments are represented in figure 4. Near the surface of irradiated sample appears a steam and gas bubble. At the
first stage of process its form is spherical. A bubble rapidly grows (especially during the early stages of process). Approximately in 500 $\mu$s after beginning of laser treating of the lead sample form of the bubble begin to change (figures 4cd). After the cessation of laser irradiation of the sample ($\sim$ 1.2 ms) dimension of the bubble stabilize and only in $\sim$ 1.5 ms starts its slow decay. It is important that the form of bubble at this stage of the process changes accidentally and it don’t repeat oneself from one experiment to the other.

Figure 5 represents defined from the shadow pictures temporal dependences of the bubble radius and velocity of its growth.

It is to be mentioned that the metal drops illuminated by laser radiation were seen in the bubble and out of it at all stages of laser treating of metal sample. Both spectral analysis an X-ray analysis provided using devise ElvaX showed that a small amount of lead appear in the water after laser treating of a lead sample because of nanoparticle gel formation.

3. Discussion

During the treating of metal sample mounted in air under normal condition (pressure $\sim 10^5$ Pa) by laser radiation with the parameters corresponding to our experiment [3] dimension of generated plasma plume reached several centimeters. In the water shining zone of plasma plume has dimension $\sim$ 1 mm; temperature on the plume board reaches $\sim$ 7000 K [5].

The difference is explained by intensive heating and evaporation of water that leads to steam and gas bubble formation. There are two components inside the bubble: products of the irradiated sample erosion (lead steam) and water steam. The motion equations of these components are

$$\rho_1 \frac{\partial \vec{V}}{\partial t} + \rho_1 \left( \vec{V} \cdot \nabla \right) \vec{V} = -\nabla p$$

$$\rho_2 \frac{\partial \vec{U}}{\partial t} + \rho_2 \left( \vec{U} \cdot \nabla \right) \vec{U} = -\nabla p$$

(Eiler equations for every component),
\[
\frac{\partial \rho_1}{\partial t} + \text{div} \left( \rho_1 \vec{V} \right) = A(t) \delta(r-r_0), \quad \frac{\partial \rho_2}{\partial t} + \text{div} \left( \rho_2 \vec{U} \right) = B(t) \delta(r-r_0)
\]

(continuity equations for every component),

\[
p = p_1 + p_2, \quad p_1 = \rho_1 \frac{R_1 T}{\mu_1}, \quad p_2 = \rho_2 \frac{R_2 T}{\mu_2}
\]

(state equations for every component),

\[
\left( \rho_1 c_{p_1} + \rho_2 c_{p_2} \right) \frac{\partial T}{\partial t} + \left( \rho_1 c_{p_1} \vec{V} + \rho_2 c_{p_2} \vec{U} \right) \cdot \nabla T = \text{div} \left( (\alpha_1 + \alpha_2) \nabla T \right)
\]

(heat and mass transfer equation).

Here \( \rho_1 \) – ablation products gas density, \( \rho_2 \) – water steam density, \( V \) – ablation products gas velocity, \( U \) – water steam velocity, \( A(t) \) – power density of the ablation products source (its temporal form repeats a temporal form of the laser pulse, figure 6), \( r = r_0 \) is the equation of the plasma plume board, \( B(t) \) – power density of the water steam source, \( r = r_0 \) is the equation of the bubble board, \( p_1 \) – ablation products partial pressure, \( p_2 \) – water steam partial pressure, \( T \) – temperature of the system, \( \mu_1 \) – ablation products molar mass, \( \mu_2 \) – water steam molar mass, \( R_0 \) – universal gas constant, \( c_{p_1} \) – ablation products specific heat capacity under constant pressure, \( c_{p_2} \) – water steam specific heat capacity under constant pressure, \( \alpha_1 \) – ablation products heat conductivity, \( \alpha_2 \) – water steam heat conductivity, \( h \) – specific heat of water evaporation, \( D \) – coefficient, \( p_b \) – atmospheric pressure, \( M \) – mass of the water in the cuvette, \( S_b \) – area of the bubble surface, \( a \) – bubble surface acceleration, \( B(t) = D \left( (\alpha_1 + \alpha_2) \nabla T / h \right) \big|_{r=r_0} \).

The solution of this equation system with the boundary conditions

\[
T \big|_{r = r_0} = 7000 \, K, \quad T \big|_{r = r_b} = 373 \, K, \quad V_r \big|_{z = 0} = U_a, \quad z = 0 = 0, \quad (p - p_a) \big|_{r = r_b} = a \cdot M / S_b
\]

gives the following results.

A small plasma plume emits a stream of hot ablation products in the opposite direction with respect to the laser beam. At the first stage \((t \leq 10 \, \mu s)\) because of the high density and temperature \((T \big|_{r = r_0} = 7000 \, K)\) of erosion products plasma motion is similar to observed in air. Here \( r_0 \) is plasma plume near treated surface radius. The motion of erosion products is supersonic and practically one-dimensional (radial). Erosion products cool evaporating water. Velocity of bubble board motion is also supersonic. An intensive flow of the lead drops from the zone of erosion is typical for this stage.

At the second stage \((10 \, \mu s \leq t \leq 50 \, \mu s)\) the motion of erosion products is also supersonic, but at this stage water steam mass is considerably greater then mass of erosion products in the bubble. Velocity of bubble board \( U_b \) is under-sonic, velocity of water steam motion \( U \) is also under-sonic and considerably less \( U_b \), but \( |U| \) increases. The motion of two-component (lead and water steam) system is radial. A part of evaporated products of erosion leave the bubble and form the water and lead nanoparticle gel.

At the third stage \((50 \, \mu s \leq t \leq 500 \, \mu s)\) velocities of all components of the bubble become under-sonic. The system of components of the bubble motion equations can be transformed to linear and solved analytic.

Figure 6 represents the temporal dependences of ablation products and water steam velocities at the distance \( r = \Delta r / 2 \) from the bubble surface. It is considerable that at the end of this stage of process a stream of water steam becomes supersonic.

At the forth stage \((t \geq 500 \, \mu s)\) water steam motion becomes not one-dimensional (radial). Reaching a bubble board the water steam stream moves transversal to bubble board to the treated sample, reaches it, moves along a sample to its centrum, reaches a plume, heats and moves opposite a laser beam together with erosion products. So a stream of water steam moving along a sample to its centrum, don’t avoid a melted metal flow out of the crater and froths it. In the zone contact of “direct”
and “reverse” streams appear vortexes. These vortexes fill among all bubble. This is the cause of incidental decay of a steam and gas bubble.

![Figure 6. Temporal dependences of ablation products (*) and water steam (○) velocities at the distance $r = \Delta r/2$ from the bubble surface.](image)

4. Conclusion

The investigations showed that the substantial difference of the forms of crater surfaces developed as a result of processing of the identical targets by laser pulses with the identical parameters of the identical targets being in water or air determines by principally different character of plasma and steam and gas mixture flow in the mentioned cases.

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