Characteristic of plasma flare stimulated by steel ablation with nanosecond laser

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Abstract. In this paper the behaviour of steel under the influence of the first harmonic YAG: Nd laser is investigated. The energy density in the spot varied from 0.1 to 50 J/cm². The amplitude of the glow of the plasma flare; a pressure pulse propagation into the sample; initial velocity of expansion of the plasma were measured. Experimental dependences of the plasma emission amplitude, the rate of its expansion into vacuum, and the pressure under plasma limitation and expansion conditions on the energy density of the laser pulse are obtained. The values of all these parameters increase with the level of laser action. Characteristic growths slow at high levels (>10 J/cm²) of laser exposure. Attenuation of the energy supplied to the sample surface with ns laser pulses is negligible. The pressure of expanding plasma reaches values sufficient to provide shear deformations.

1. Introduction
In laser engraving of metals in the nanosecond mode of exposure energy density reach tens of J/cm², power density – units and tens of GW/cm² [1-3]. The resulting vapor-plasma plume can propagate with a large (supersonic) initial velocity in the environment. The plume consist of contains free electrons, ions, neutral atoms, and fragments [4]. There the formation of shock [5] and laser-supported detonation waves, absorption and scattering of laser radiation by plasma can occur. Shock compression wave [6] can be formed in the near-surface layer of the material. Thus, the flare arising during the laser action can influence the level and dynamics of the energy input to the sample and, consequently, the temperature and pressure profile in the near-surface layer.

In this paper, the behavior of steel (plates 0.5 to 10 mm thick) was experimentally studied with impact of the first harmonic YAG: Nd laser LQ-939 by Solar LS (1064 nm; 12 ns). The laser beam was formed on the surface of the sample 8 in a projection method into a spot with a diameter of 0.1 to 1 mm (see figure 1). The energy density in the spot varied from 0.1 to 50 J/cm². An amplitude of the glow of the plasma flare, a pressure pulse propagating into the interior of the sample, initial velocity of expansion of the plasma were measured. The experiments were carried out in air and in a vacuum (10 Pa) [7]. The sample was put into 2 conditions. In first case the surface of the sample was opened. The second case the surface of the sample was covered with 10 mm thick glass plate 7 to block the expanding plasma. The plasma glow pulse was recorded with a photomultipliers 12 (photo module H-5773-04 from Hamamatsu), the pressure pulse was detected with a piezoelectric transducer 9 with a high (about 10 ns) time resolution [6], the plasma expansion velocity was measured in a shadowed manner by means of a double slit 8 with a view angle of 10⁻³ rad. The time position and shape of the laser pulse were recorded by a photodiode 12 (photoelectric colorimeter FEK-29KPU). Timing of the
signals of the photodetectors was carried out by excitation of the glow pulse in standard phosphors, the acoustic sensor signal – by evaporation of a thin absorbing film in acoustic contact with the input window of the sensor.

Figure 1. Optical scheme of the experiment. 1 – laser, 2 – forming diaphragm, 3 – laser beamsplitter, 4 – dielectric rotary mirror, 5 – lens, 6 – rotary prism, 7 – glass plate, 8 – sample, 9 – acoustic sensor, 10 – calorimeter, 11 – photodiode, 12 – photomultiplier, 13 – vacuum chamber, 8’ – double slit.

2. Main part
In the first part of the work, the emission of the plasma and the acoustic response of the target were studied at different levels of laser action on its surface. Typical oscillograms of pulses for small and large energy densities $H$ are shown in figure 2. The dependences of the glow intensity of the plasma flare and the amplitude of the pressure pulse on $H$ are shown in figure 3 a,b. When analyzing the results, we first of all pay attention to the fact that as the energy density increases from 1 to 10 J/cm\(^2\) (an order of magnitude) the intensity of the plasma emission increases by almost four orders of magnitude, which confirms the thermal nature of the glow (figure 3a). A further energy density increase leads to a certain decrease in the rate of increase of the glow intensity. This behavior is typical for an open and covered surface, but the glow intensity an exposed surface is almost an order of magnitude higher. Such a large difference can not be attributed to Fresnel losses when the surface is covered with a glass plate, since these losses were taken into account in calculating the values of $H$. Perhaps this difference is due to the additional intense glow of air on the front of the forming shock wave when the expanding plasma collides with it in the case of an exposed surface.

Figure 2. Typical oscillogram. 1 – laser pulse, 2 – glow intensity of plasma flare, 3 – pressure pulse amplitude of plasma flare.
The slowing of the rate of increase in the flow intensity from the exposed surface of the target at \( H > 10 \) J/cm\(^2\) is most likely not related to the beam locking by the expanding plasma flare, since the same behavior is observed in the case of a closed target.

The most probable cause of this phenomenon may be the cut-off effect of the UV region of the radiation spectrum, the relative fraction of which increases with increasing \( H \). Thus, the analysis of figure 3a indicates that the plasma flare does not have a significant effect on the screening of the laser beam.

Therefore, the behavior of the pressure pulse in the region of high values of the energy densities of the laser pulse is of interest (see figure 3b). It can be seen that the pressure curves have a rather complicated form. This is especially noticeable in open surface, where heating at high values of \( H \) is complicated by plasmodynamic processes. Due to these processes, the pressure in the area of action is much less than the pressure in the case of a closed target. In the region of small values of \( H \) (\( H < 10 \) J/cm\(^2\)) in covered samples, the growth of the amplitude is practically linearly related to the increase of \( H \). This indicates a linear increase in the temperature \( T \) of the near-surface layer, which can be estimated in the first approximation by the relation

\[
T = \frac{H}{h c_p}
\]  

where \( h \) is the thickness of the heated layer; \( c_p \) is the specific heat.

**Figure 3.** Dependences of the glow intensity of the plasma flare (a) and the amplitude of the pressure pulse (b) on the power density. 1 – exposed surface, 2 – covered surface.

In the region of large values of \( H \) (\( H > 10 \) J/cm\(^2\)), the growth of the pressure amplitude slows down. It can be assumed that this is due either to the screening of the laser beam (as discussed above) or to the nonlinear dissipation of the energy of the shock wave in the material of the entrance window of the acoustic sensor. Based on the analysis of the glow of the plasma, the former is unlikely. To justify the second, it is important to make an estimate of the pressure pulses propagating deep into the sample, and to estimate the possibility of dissipation of the energy (damping) of the compression pulses. In the case of a covered target, the pressure \( P \) can be estimated as

\[
P = \Gamma \frac{H}{h}
\]

where \( \Gamma \) is the Grüneisen constant.

The value of \( h \) can be estimated approximately by one of two formulas:
The value of $h$ is unknown and can be estimated earlier in [8] from measurements of the velocities of the front of the plasma clot of the gap was reached, which was established at various distances from the irradiated surface of the sample. The value of $h$ and the plasma concentration were estimated from the expansion velocity and the duration of the glow pulse. Typical oscillograms of the glow of the plasma at the moment of reaching the slit are given in atmospheric conditions and vacuum, respectively. It can be seen that a precise determination of the escape velocity in air is difficult because of the powerful glow (figure 4a) at the front of the shock and light-detonation waves. At the same time, in the vacuum (figure 4b), the arrival of the front is determined quite accurately. The front speed was $V=20$, 40 and 55 km/s at $H=10$, 25, 50 J/cm$^2$, respectively. The thickness of the plasma bunch was 200, 400, and 550 μm, respectively, with a diameter of the laser beam at the surface $d_s=110$ μm. In this case, the plasma can be considered homogeneous, and the radial expansion can be neglected. The plasma concentration $n$ is about $4.6 \cdot 10^{20}$, $5.75 \cdot 10^{20}$, $7.8 \cdot 10^{20}$ cm$^{-3}$, respectively. The plasma temperature at the given $H$ will be 100 eV (1.1$ \cdot 10^6$ K), 150 eV (1.65$ \cdot 10^6$ K) and 200 eV (2.2$ \cdot 10^6$ K), respectively.

The plasma pressure on the surface of the sample into vacuum will be [8]

$$P = 0.65 \cdot n \cdot k \cdot T$$

where $k=1.38\cdot10^{-23}$ J/K.

Substituting the obtained values of $n$ and $T$, we obtain for the chosen values of $H$:

$H=10$ J/cm$^2$, $P=4.5\cdot10^4$ atm $\approx 5\cdot10^9$ Pa, $H=25$ J/cm$^2$, $P=8.4\cdot10^4$ atm $\approx 8.5\cdot10^9$ Pa, $H=50$ J/cm$^2$, $P=14.8\cdot10^4$ atm $\approx 1.5\cdot10^{10}$ Pa.

Comparison of the calculated pressure estimates with the results obtained from the experiment for atmospheric conditions (open target in air) shows that the reactive pressure of the expanding plasma

\[
h = \frac{1}{\mu} (\alpha \tau)^{1/2}
\]

where $\mu=10^{-5}$ cm$^{-1}$ is the absorption index; $\alpha=0.1$ cm$^2$/s – coefficient of thermal diffusivity; $\tau=10^{-8}$ s – pulse duration; $\rho_0=8$ g/cm$^3$ is the density of matter; $\omega=6000$ J/g – latent heat of evaporation.

From (3) and (4) we obtain the values $h=3\cdot10^{-5}$ cm and $10^{-4}$ cm, respectively. Taking $h=10^{-4}$ cm, $H=10$ J/cm$^2$ and $\Gamma=0.5$ [8], we obtain from (2) (with underestimation) the value of $P=5\cdot10^{10}$ N/m$^2$, at $H=25$ J/cm$^2$, $P=1.25\cdot10^{11}$ N/m$^2$. Obviously, pulses of similar amplitude with the duration of the leading front of the order of 10 ns are strong shock waves that, when propagated deep into the material, lose their energy for heating and shear deformations, which leads to a decrease in the compression amplitude. Moreover, the higher the pressure, the greater the relative losses. And this is a possible explanation of the behavior of the curves in figure 3b. A simple estimate of the pressure caused by laser action on an exposed surface is difficult, since the value of $h$ is unknown and can be obtained by experiment. However, knowing the pressure in the covered target it is possible to estimate the pressure in exposed sample with respect to the obtained amplitude of the acoustic sensor obtained under these and other conditions (relative to the experiment). Such an estimate gives the pressure on the surface of the open target to $P=5\cdot10^6$ N/m$^2$ at $H=10$ J/cm$^2$ and to $P=1.25\cdot10^{10}$ N/m$^2$ at $H=25$ J/cm$^2$. Such pressures are also sufficient for shear strains. It should be noted that these estimates were obtained with an overestimate, since damping of shock waves in the case of an exposed surface is less pronounced, i.e. the readings of the acoustic sensor (the thickness of the entrance window made of steel is 3 mm) are relatively high.

Of interest is the experimental determination of the expansion velocity of the plasma flare and the value of $h$ both in the air atmosphere and in a vacuum. We carried out such experiments using the shadow method. In this case, the plasma flare glow moment was determined when the front of the plasma clot of the gap was reached, which was established at various distances from the irradiated surface of the sample. The value of $h$ and the plasma concentration were estimated from the expansion velocity and the duration of the glow pulse. Typical oscillograms of the glow of the plasma at the moment of reaching the slit are given in atmospheric conditions and vacuum, respectively. It can be seen that a precise determination of the escape velocity in air is difficult because of the powerful glow (figure 4b) at the front of the shock and light-detonation waves. At the same time, in the vacuum (figure 4b), the arrival of the front is determined quite accurately. The front speed was $V=20$, 40 and 55 km/s at $H=10$, 25, 50 J/cm$^2$, respectively. The thickness of the plasma bunch was 200, 400, and 550 μm, respectively, with a diameter of the laser beam at the surface $d_s=110$ μm. In this case, the plasma can be considered homogeneous, and the radial expansion can be neglected. The plasma concentration $n$ is about $4.6\cdot10^{20}$, $5.75\cdot10^{20}$, $7.8\cdot10^{20}$ cm$^{-3}$, respectively. The plasma temperature at the given $H$ will be 100 eV (1.1$ \cdot 10^6$ K), 150 eV (1.65$ \cdot 10^6$ K) and 200 eV (2.2$ \cdot 10^6$ K), respectively.

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Comparison of the calculated pressure estimates with the results obtained from the experiment for atmospheric conditions (open target in air) shows that the reactive pressure of the expanding plasma...
into a vacuum is smaller than into air, but insignificantly. Proceeding from this, it can be considered that errors in the determination of pressure during laser treatment of open steel surfaces (steel engraving) are not large. On the contrary, the resulting pressure pulses are huge and can lead to plastic deformations of the material.

![Figure 4. Typical oscillograms in: a – atmospheric conditions, b – vacuum. 1 – laser pulse, 2 – glow intensity of plasma flare from zone, 3 – glow intensity of plasma flare after double slit.]

3. Conclusion
The experimental dependence of the amplitude of the plasma glow, the speed of its expansion into the vacuum pressure under the conditions of retention and expansion of the plasma density of the laser pulse energy are obtained. It is shown that the values of all these parameters increase monotonically with the level of laser action. However, the dependencies are nonlinear. Characteristic is the slowing of growth at high levels of laser exposure. Estimates of the plasma temperature, thickness and density of the plasma bunch are made. It is shown that for a given duration of the laser pulse the role of the plasma bunch in the attenuation of the energy supplied to the sample surface is negligible. It is shown that the pressure at the expansion of the plasma can reach values sufficient to provide shear deformations. The latter must be taken into account when analyzing the structure of near-surface layers during laser engraving of metals.

In conclusion, we note that to further study the role of the plasma flare in the process of metal surface treatment at high laser radiation densities, it is necessary to go over to the region of higher laser pulse durations (from 100 to 500 ns). At the same time, changes should be made in the optical scheme of the research stand and the design of the acoustic sensor, taking into account the features and drawbacks discussed above.

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