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Laser microprocessing in a gas environment at a high repetition rate of ablative pulses

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Abstract. **The parameters of laser ablation of channels in steel are studied in a wide range of nanosecond pulse repetition rates f (5 Hz $\leqslant f \leqslant$ 200 kHz). It is found that for $f \geqslant$ 4 kHz, the results of ablation in air are identical to those obtained under the action of single laser pulses in vacuum. The experimental data as well as the estimates of the parameters of laser plasma and the gas environment in the region of the laser action lead to the conclusion that there exists a long-lived region of hot rarefied gas, known as a fire ball in the theory of explosions. The emerging rarefaction reduces the screening effect of the surface plasma formed under the action of subsequent pulses. This makes it possible to use lasers with a high pulse repetition rate for attaining ablation conditions close to the conditions in vacuum without complicating the technology of microprocessing by using vacuum chambers and evacuating pumps.**

Keywords: *ablation of metals, nanosecond laser pulses, laser plasma in air.*

1. Introduction

The tendency towards an increase in the repetition rate f of pulses irradiating the target material observed in modern laser processing technology in recent years is due to the growing demand to increase the efficiency of the process. As a rule, the pulse repetition rate lies in the range 1 – 10 kHz at present, and in some cases even exceeds hundreds of kilohertz. Due to the use of such high pulse repetition rates, the parameters of the target and its gas environment do not have sufficient time to relax to their initial values in the interval between pulses and the change in their values starts exerting a considerable effect on the process of ablation by the subsequent pulses.

The estimate of these parameters at the time of the next irradiation and their effect on laser microprocessing requires special investigations. However, the publications on this subject known to the authors deal either with the expansion of plasma plume [1] in a characteristic time interval not exceeding a few hundred nanoseconds, or with the process of cooling down of the surface being ablated during the period between pulses due to heatsink to the bulk of the sample [2]. It was emphasised in Ref. [3] that crystallisation of the melt at the sample surface is necessary to ensure a predominantly vapour-phase removal of the target material.

In this paper, we study the pulsed laser microdrilling of steel in the range of pulse repetition rates of several hundred kilohertz. The observed peculiarities are analysed in terms of the long-lived (several hundred microseconds) variations in the parameters of the gaseous environment surrounding the ablated crater, which are known from the theory of explosion as 'a fire ball' [4].

2. Experiment

Experiments on ablative drilling of 0.5-mm-thick steel plates were carried out using several Nd : YAG lasers generating 20-ns pulses with a repetition rate between 5 Hz and 2 kHz, as well as a laser generating trains of picosecond and nanosecond pulses (containing up to 20 pulses) with an equivalent pulse repetition rate of 200 kHz [5]. To compare the ablation rates for different values of pressure of the air surrounding the sample under investigation, the sample was placed in a vacuum chamber. The average linear ablation rate was measured optically by using an integrating sphere [6] mounted behind the output window of the chamber at the back of the plate being ablated. The penetration of radiation into the sphere indicated the drilling of a through hole.

In our experiments, we measured the dependence of the linear ablation rate on the surrounding air pressure, energy density and repetition rate of the laser pulses. The repetition-rate dependences obtained under atmospheric pressure as well as in a rarefied atmosphere under a pressure of 300 mbar (Fig. 1) are of considerable interest. In both cases, the incident energy density was 100 J cm^{-2}. A comparative analysis of the results shows that the measured ablation rates are almost independent of the pulse repetition rate for $f \leqslant 500 - 700$ Hz, while the ablation rates under atmospheric and reduced pressures differ almost by an order of magnitude.

This ratio changes considerably as the value of f increases from 700 to 2000 Hz. In spite of a tendency towards an increase shown by both dependences in Fig. 1, the rate of ablative drilling under a pressure of 1000 mbar increases much more rapidly, and subsequent

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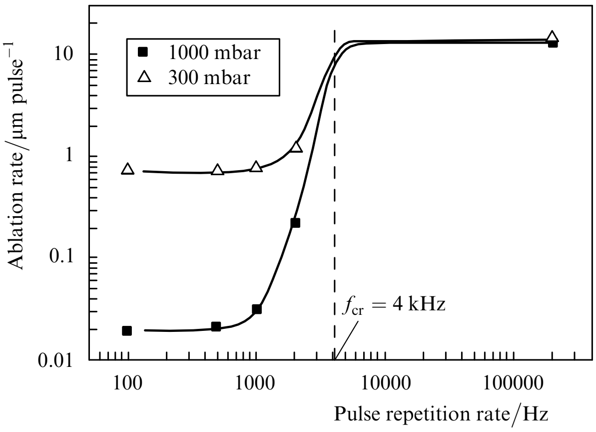

Figure 1. Dependences of the ablation rate for 0.5-mm thick steel plates on the laser pulse repetition rate for an energy density of 100 J cm^{-2} under various pressures of the surrounding air.

extrapolation of the curves leads to the assumption that the two dependences merge at a frequency $f_{cr} \approx 4$ kHz. The increase in the ablation rate in vacuum in this frequency range can be attributed to an increase in the target temperature. The assumption about the coincidence of ablation rates at ultrahigh pulse repetition rates is further confirmed by the results of our experiments using ablative trains of nanosecond laser pulses with an equivalent repetition rate of 200 kHz. These measurements correspond to the pair of coinciding points on the right-hand side of Fig. 1. Thus, the linear ablation rate in this range is no longer a function of the atmospheric pressure, and the parameters characterising the ablation of steel at $f > f_{cr}$ approach the values attainable in vacuum.

The same is true for the morphology of ablated craters and channels that also had close values of diameter and similar surface reliefs in both cases. Channels formed in air at low pulse repetition rates had a much larger diameter (150 μm as compared to 30–40 μm in vacuum and 40–50 μm at $f = 2$ kHz).

This similarity is also illustrated by the pressure dependences of the ablation rates measured at two different pulse repetition rates for identical values of the energy density (Fig. 2). The considerable difference in the ablation rates vanishes quite rapidly as the pressure is lowered to 400 mbar. Upon a subsequent decrease in pressure, both dependences attain plateaus at which the slight difference in the maximum attainable ablation rates can also be attributed to a stronger heating of the ablation zone for a lower pulse repetition rate. A comparison of the dependences shown in Fig. 2 indicates that the effect of pressure is weakened with increasing pulse repetition rates. The changes in the ablation rate observed for $f = 2000$ Hz are not so significant, and the curve near the threshold pressure is sloping more gently.

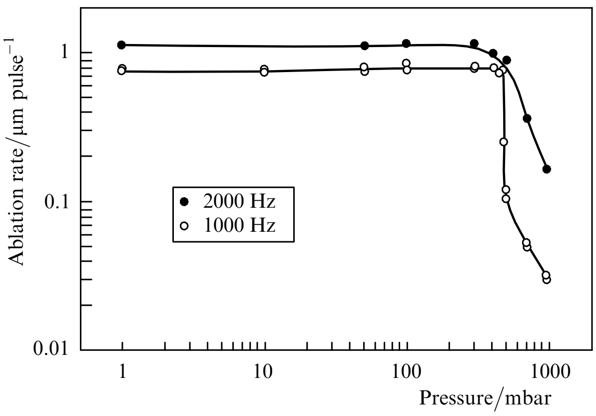

Figure 2. Pressure dependences of the ablation rate for two repetition rates of 20-ns laser pulses for an energy density of 100 J cm^{-2}.

The difference in the ablation rates of steel samples in vacuum and in air is manifested quite strongly only in a limited range of energy densities as illustrated by the dependences shown in Fig. 3. A high and sharp energy threshold ~70 J cm^{-2}, beyond which the difference in the ablation rates quickly increases by one and a half order (see Fig. 3), indicates that this could be due to the peculiarities of plasma formation in the vicinity of the ablated surface. The characteristic time interval $\tau_{cr} = (f_{cr})^{-1}$ indicates that these peculiarities arise only a long time after the laser pulse and do not vanish at least for several hundred microseconds.

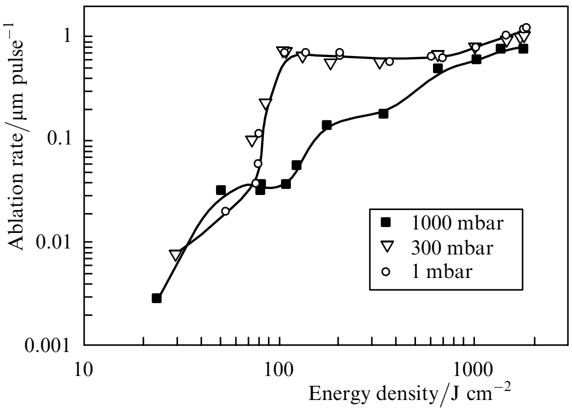

Figure 3. Dependence of the ablation rate on the energy density of nanosecond pulses under various pressures of the surrounding air.

3. Estimate of gas parameters and critical pulse repetition rate

Let us estimate the parameters of the gas environment in a crater or a channel, taking into account several stages of the process: the expansion of the plasma plume during laser irradiation, a further expansion of the plasma region due to a difference in the pressures inside and outside this region, and subsequent cooling of the heated gas near the ablated area.

The maximum velocity of the plasma plume expansion during the action of a nanosecond pulse can be estimated from a simple relations [1]:

$$v = \left(\frac{ZT_e}{m_i}\right)^{1/2}, \tag{1}$$

where m_i is the mass of the ions (in grams), and

$$T_e = 16\left(\frac{I}{10^9}\right)^{1/3}, \tag{2}$$

where T_e is the characteristic electron temperature (in electron-volts).

Expression (2) was obtained for an aluminum target. In the case of steel, the numerical coefficient should be somewhat different. However, in view of the close values of the ionisation potentials and population of the conduction band levels by electrons, this difference should be insignificant. It is mainly due to different reflectivities of the sample surfaces. For typical laser pulse intensities $I = 5\times10^9$ W cm^{-2} used in the experiments, the degree of plasma ionsation is $Z\approx7$ [1]; as a result, the velocity of the plasma expansion and temperature achieve 4×10^6 cm s^{-1} and 3×10^5 K, respectively. Taking into account the plasma expansion and duration of irradiation, we find that the one-dimensional expansion of the plasma at the end of this stage may achieve ~0.8 mm. This value exceeds the characteristic channel length ($\leqslant 0.5$ mm) in our experiments, and the one-dimensional expansion is possible only within such lengths of the channel. As a result, the plasma inevitably reaches the sample surface during the laser pulse action, its further expansion becomes nearly hemispherical, and the estimate of the expansion velocity from (1) turns out to be overstated.

After completion of the laser pulse, the plasma region continues to expand hemispherically at the expence of the energy stored in it. When the pressure in the plasma becomes equal to the atmospheric pressure, the expansion terminates and a fire ball (a hemisphere in the case considered by us), which is a well-defined and relatively long-lived area of hot gas, is formed in the vicinity of the irradiated surface [7]. The temperature of this region decreases during the plasma expansion [7, 8]: the decrease is quite fast at the initial stage ($\sim100-300$ ns) due to radiative losses, and is slower during the next stage (beginning from $T\sim10000$ K) due to an increase in the plasma volume and transfer of heat to the metallic surface [9].

Theoretical estimate of temperature at the centre of hot plasma region becomes difficult towards the end of its expansion due to the variety of intricate processes and, in particular, due to the uncertainty in energy losses related to a shock-wave formation. Therefore, we determined the temperature by using the experimental results obtained in Refs [7, 8] under identical conditions, according to which, $T_f\approx5000-8000$ K. Note that the theory of point explosion neglecting heat losses [10] leads to a close value of temperature, but gives considerably overstated values of the fire ball size and the time of its formation.

The time τ_f of formation of a hot hemispherical region and its maximum radius R_f can be determined by using semiempirical relations for the fire ball near the surface [7] based on the data of model experiments on pulsed laser irradiation of metals. Using these relations and taking into account the laser pulse energy E_0, the velocity of sound u_0 in the plasma at a temperature T_f, and pressure of the surrounding air p_0, we obtain

$$\tau_f \simeq 0.07\frac{(20E_0)^{1/2}}{u_0}\approx 2\ \mu\text{s}, \tag{3}$$

$$R_f \simeq 0.35\left(\frac{E_0}{p_0}\right)^{1/3}\approx 0.6\ \text{mm}. \tag{4}$$

In the cooling stage under atmospheric pressure following the formation of a hemispherical fire ball, the processes of heat transfer to the metallic surface play a dominant role. By neglecting the radiative component at this stage [9], we determine the basic mechanism of heat transport. For this purpose, we use the Grashof number Gr [11] characterising the intensity of vortex formation for free convection of a gas driven by a temperature gradient:

$$\mathrm{Gr} = \frac{g\beta l^3}{\nu^2}\Delta T. \tag{5}$$

Here, g is the gravitational acceleration; β is the coefficient of volume expansion; ν is the kinematic viscosity of the gas; and ΔT is the temperature drop over a characteristic length l. In the case considered by us, the Grashof number is found to be much smaller than the value 10^4 corresponding to a transition to the turbulent gas flow. This condition is satisfied over the entire calculated temperature range both for the ablated channel and the outer hemispherical region, thus suggesting the absence of convection currents and the domination of the conductive mechanism of heat transport.

Further, it can be assumed that the hot gas inside the channel is cooled more rapidly than in the outer hemisphere because of a higher ratio of the gas–surface area to its volume. The cooling rate of the gas was calculated in the approximation of an infinite cylindrical channel of radius 20 μm taking into account the temperature dependence of the specific heats and thermal conductivities of the gas and the metal in the form of step functions. Figure 4 shows the results of numerical calculations for the gas temperature and density at the centre of the channel. A comparison of the cooling time of the gas with the above-mentioned critical interval τ_{cr} between the laser pulses (the inflection point in the frequency dependence shown in Fig. 1 corresponds to $\tau_{cr}\approx250$ μs) shows that a temperature of $\sim1500-2300$ K should be preserved at the centre of the channel by the end of the interval. In this case, the gas density proves to be several times lower than the atmospheric value under normal conditions. Moreover, this value of density numerically corresponds to the critical pressure (400 mbar) on the experimental dependence shown in Fig. 2, i.e., the gas density below which the rate of ablation in steel increases abruptly. This value is indicated by a horizontal dashed line in Fig. 4. Therefore, τ_{cr} correlates quite well with the gas cooling time in the ablated channel.

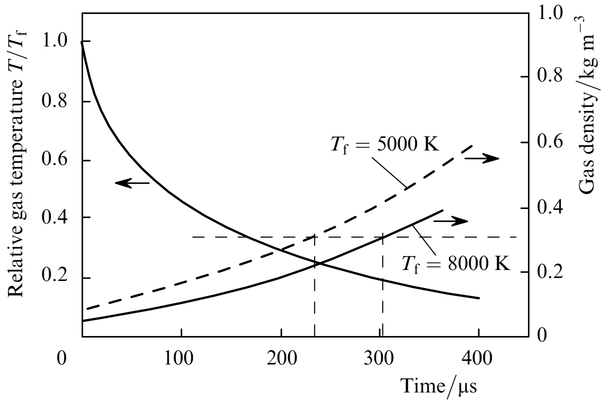

Figure 4. Time dependences of the relative temperature and gas density at the centre of a channel.

4. Conclusions

The results of laser ablation experiments for steel in air at high pulse repetition rates and the estimates of gas parameters show that a relatively long-lived region of rarefaction (lower gas concentration at a higher temperature) emerges in the channels being formed as well as on the surface. The rarefaction considerably affects the processes of plasma formation by the subsequent laser pulses with a high repetition rate. The screening effect of plasma is considerably lowered in this case. As a result, the linear ablation rate increases by more than an order of magnitude while the diameters of the ablated channels decrease due to the absence of a noticeable lateral expansion of the plasma plume.

It was shown in Ref. [6] that one of the main reasons behind such an expansion is the low-threshold breakdown of the air containing the ablated microparticles. Consequently, a prolonged existence of hot gas in the channel and near the surface can also significantly retard the process of their condensation. Thus, the use of high repetition rates of laser pulses has a dual effect. On the one hand, the rarefaction of the atmosphere decreases the amount of the plasma-forming matter and hence reduces plasma screening. On the other hand, the high temperature reduces the probability of formation of low-threshold breakdown nucleation particles.

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