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Specific features of metal surface processing by nanosecond laser pulse trains

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***Abstract*. The process of melt formation upon irradiation of a metal by a train of nanosecond laser pulses is studied theoretically and experimentally. A method is developed for determining the parameters of a train at which the amount of melt is minimal, and the material is removed in the vapour state upon laser irradiation.**

Keywords: *laser processing of metals, Nd laser.*

1. Introduction

The processing of a metal surface by the laser projection technique assumes a simultaneous formation of the entire graphic image of the object or its considerable part on the surface. The precision and quality of the image are determined to a considerable extent by the regime of processing. The best quality characteristics and reproducibility of results are attained in the evaporation regime [1]. In this case, powerful nanosecond laser pulses are required for irradiation of the surface. In order to obtain deep lines of the image, repetitively pulsed lasers are used. All this fully applies to the formation of precision holes by the laser projection technique.

A train of identical short radiation pulses with a constant pulse repetition rate can be obtained by using a passively Q-switched Nd : YAG laser. It is assumed that the processing of a surface by a train of such pulses ensures a high precision and reproducibility of the results [2].

To obtain high-quality results, each laser pulse should evaporate the metal, while the amount of the melt should be minimal. The time interval between the pulses must be longer than the time of cooling of the surface to the crystallisation point, and the off – duty ratio must satisfy the condition $t_s/\tau \geqslant 3.2 \times 10^{-3} \times (L/\rho c T_m)$. These conditions were obtained assuming that the action of each pulse on the metal is completely independent of the action of other pulses in the trains [1]. Here, τ and t_s are the pulse duration and the time interval between pulses; L and T_m are the specific heat of evaporation and the melting point of the metal, and ρ an c are the density and specific heat of the metal, respectively.

However, it was found experimentally in recent works [3, 4] that irradiation of a metal by a train of nanosecond pulses satisfying the above conditions leads to the formation of a considerable amount of melt, which affects significantly the rate of processing of the metal (in particular, the rate of formation of a hole in it) [4].

In this paper, we make an attempt to determine experimentally and theoretically the mechanism of melt formation upon irradiation of a metal by train laser pulses.

2. Theory

When a metal is irradiated by laser pulses of duration longer than 10^{-10} s, the heat propagation from the region of absorption of light should be taken into account [5]. In this case, a part of laser energy is spent on evaporation of the metal and another part, on its heating. The irradiation of the metal surface by periodic laser pulses may lead to a considerable heating of the irradiated and surrounding regions with the formation of a large amount of melt.

To understand the mechanism of melt formation, we should solve the problem of heat propagation inside the metal upon heating its surface by periodic laser pulses, taking into account the energy spent for evaporation.

The problem can be solved in two stages. First, the fraction of laser pulse energy absorbed by the metal and heating is determined. Then the change in the temperature of the metal caused by the action of a repetitively pulsed source of heat on its surface with a pulse energy equal to the energy of a laser pulse remaining in the metal is estimated.

In the intense evaporation regime, almost the entire energy of a laser pulse is spent to remove the metal from the irradiation region. The temperature of the surface in this case attains $(2-3)T_b$ [9] (T_b is the boiling point of the material under standard conditions). The optimal density Q of the laser power, required for intense metal evaporation, can be calculated from the expression [5]

$$Q = [3\chi(L\rho)^2\tau]^{1/2}, \tag{1}$$

where $\chi = \lambda/c\rho$ is the thermal diffusivity and λ is the thermal conductivity.

An estimate for a nanosecond radiation pulse gives $Q \approx 10^9$ W cm^{-2}. However, it is difficult to process a material by a radiation of this intensity because it causes an optical breakdown above the surface, in which a plasma

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efficiently absorbs and scatters laser radiation [5]. For this reason, the laser radiation used in practice for this purpose must be several times weaker (the value of Q is approximately equal to $(1-6)\times 10^8$ W cm^{-2}). In this case, the temperature of the irradiated surface can be estimated from the relation [1]:

$$T = \frac{2(1-R)Q(\chi\tau)^{1/2}}{\lambda\sqrt{\pi}}, \tag{2}$$

where R is the reflection coefficient for the metal surface.

For $\tau \approx 10^{-8}$ s, the temperature of the irradiated surface of iron ($R \approx 0.7, \chi \approx 0.22\,\text{cm}^2\,\text{s}^{-1}$, and $\lambda \approx 0.75\,\text{W cm}^{-1}\,\text{K}^{-1}$) by the end of a pulse must be $\sim 6000\,^\circ$C, which corresponds to the lower boundary of intense evaporation regime. This means that evaporation process becomes intense only by the end of the laser pulse, and the major part of the material is removed from the irradiated region only after the end of the pulse. In this case, we can assume that evaporation does not affect the heating process and confine our theoretical analysis only to the solution of the thermal problem, disregarding the propagation of the evaporation front inside the material.

For solving the first part of the problem, we use the following standard constraints and assumptions [6].

1. It is assumed that heat conduction is a one-dimensional process because we consider the surface metal processing by the projection technique, in which the depth of image lines is much smaller than the size D of the irradiated surface and the medium length; i.e., the condition $D \gg (\chi\tau)^{1/2}$ is satisfied [5].

2. Evaporation does not affect the heating process as long as the temperature is lower than the equilibrium temperature of evaporation. In the case under study, the equilibrium temperature of evaporation amounts to $(2-3)T_b$ [7, 9].

3. The temperature dependence of thermal and optical parameters of the material is insignificant.

4. The source of heating is two-dimensional with an equilibrium distribution of the heat release; this assumption is valid because radiation is absorbed in a surface layer whose thickness is much smaller than the radiation wavelength.

Under the conditions listed above, the 1D linear equation of thermal conductivity, which describes the heating of a semi-infinite medium ($z > 0$), has the form

$$\frac{\partial T}{\partial t'} = \chi\frac{\partial^2 T}{\partial z^2}. \tag{3}$$

The action of a homogeneous surface source of heat is taken into account by the boundary condition

$$\left.\frac{\partial T}{\partial t}\right|_{z=0} = -\frac{Q}{\lambda}. \tag{4}$$

The initial condition has the form: $T(0, x) = T_1$, where T_1 is the temperature of the medium before irradiation.

To solve the formulated problem, it is convenient to use the dimensionless time and coordinate: $t = t'/\tau, t' = \tau t, x = z/d$, where $d = (\chi\tau)^{1/2}$ is the characteristic depth of heat penetration into the material during irradiation.

In this case, Eqn (3) takes the form

$$\frac{\partial T}{\partial t} = \left(\frac{\chi\tau}{d^2}\right)\frac{\partial^2 T}{\partial x^2} \equiv \frac{\partial^2 T}{\partial x^2}. \tag{5}$$

The solution of Eqn (5) can be obtained by using the Laplace operator method [8]:

$$T(t,x) = T_1 + \frac{dQ}{\lambda}\left[2\left(\frac{t}{\pi}\right)^{1/2}\exp\left(-\frac{x^2}{4t}\right) - x\,\text{erfc}\left(\frac{x}{2\sqrt{t}}\right)\right]. \tag{6}$$

Assuming that $T_1 = 0$, we finally obtain

$$T(t,x) = T_0\left[\sqrt{t}\exp\left(-\frac{x^2}{4t}\right) - x\frac{\sqrt{\pi}}{2}\text{erfc}\left(\frac{x}{2\sqrt{t}}\right)\right]. \tag{7}$$

Here

$$T_0 = \frac{2dQ}{\lambda\sqrt{\pi}}$$

is the temperature of the surface by the end of the pulse.

Fig. 1 shows a typical temperature distribution in an iron target by the end of a radiation pulse, calculated by expression (7).

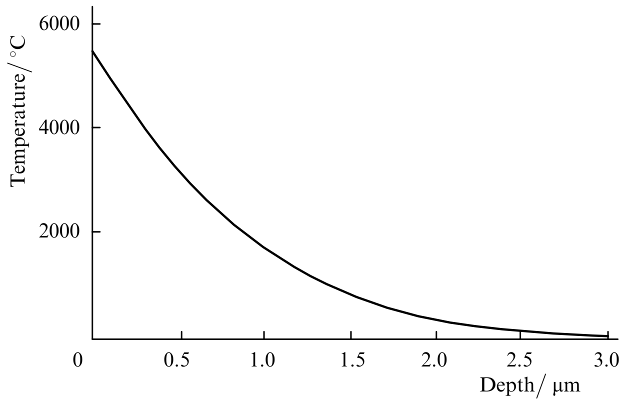


Figure 1. Temperature distribution in the target by the end of a laser pulse.

It is logical to assume that the layer of the material heated to above the boiling point T_b evaporates. The thickness of the melt layer is insignificant (~ 0.5 μm), and the melt cannot be removed under the action of vapour pressure [4]. Obviously, the removal of the material from the irradiated region occurs in the evaporation regime, evaporation mainly occurring only after termination of the laser pulse because the temperature of the surface attains the value for which intense evaporation is possible only by this instant. The remaining heat penetrates inside the material. The action of periodic radiation pulses on the target leads to gradual heating of the material surrounding the irradiated region. In this case, the thermal field in the target by the moment of arrival of the nth pulse is described by the expression [4]

$$T(z,t) = T_b t_b^{1/2}\sum_{k=1}^{n-1}\frac{1}{(nt_s)^{1/2}}\exp\left(-\frac{z^2}{4\chi^2 nt_s}\right). \tag{8}$$

Here, t_b is the time over which the surface of the target is heated to a temperature T_b and t_s is the time interval between pulses in a train.

After simple transformations, we can write expression (8) in the form

$$T(z,t) = \frac{T_b^2 \lambda \sqrt{\pi}}{2Q\sqrt{\chi}} \sum_{k=1}^{n-1} \frac{1}{(nt_s)^{1/2}} \exp\left(-\frac{z^2}{4\chi^2 n t_s}\right). \quad (9)$$

Expression (9) can be used only when the surface temperature exceeds T_b during the action of a laser pulse.

If the temperature in the region under study becomes comparable with the crystallisation temperature of the material, we can expect the formation of melt in an amount sufficient for its removal from the irradiated region under the action of the vapour pressure [4]. In this case, the material can be removed not only by evaporation.

The dependence of the surface target temperature ($z = 0$) on the number of pulses in a train is shown in Fig. 2. One can see that the temperature of the target surface increases with the number of absorbed laser pulses. For a train with the number of pulses exceeding 60, the temperature in the surface region exceed the crystallisation temperature of iron. Obviously, in this case, the material will be removed from the irradiated region in the liquid form, and damage of the iron target is accelerated considerably. As applied to the surface processing of a material, this means that the quality of the image formed on the surface will deteriorate due to considerable thermal distortion.

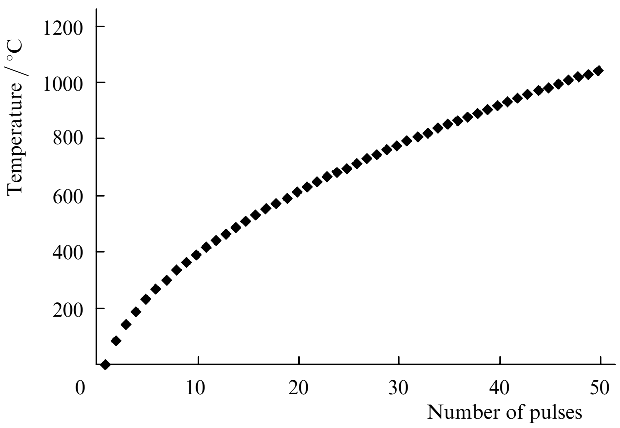


Figure 2. Dependence of the temperature of the target surface on the number of pulses in a train.

An analysis of temperature variation in the irradiated region can be used to determine the parameters of a train of laser pulses, for which the material is removed from the irradiated region in the evaporation regime.

3. Experimental investigation of the mechanism of melt formation

The schematic diagram of the experimental setup is shown in Fig. 3. The source of radiation was a flashlamp-pumped, Q-switched Nd laser (*1*). The laser produces pulse trains with a total duration up to 3 ms. The duration and energy of an individual pulse in the train are approximately 35 ns and 9 mJ, respectively. The pulse repetition rate in the train is varied by changing the pump current pulse amplitude and

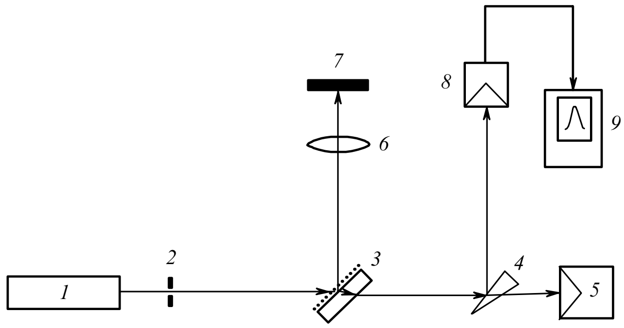


Figure 3. Schematic of the experimental setup: (*1*) laser, (*2*) diaphragm, (*3*) deflecting mirror, (*4*) optical wedge, (*5*) power meter AN/2, (*6*) focusing lens, (*7*) target, (*8*) photodiode LFD-2, (*9*) oscilloscope.

using $YAG:Cr^{4+}$ active elements with different optical densities.

The radiation beam passes through diaphragm (*2*), is reflected by the deflecting mirror (*3*) and is incident on lens (*6*), which forms a diminished image of the diaphragm on the surface of target (*7*). The reflection coefficient of mirror (*3*) at a wavelength 1.06 μm is 96 %. The radiation transmitted through the mirror is directed to the power meter (*5*) measuring the power of a train of pulses. A part of radiation is reflected by the optical wedge (*4*) and directed to photodiode (*8*), after which the signal is fed to the input of oscilloscope (*9*).

Lens (*6*) forms on the surface of the target a circular radiation spot of diameter 360 μm with a sharp edge and a relatively uniform intensity distribution with the power density $Q \approx 2.0 \times 10^8$ W cm^{-2}. Irradiation of the surface of the target leads to the formation of a crater whose depth depends on the laser pulse parameters. We used massive iron and copper plates of size $50 \times 40 \times 10$ mm as targets. A series of craters is formed consecutively upon irradiation of the target by a train of pulses. The first crater is formed by a single pulse, the second by two pulses, the third by three pulses, and so on.

The efficiency and the type of removal of the material from the irradiated region were determined by measuring the geometrical parameters of the formed crater and by estimating the amount of the removed material. Fig. 4 shows the experimental and theoretical dependences of the increase in the mass of the removed material on the number of pulses in a train for iron and copper. The theoretical dependences were determined for the evaporation regime of the removal of the material from the irradiated region. We assumed that irradiation by each pulse resulted in the evaporation of a layer of the material heated to above $T_b = 3050$ °C for iron and $T_b = 1050$ °C for copper, taking into account the heating of the irradiated region by all previous pulses in the train.

The results described above show that the material is removed in the evaporation regime if the number of pulses in a train acting on the target does not exceed 20. When the number of pulses increases, the effect of surface heating becomes significant, which leads to the formation of a layer of melt that can be removed by vapour pressure [4]. As a result, the rate of increase in the crater depth becomes higher because the melt splashes, and the material removal is no longer controlled by evaporation only. The increase in the crater depth is most intense for trains with more than 50

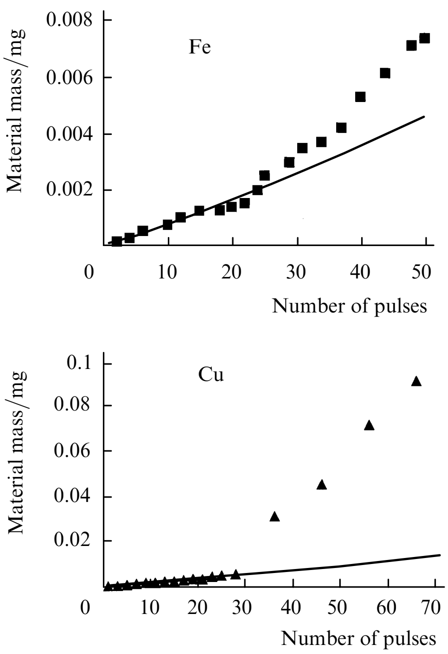
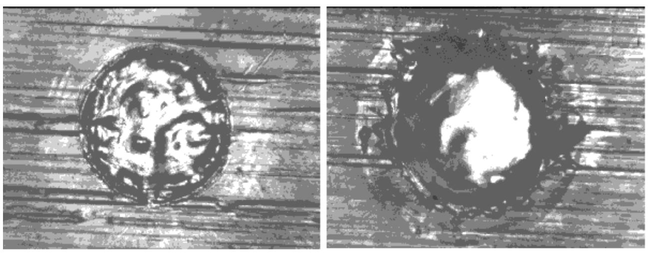


Figure 4. Experimental (symbols) and calculated (curves) dependences of the mass of the removed material on the number of pulses for an iron and a copper target.

pulses, because the temperature of the crater bottom in the interval between pulses in a train approaches the melting point according to estimates.

Fig. 5 shows the photographs of craters formed upon irradiation of an iron target by pulse trains with different numbers of pulses. The crater in Fig. 5a was formed by a train of 6 pulses. There are no thermal distortions, and the crater edges are sharp. Fig. 5b shows a crater formed by 34 radiation pulses. In this case, splashes of the melt can be clearly seen on the perimeter of the crater. Similar photographs were also obtained in experiments with a copper target.



a b

Figure 5. Photographs of typical craters formed upon irradiation by trains of 6 (a) and 34 (b) pulses.

4. Conclusions and recommendations

When a metal is irradiated by long trains of nanosecond laser pulses, the irradiated region is gradually heated, and the temperature in this region may exceed the melting point of the metal. In this case, the main mass of the metal is removed from the irradiated region in the form of melt under the action of the vapour pressure.

The surface processing and drilling of holes in metal plates by the projection method are performed, as a rule, by irradiating the metal by a large number of pulses with a typical intensity of the order of 10^8 W cm^{-2}. In this case, the number of pulses in a train must be limited to 20 – 30 in order to ensure a high quality and reproducibility of the results of processing. This limitation makes it possible to operate in a pure evaporation regime.

If the requirements to the precision of processing are not very stringent, the number of pulses in a train can be increased to 50. In this case, a considerable part of the metal will be removed from the irradiated region in the form of a melt, which considerably increases the efficiency of the process (by a factor of 2 – 3).

The admissible number of pulses in a train can be estimated from expressions (7) – (9).

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