CALCULATION OF THE DYNAMICS OF FRACTURE OF METALS IN THE DEEP PENETRATION OF A TARGET BY A LASER BEAM

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1. Introduction. The deep penetration of a laser beam into absorbent materials occurs through the formation of a crater (cavity) in the specimen. Radiation is propagated through this cavity, and products of the destruction of the material – vapor, drops of liquid, etc. – are removed through the cavity. The general laws governing the formation of the cavity under the influence of a powerful light flux have been examined in detail in connection with the development of powerful lasers operating in the visible and near-infrared ranges [1]. However, periodic-pulse (PP) lasers operating on carbon dioxide and generating radiation with a wavelength λ = 10.6 μm have come into broad use in recent years [2]. Studies made of the interaction of powerful infrared radiation with metals (mainly experimental studies) have revealed several qualitative features of this process which are not encountered in the use of lasers operating at shorter wavelengths. The most interesting finding is the possibility of achieving a high values of the "penetration parameter" of the vapor–gas channel (the ratio of the depth to the mean diameter) created in the specimen both in a welding regime and in the hole-piercing regime (laser drilling). For example, this parameter may reach a value of 10 in welding with a continuous beam [3] and 20 or more in a periodic-pulse regime [4]. For comparison, we note that the value of this ratio usually does not exceed three for lasers operating in the visible and infrared regions [1].

Another typical feature of the process of interaction of radiation from CO_2 lasers with metals is seen in analyzing the dependence of the rate of deepening of the cavity on the time and in comparing it with the analogous dependence for short-wave generators. As is known [1], in the last case this dependence is monotonically decreasing. This has to do with the geometric divergence of the laser beam. In the case of CO_2 lasers, an experiment shows a significantly nonmonotonic dependence of the rate of deepening of the cavity on time [4, 5].

A study was made in [6] of the distribution of radiation intensity in a cavity with a high value of the "penetration parameter." It was shown that due to the low coefficient of absorption of infrared radiation on the surface of metals, light beams undergo a great number of reflections from the side walls, and a waveguide regime of radiation propagation may arise.* Here, electromagnetic energy is concentrated near the bottom of the cavity. The assumption of the existence of a waveguide regime has made it possible to explain qualitatively the high values of the "penetration parameter" and the depth of penetration of a continuous laser beam into a target in the welding regime. It has also helped to explain the appearance of the inflection on the dependence of cavity depth on the time of action of the beam [4, 7]. In [8] the phenomenon of a sharp change in the form of the liquid bath at a certain laser power was connected with the appearance of rereflected beams.

Here we study numerically a model of "capture" of laser radiation and the occurrence of a waveguide regime of propagation of this radiation in the cavity formed in the metal by the beam of a periodic-pulse laser. We examine the case of low mean laser power (limiting case of low pulse repetition frequency), when it is possible to ignore the effect of the liquid film formed on the surface of the target. Generally speaking, consideration of this film seriously complicates the analysis of the phenomena occurring in the zone of action of the radiation.

2. Formulation of the Problem. We will assume that the target is a half-space with its surface turned toward the laser beam and coincidence with the plane z = 0 of the Cartesian coordinate system. Focused radiation of mean intensity P begins to act on the specimen at

*The possible role of repeated reflections of light in a deep channel was first discussed by V. P. Veiko and M. N. Libenson (see [1], p. 253).

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the moment of time $t = 0$; the focus is located a distance Δ above the plane $z = 0$. At subsequent moments of time the surface of the target is described by the function $z = z(x, y, t)$. Absorption of radiant energy by the surface layer of the substances causes its heating and removal from the cavity in the form of vapor and/or liquid. The rate of displacement of the surface in the normal direction is determined from the law of energy conservation

$$v_s = Q_a/\rho L, \tag{2.1}$$

where Q_a is the mean density of the absorbed energy per unit of time at a given point; ρ is density; L is the effective disintegration energy per gram of substance. Expressing v_s through the derivatives of $z(x, y, t)$, we obtain the following equation* from (2.1):

$$\frac{\partial z}{\partial t} = \sqrt{1 + \left(\frac{\partial z}{\partial x}\right)^2 + \left(\frac{\partial z}{\partial y}\right)^2}\,\frac{Q_a}{\rho L}. \tag{2.2}$$

In the case of a periodic-pulse CO_2 laser with a fixed mean power, the quantity L is generally a complex function of the pulse width τ and Q_a. It increases rapidly in the region of large and small values of the density of absorbed energy (with a fixed τ) [9]. We will henceforth examine the case pertaining to small values of Q_a. In connection with this, we use the following approximation of the function L:

$$L = L_0\begin{cases} 1, & Q_a \geqslant Q_0, \\ \infty, & Q_a < Q_0, \end{cases} \quad Q_0 = Q_0(\tau). \tag{2.3}$$

The quantity Q_a in (2.2) and (2.3) is a functional of $z(x, y)$, and it also depends on the displacement of the focus Δ and the angle of focus of the radiation. Here, we described the laser radiation in an approximation of geometrical optics, i.e., we assumed that $\lambda/(\Delta\theta_0) \to 0$. Meanwhile, we examined only planar and axially symmetrical cases. The value of Q_a for a specified function $z(x, y)$ was calculated as follows. The focused radiation was represented as a set of N rays taken with a certain weight, such that the distribution function of the rays with respect to the angles at the focal point was Gaussian:

$$f(\theta) = \frac{N}{\pi\theta_0^2}(2\pi)^{\nu}\exp\left(-\frac{\theta^2}{\theta_0^2}\right), \tag{2.4}$$

where $\theta_0 \ll \pi$ is the focusing angle; $\nu = 0$ in the axially symmetrical case and $\nu = 1$ in the planar case. The energy transported by the rays per unit of the solid angle was assumed to be proportional to their weight and was normalized for the total power of the laser P. We then constructed the trajectory of each ray in the cavity. Here, the weight of the ray after the next reflection from the wall was multiplied by the reflection coefficient, which was calculated from the formulas [10]

$$R_{\perp} = 1 - 4\zeta_0\cos\alpha, \quad R_{||} = \left|\frac{\cos\alpha - \zeta}{\cos\alpha + \zeta}\right|^2, \quad \zeta = \zeta_0(1 - i),$$

where the subscripts $\perp$ and $||$ pertain to rays polarized perpendicular and parallel to the plane of incidence, respectively; ζ is the surface impedance of the metal; α is the angle of incidence of the ray on the surface. If the weight of the ray becomes less than 10^{-4} of the initial value, it is eliminated from further consideration. The energy absorbed on the given element of the cavity surface was calculated by summing the contributions of the individual rays (with allowance for the weight). The value of Q_a calculated as described above was inserted into Eq. (2.2), which was solved on a BÉSM-6 computer by an explicit scheme. Most of the computations were performed with N = 500, while some of the control computations were performed with N = 1000 and N = 2000.

It should be noted that the method used here to model the dynamics of cavity formation is not limited to explicit forms of the functions L (2.3) and $f(\theta)$ (2.4), which are employed and can be used in a more general case.

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*This equation can be written in dimensionless form by making the substitutions $\mathbf{r} \to \mathbf{r}/a$, $t \to t/t_0$, $a = \Delta\theta_0$; $t_0 = \pi^2(\Delta\theta_0)^3\rho L/P$, $Q_0 \to Q_0/Q^*$, $Q^* = P/\pi(\Delta\theta_0)^2$.

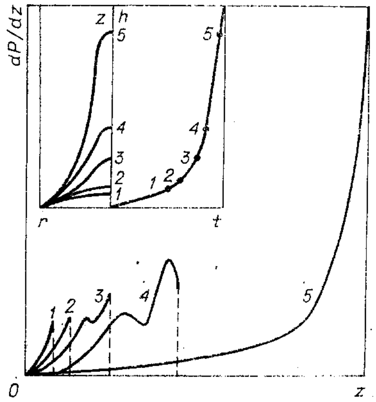

Fig. 1

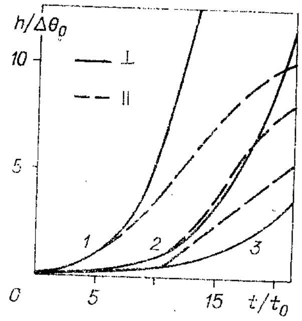

Fig. 2

3. "Capture" of Radiation and Occurrence of a Waveguide Regime in Cavity Formation. Figure 1 shows results of calculation of the dynamics of the formation of a cavity by an axially symmetrical laser beam polarized parallel to the plane of incidence. The numbers 1-5 denote the dependence of the energy release on the walls of the cavity on the coordinate z for different moments of time from the beginning of action of the radiation. The form of the cavity for these moments of time and the function h(t) are shown in the insert (the dashed lines in Fig. 1 denote the position of the bottom of the crater). At short times, when the cavity is shallow, all of the rays incident on the surface of the target interact with the target only once. Here, the rate of deepening of the crater is determined by the initial intensity and divergence of the beam and is proportional to the absorption coefficient of the material. This is evident from Fig. 2, which shows graphs of the initial sections of the curve h(t) for $\zeta_0 = 5 \cdot 10^{-2}$. $2.5 \cdot 10^{-2}$, and $1.25 \cdot 10^{-2}$ (lines 1-3, respectively). The dashed lines correspond to polarization perpendicular to the plane of incidence, while the solid lines correspond to polarization parallel to this plane. At a certain critical value of cavity depth $h^* \approx \theta_0 \Delta$, some of the rays, reflected from the side walls, strike the bottom of the cavity and thereby undergo several reflections. At $h = h^*$, the distribution of the intensity of the radiation absorbed on the cavity walls undergoes significant changes: A local maximum appears near the point of rotation of the group of rays propagated at an angle $\theta \sim \theta_0$ to the axis of the cavity. At this moment there is a sharp change in the form of the cavity near its bottom (see curves 2 and 3 in Fig. 1). With a further increase in h, the number of maxima on the dependence of the absorbed energy on the coordinate z increases, which corresponds to a greater number of reflections of rays near the bottom; their amplitude increases, while the position is shifted toward the bottom of the crater. By a certain moment of time, all of the local maxima have merged into a single maximum located near the bottom. The intensity of the radiation on the bottom at this moment exceeds the intensity at t = 0, i.e., the rays reflected from the side walls are focused on the bottom of the cavity,† which leads to a sharp decrease in the rate of deepening of the cavity (see Figs. 1 and 2).

At subsequent moments of time, the absorbed-energy maximum is located on the bottom of the cavity and is determined mainly by rereflected rays. This indicates the creation of a waveguide regime of radiation propagation in the channel.

The increase in the number of reflections in the channel leads to an increase in the effective coefficient of absorption K of the incoming energy by the specimen. Figure 3 shows graphs of the dependence of K on the "penetration parameter" of the cavity calculated as an example for a parabolic cavity shape. A similar relationship is seen in experiments involving the laser welding of metals, when the value of h/d changes in relation to the rate of movement of the beam [8].

†The possibility of the occurrence of such a phenomenon was first noted in [11], where it was concluded from experimental data on the destruction of acrylic resin by laser radiation that light intensity increases on the bottom of the cavity. However, no quantitative model permitting description of this phenomenon was proposed.

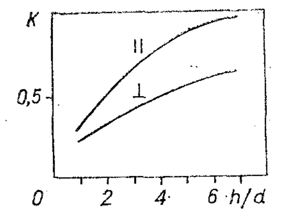

Fig. 3

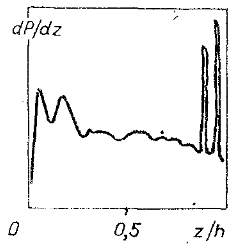

Fig. 4

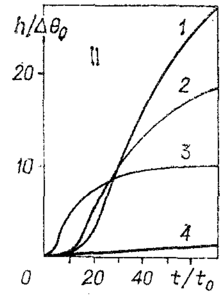

Fig. 5

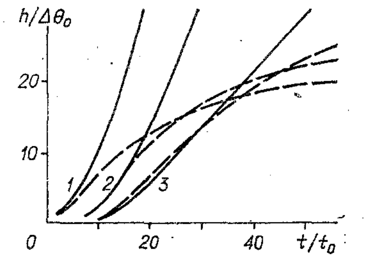

Fig. 6

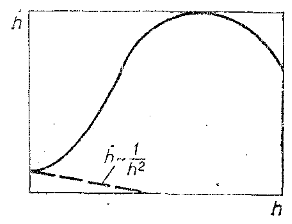

Fig. 7

The relative role of rereflections increases with a decrease in the absorption of radiation on the surface of the target: It follows from Fig. 2 that the ratio of the rates of deepening of the cavity at $h > \Delta\theta_0$ and $h \ll \Delta\theta_0$ increases with a decrease in ζ_0. This relation is truer for rays polarized perpendicular to the plane of incidence than for rays with parallel polarization, which also has to do with the lower coefficient of absorption of light by the metal in the last case.

It must be emphasized that the distribution of light absorption along the axis of the cavity depends appreciably on the specific form of the function $f(\theta)$. As an example, Fig. 4 shows the distribution of intensity for the case when $f(\theta)$ is constant within the range of the focusing angle $[f(\theta) = f_0\theta(\theta_0 - |\theta|)]$. The oscillation in the graph is connected with the arrival at the given point of rays which have undergone different numbers of reflections from the cavity walls.

4. Limiting Depth of Penetration of Laser Beam into Metal. It is interesting for several applications to study the limiting parameters of the cavity formed in a specimen in the case of long times of action of the radiation. The maximum cavity depth is determined from the condition of equality of the absorbed intensity on the bottom to the value of Q_0 [see (2.3)]. The family of curves $h(t)$ for different values of Q_0 is shown in Fig. 5 (lines 1-4 correspond to $Q/Q^* = 0$, 0.075, 0.3, and 0.4). As might be expected, the limiting cavity depth decreases with an increase in the threshold intensity. It is interesting to note that with an increase in Q the "capture" of the beam in the cavity occurs with shorter times of action of the radiation. This is connected with the fact that the diameter of the resulting cavity d turns out to be smaller in this case. Thus, the "capture" condition $h \gtrsim d$ begins to be satisfied at smaller values of cavity depth.

Figure 6 shows calculated curves $h(t)$ for $\zeta_0 = 5 \cdot 10^{-2}$, $2.5 \cdot 10^{-2}$, and $1.25 \cdot 10^{-2}$ (lines 1-3, respectively). The solid lines correspond to rays polarized perpendicular to the plane of incidence, while the dashed lines correspond to rays polarized parallel to this plane. At short times, h increases with an increase in ζ_0 [1]. However, the reverse situation prevails at long times: A large limiting cavity depth corresponds to a lower coefficient of absorption on the surface of the metal. Such a finding can be explained on the basis of waveguide considerations [4, 6, 7]: A lower value of ζ_0 corresponds to a greater depth of penetration of the radiation in the narrow channel and, thus, to a greater cavity depth (with roughly the same diameters). From this point of view, it is natural to expect a deeper cavity when the radiation is polarized perpendicular to the plane of incidence (see Fig. 6). In waveguide terminology, this case corresponds to the propagation of magnetic-type modes having the greatest quality factor [10].

It should be noted that a dependence of the penetration of a laser beam into a specimen on polarization that was similar to the dependence found here was discovered experimentally for a cutting regime in [12] and was connected with the occurrence of a waveguide regime of radiation propagation in the cavity.

Our study showed that the rereflection of rays from the side walls may have a significant effect on the dynamics of the destruction of metals. The role of these reflections increases with a decrease in the coefficient of absorption of radiation on the surface of the target. Figure 7 shows the dependence of the rate of deepening of the cavity on the depth of the cavity, with the dashed line showing the monotonically decreasing relation obtained in [1] when rereflection of rays was ignored. The sharp increase in $\dot{h}$ at $h \approx d$ is connected with the "capture" of radiation in the channel, while the decrease at large h is due to attenuation of light in the repeated reflections in the metallic waveguide that is the cavity. The ratio of the maximum rate of deepening of the cavity to the initial rate ($t \to 0$) obtained by calculation with $\zeta_0 = 2.5 \cdot 10^{-2}$ reaches a value on the order of 10. This result agrees well with the experimental value of this quantity obtained in the case of interaction of radiation from a periodic-pulse CO_2 laser with stainless steel [4, 5].

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LITERATURE CITED

1. S. I. Anisimov, Ya. Imas, Yu. S. Romanov, and G. V. Khodyko, Effect of Powerful Laser Radiation on Metals [in Russian], Nauka, Moscow (1970).
2. A. A. Vedenov, Physics of Electric-Discharge CO_2 Lasers [in Russian], Énergoizdat, Moscow (1982).
3. C. Banas, "High-power laser welding," Opt. Eng., 17, No. 3 (1978).
4. A. A. Vedenov, G. G. Gladush, et al., "Physical processes in the deep penetration of a laser beam into metals," Izv. Akad. Nauk SSSR, Ser. Fiz., No. 8 (1983).
5. P. C. Hamilton and I. R. Pashby, "Hole drilling studies with a variable pulse length CO_2 laser," Opt. Laser Technol., No. 8 (1979).
6. G. G. Gladush, A. A. Ezhov, E. B. Levchenko, and A. N. Yavokhin, "Theoretical examination of the channeling of a laser beam during deep melting," in: All-Union Conference on the Application of Lasers in Machine-Construction Technology, Nauka, Moscow (1982).
7. A. A. Vedenov and E. B. Levchenko, "Limiting depth of penetration of a laser beam into an absorbent medium," Kvantovaya Elektron., 12, No. 10 (1983).
8. H. Maruo, I. Miyamoto, and Y. Arata, "Mechanism of welding with a CO_2 laser," Tool Eng., 25, No. 6 (1981).
9. A. A. Vedenov, G. G. Gladush, et al., "Study of the destruction of metals by radiation from a pulse-type CO_2 laser," Kvantovaya Elektron., 8, No. 10 (1981).
10. L. D. Landau and E. M. Lifshitz, Continuum Electronics [in Russian], Nauka, Moscow (1982).
11. Y. Arata and I. Miyamoto, "Some fundamental properties of high power laser beam as a heat source (Report 1). Beam focusing characteristics of CO_2 laser," Trans. Jpn. Weld. Soc., 3, No. 1 (1972).
12. F. O. Olsen, "Studies of sheet metal cutting with plane-polarized CO_2 laser," in: Opt. Elektron. Tech.: Vortr. 5. Int. Kongr. "Laser 81," Munich, 1981, Berlin et al. (1982).