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PLASMA DYNAMICS OF OPTICAL BREAKDOWN DURING DEEP MELTING OF METALS

R. V. Arutyunyan, L. A. Bol'shov,
M. F. Kanevskii, K. A. Krivoruchko,
V. P. Reshetin, and R. I. Soloukhin*

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The perspectives for using pulsed-periodic CO_2-lasers for dimensional machining (laser cutting, welding, and drilling) has stimulated experimental and theoretical studies for the reaction of pulsed-periodic (PP) radiation with metals. A thermohydrodynamic (TH) model was developed in [1-4] for deep melting by pulsed-periodic radiation. According to [1-4] movement of melt in the cavity is cyclic. Retention of the melt on walls occurs as a result of vertical melt acceleration during the vapor pressure pulse and subsequent retardation of its movement by gravitation and capillary forces. The average temperature in the optimum regime for reaction is close to the melting temperature $T \sim T_m$. Equations for thermal balance within the model of a linear heat source and melt movement [1-4] make it possible to determine the optimum energy E and pulse frequency f, and to study their dependence on depth h, cavity radius a, beam displacement velocity v and target thermophysical properties, shape and duration of the radiation pulse. In particular, with prescribed cavity parameters a and h and velocity v the optimum laser pulse (LP) energy is only governed by its duration.

Within the limits of the TH-model for deep melting by PP-radiation it was assumed a priori that the required energy was put into the cavity and its absorption over the depth was uniform. The question remains open about whether radiation parameters are sufficient for melting large thicknesses of metal taking account of radiation propagation through the plasma above the metal surface and within the deep melting channel.

The plasma of optical breakdown above the metal surface may transform considerably the space-time structure of the laser pulse up to complete screening of the cavity. Currently the question of passage of a LP through a jet with different duration of pulses and the provisional shape of them has not been studied sufficiently either theoretically or experimentally. However, the effect of the jet above the metal surface with deep melting may be avoided by reducing the pressure and selecting the surrounding gas and the provisional shape of the pulse. For example, for radiation pulses with a leading spike with an intensity exceeding the threshold for a light-detonation wave (LDW) a regime appears to be possible when the "tail" of radiation pulses passes through the LDW plasma channel and when its expansion leads to almost complete restoration of transparency. Limitations connected with the radiation propagation processes within the deep melting cavity and optical breakdown in a vapor-gas mixture in the channel are fundamental in character.

Numerical calculation of CO_2-radiation propagation by the procedure in [5] in metal channels with a shape close to that observed experimentally in welding with considerable tapering (~20) indicate that LP self-absorption at the walls of the channel in the absence of optical breakdown is small (at the level of 10%) and it does not provide uniform insertion of a significant part of the energy.

One of the mechanisms for putting LP energy in effectively may be release of absorbed energy by the plasma within the deep melting cavity. With this approach limitations develop on the pulse duration τ_u, and from the selection of optimum curves for energy and pulse repetition frequency corresponding to different τ_u, one is separated.

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*Deceased.

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In order to solve the question of the optimum time for operation it is possible to draw on the following ideas. In regimes which are optimum from the point of view of melting and melt movement the average laser radiation current for the time of pulse operation varies as a rule within the limits 1-100 MW/cm^2. Close to the bottom of the cavity with these radiation currents there is optical breakdown as a result of which a vapor-gas plasma layer forms which is not transparent for laser radiation. Depending on the initial gas pressure filling the cavity and the laser radiation current, plasma front propagation proceeds in a light combustion [5, 6] or detonation [7] regime. The gas plasma temperature does not exceed values of the order of magnitude of 2.5-3.5 eV. Plasma jet movement rate along the channel may be estimated as follows. In the case when laser radiation intensity is constant with time and the channel radius changes weakly ("needle" melting [8]) the plasma front propagation rate is of the order

$$v_f = \left(\frac{2(\gamma-1)}{\gamma(\gamma+1)}\frac{I}{\rho_0}\right)^{1/3} \tag{1}$$

(ρ_0 is the initial gas filling density). With laser radiation currents less than the threshold values for the occurrence of detonation ahead of the plasma front there is propagation of a shock wave. Almost complete absorption of laser radiation occurs in the plasma layer with a temperature of 1.5-2 eV. It is noted that the rate of optical discharge front propagation along the channel changes markedly, even with the operation of laser radiation currents which are constant with time. After emergence of the shock wave from the channel the plasma front propagation rate decreases. Certain features in plasma dynamics for the optical breakdown occur in deep channels ($h \sim$ 5-10 cm). Here as the distance between the shock wave and the plasma front increases there is pressure leveling behind the shock-wave front; the rate of optical discharge front movement along the channel falls. Various situations, including a changeover from a light combustion to a detonation combustion regime occurs with pulsed operation.

At the start of laser pulse operation with a duration of 10-1000 μsec (with radiation current exceeding the value of ~1 MW/cm^2) a layer of screening plasma forms in the channel [9]. As a result of this only a small amount of the laser pulse reaches the bottom of the cavity and is absorbed. There may also be a marked reduction in laser radiation absorption in the walls of the channel [10]. As an example we point out that with "needle" melting and use of CO_2-laser beams with convergence angles of $\sim 10^{-3}$ the proportion of radiation absorbed in the walls of a channel with diameter ~1 mm and with a depth of several centimeters is not more than 1-3%. Under these conditions laser radiation is absorbed in the optical discharge plasma layer, and wall heating occurs due to absorption of plasma self-radiation.

We estimate losses of laser plasma connected with absorption of its self-radiation in the walls. First of all it is noted that in spite of the fact that the intensity of plasma self-radiation q is as a rule less than laser intensity I, total currents of self-radiation at the walls and laser radiation across the transverse section of the channel are comparable with $q \sim Ia/\ell << I$ ($a << \ell$, ℓ is width of the plasma front). With a constant laser radiation current the temperature of the plasma is of the order of $T \sim (\mu/R)[(\gamma - I)I/\rho_0]^{2/3}$, where μ is molecular weight; R is universal gas constant. The plasma of an optical discharge transforms laser radiation with a low angle spectrum into self-radiation with a wide angle spectrum. In a deep channel ($h/a >> 1$) due to the large number of reflections from the walls ($\sim h/a$) self-radiation is almost completely absorbed ($(1 - r)h/a \sim 1$, r is wall reflection factor). During plasma front movement along the channel gas plasma losses are of the order of $2\pi a \ell h q/v_f$. By using an estimate for the self-radiation current $q \sim \sigma T^4 \alpha$ [$\alpha \sim \min(ka, 1)$ (k is average Planck absorption factor] and the plasma temperature, it is possible to establish that total losses by self-radiation are comparable with the energy put into the plasma ($I\pi a^2 h/v_f$) with a laser radiation intensity

$$I \gtrsim \left(\frac{R}{\mu}\right)^{12/5}\left(\frac{a}{\alpha\sigma l}\right)^{3/5}\left(\frac{\rho_0}{\gamma-1}\right)^{8/5}. \tag{2}$$

For typical values $a/\ell \sim 1/20$, $\rho_0 \sim 1$ kg/m^3, $\alpha \sim 1$ condition (2) is fulfilled starting with a laser radiation intensity of the order of 3 MW/cm^2. Thus, in cases of practical interest when pulse duration and energy are the optimum for melting and melt movement, channel wall heating occurs during optical-discharge front propagation along the channel. With $\tau_u < h/v_f$ only the part of the channel adjacent to the bottom warms up. With operation of long pulses ($\tau_u > h/v_f$) after arrival of the plasma front at the exit from the channel, plasma transparency is restored after $\sim \ell/v_f$. A corresponding part of the laser pulse is screened and it does not enter into the channel. The optimum laser pulse duration thus in order of magnitude coincides with the time for plasma front movement along the channel:

$$\tau_u \approx h/v_f. \tag{3}$$

By using Eqs. (1) and (3) it is easy to find that

$$\tau_u \sim \left[\frac{\gamma(\gamma+1)}{2(\gamma-1)}\right]^{1/2} h^{3/2} a \rho_0^{1/2} E^{-1/2} \tag{4}$$

(E is laser pulse energy). Equation (4) establishes the relationship between pulse energy and duration in a channel with prescribed a and h. With $h \sim 5$ cm, $a \sim 0.25$ cm, $\rho_0 \sim 1$ kg/m^3, $v \sim 1$ cm/sec, $\gamma = 1.2$, $E \sim 40$ J the optimum pulse duration in order of magnitude is ~100 µsec.

During numerical study of the thermal effect of a laser beam on the channel walls the following model was used. Laser radiation propagation is described in a parabolic approximation taking account of absorption at the channel walls [5, 10]. Movement of the optical breakdown plasma is described by equations of radiation gas dynamics for whose solution a unidimensional variant of the coarse particle method is used. Transfer of self-radiation is described in a diffusion approximation correspondingly for the quanta of two groups of energy spectra: 0.015-7 and 7-18.6 eV. In metal channels self-radiation is absorbed as a result of some reflections from the walls traveling a distance in the plasma in order of magnitude equal to $a/(1 - \langle r(\omega, \theta)\rangle)$ ($\langle r(\omega, \theta)\rangle$ is reflection factor averaged for angular and energy spectra of self-radiation). In channels with a quite small radius a, $\langle \varkappa(\omega, p, T)\rangle/(1 - \langle r(\omega, \theta)\rangle) \ll 1$, ($\langle \varkappa(\omega, p, T)\rangle$ is the absorption factor for self-radiation averaged for beam path and energy spectrum) it is possible to ignore reabsorption of self-radiation reflected from the walls. Thus, in numerical calculations it is possible to use a simple absorption model for self-radiation in the channel walls by assuming that $r_{eff}(\omega, \theta) = 0$. With the aim of simplification it is assumed that the channel internal diameter is constant. Values of a and h relate to typical channel dimensions occurring with deep melting. Since during reaction of radiation with the walls metal evaporation is not considered, the different gas medium conditions in the channel were modeled by a change in initial gas pressure. It is natural that this situation limits the field of application for the model, which in cases of interest from a practical viewpoint only establishes the qualitative regularities. In describing the thermodynamic condition of an air plasma use is made of quite accurate approximation tables from a well-known reference book [11]. Optical properties of the plasma are considered in accordance with the tables in [12].

A detailed account of the calculation procedure used in present work is provided in [13, 14]. In particular, as test problems, calculations were carried out for subsonic laser wave absorption of plane geometry (stream of self-radiation in the radial direction equals zero). Comparison of them with an experiment and more detailed calculations [15, 16], in which multigroup approximation of the transfer of self-radiation with a special refinement of the network in the plasma front region was used, showed an acceptable accuracy for the procedure (the maximum difference in determining temperatures was about 20-30%).

Several series of numerical calculations were carried out with an initial air pressure from 10^4 to 10^5 Pa and operation of laser radiation pulses of rectangular shape ($\lambda = 10.6$ µm). On the whole energy release at the channel walls corresponds to the qualitative picture which is described above, although the quantitative differences may be quite large. For example, the front propagation rate for optical breakdown in the stage of establishing screening differs markedly from values calculated by Eq. (1). This difference is observed after emergence of the shock wave from the channel when plasma front propagation proceeds in an absorption regime for subsonic laser waves [6].

Shown in Fig. 1 are distributions for energy release along the length of the channel ($a = 0.125$ cm, $h = 5$ cm, $p = 10^5$ Pa) with operation of a laser radiation pulse ($\lambda = 10.6$ µm) of rectangular shape with duration $\tau_u = 210$ and 66 µsec (lines 1 and 2) and intensity $I = 10$ MW/cm^2. In accordance with qualitative ideas during operation of short light pulses the plasma only travels a certain part of the channel; it cools off and heats sections of the channel close to the bottom. With operation of long pulses the channel warms up over the whole length. However, if the pulse duration exceeds the time in which the optical discharge front reaches the exit from the channel, then from this instant the laser beam is screened by plasma. The screening duration is in order of magnitude $\sim \ell/v_f$ (20 µsec), after which transparency is restored.

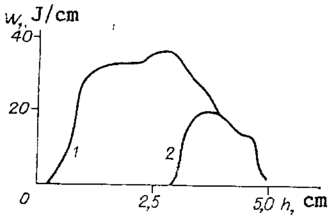

Fig. 1

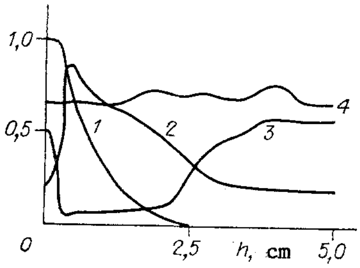

Fig. 2

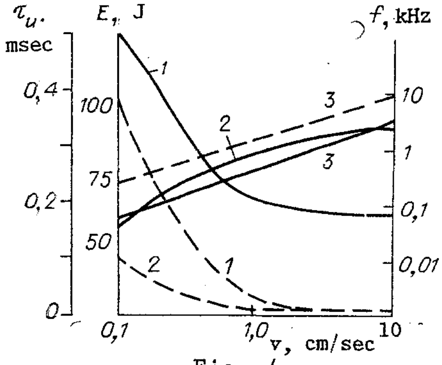

Fig. 4

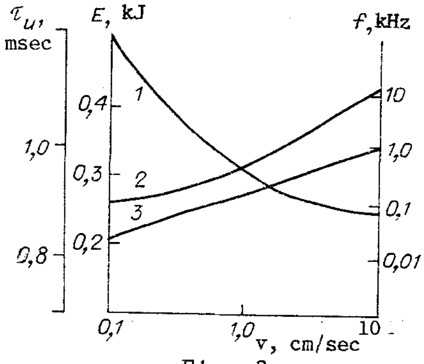

Fig. 3

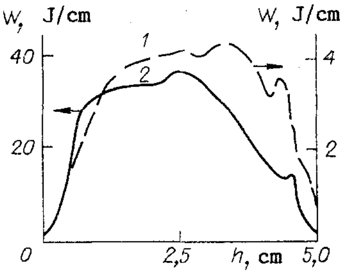

Fig. 5

Presented in Fig. 2 are distributions of laser radiation intensity 1, temperature 2, density 3, and pressure 4 along the channel length (a = 0.125 cm, h = 5 cm) at instant of time τ = 210 μsec with I = 10 MW/cm^2, when the plasma front is at the exit. The dimensionless unit on the graph corresponds to $p = 4 \cdot 10^5$ Pa, ρ_0 = 0.129 kg/m^3, T = 40 kK, I = 10 MW/cm^2. Pressure behind the front levels off; in essence optical discharge propagation depends on operation of plasma self-radiation which ionizes a cold layer of air ahead of the front.

In [1-4] the energy and frequency of a sequence of laser pulses of fixed duration which are the optimum for melting were determined. By drawing attention to the fact that the optimum laser pulse duration coincides with the time for optical-discharge front propagation along the channel, it is possible to find pulsed-periodic radiation parameters which are optimum for welding metal at a prescribed rate. Given in Fig. 3 are dependences of pulsed-periodic radiation parameters on welding rate with initial pressures in the channel $p = 10^5$ and $5 \cdot 10^4$ Pa (solid and broken lines) for a = 0.125 cm, h = 5 cm (1 is energy, 2 is duration, 3 is frequency of pulse sequence). The same dependences for a channel with a = 0.25 cm, h = 10 cm, and $p = 10^5$ Pa are given in Fig. 4. A qualitative idea of the effect of initial gas pressure on calculated parameters may be obtained from Fig. 5 which shows the distribution of energy release along the length (a = 0.125 cm, h = 5 cm) with I = 10 MW/cm^2, τ = 36 and 210 μsec, $p = 10^4$ and 10^5 Pa (lines 1 and 2) to the start of emergence of plasma from the channel.

With a "needle" shape for the channel the depth of melting is limited by optical breakdown. Screening of laser radiation by a breakdown plasma prevents penetration of the laser beam to a considerable depth. In the model suggested transfer of liquid phase from the channel is assumed to be negligibly small. The conditions with which channel wall heating by plasma self-radiation does not lead to melt splashing are determined within the limits of the TH-model for deep melting in [1, 4]. During laser welding of metals there is an overflow of melt from its leading wall to the trailing wall.

The results presented in the current work may be used for estimating pulsed-periodic radiation parameters with laser dimensional machining of metals.

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