

INTERACTION OF LASER RADIATION WITH MATTER. LASER PLASMA
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Calculation of mass transfer in the remote cutting of metals by radiation of a high-power repetitively pulsed CO_2 laser

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***Abstract*. The mechanism of remote cutting of steel plates by radiation of a high-power repetitively pulsed CO_2 laser is theoretically studied. The models of melt removal by the gravity force and the recoil pressure of material vapour are proposed and the sufficient conditions for the initiation of cutting are determined. A numerical model of a thermally thin plate was employed to describe the cutting for large focal spots.**

Keywords: *repetitively pulsed laser radiation, cutting of metals, CO_2 laser*.

1. Introduction

The use of repetitively pulsed (RP) laser radiation for remote cutting of metals (cutting without a gas jet) was proposed in Ref. [1] in the hope of enhancing mass transfer owing to the vapour recoil pressure. If the off-duty ratio for laser radiation is high, the intensity during a laser pulse can indeed be rather high even for a large focal spot, which will cause the plate surface to 'boil up' for a short time.

In Ref. [2], the mechanism of remote cutting of steels by the RP radiation of a CO_2 laser was studied by modelling this process with the aid of a CO_2 laser with an output power up to 500 W. The experiments were conducted on thin (~ 0.5 mm) plates. The focal spot diameter was so selected that the laser radiation intensity at the metal was close to the intensity of a high-power RP MLTK-50 CO_2 laser. The specific power P/h and the off-duty ratio $(\tau f)^{-1}$ were also taken to be close to the corresponding MLTK-50 parameters (h is the plate thickness, τ is the pulse duration, and f is the pulse repetition rate).

As shown in Ref. [2], the power spent for vaporising a material in the RP mode is compensated for by a more intense mass transfer, so that the efficiency of this remote cutting can exceed the efficiency of cutting by cw radiation [3, 4]. The mechanism of RP remote cutting was proposed in Ref. [4]. Its quantitative model, which involved the consideration of heat propagation along a thermally thin plate, was in satisfactory agreement with experiment. This model can be employed to calculate the cutting of thin steel plates by high-power RP radiation ($h < r_b$, r_b is the focal spot radius).

Unfortunately, the thermally thin plate approximation is not always applicable. For instance, it does not apply when a plate of maximum thickness should be cut for a given output power. Moreover, searching for efficient cutting modes and choosing the optimal parameters calls for an analytical model, which would serve as a guide in a variety of parameters characterising the remote cutting by RP radiation.

Our work is devoted to the study of the properties of remote cutting of steels by the radiation of a high-power CO_2 laser and the development of models of this process both for thin and thick plates. Before considering the cutting in these cases, we analyse the kinds of melt flow under different conditions.

2. Mechanism of melt flow

The excitation of melt flow by a laser beam with a large focal spot and a moderate intensity has several features which distinguish it from the modes considered in the literature. Because of the large focal spot and a short laser pulse duration, the inviscid flow resulting in this case will be transient [5]. As shown below, the melt does not manage to solidify during the interpulse period because of the high average output laser power, so that the liquid may have time to flow out from force of inertia during the pause, provided the outflow time is $r_m/V < 1/f$ (r_m is the radius of the melt region and V is the melt flow velocity).

Consider the threshold of cutting initiation, i.e. the minimal output laser power at which the cutting with a given speed begins. In this case, the metal vapour escapes from the surface with a subsonic velocity and the recoil pressure p decreases rapidly with decreasing the absorbed power [6]:

$$p = \left(\frac{q_v}{L}\right)^2 \frac{kT_b}{p_a m}, \tag{1}$$

where m is the mass of material vapour atoms; p_a is the atmospheric pressure; L is the specific sublimation energy; T_b is the material boiling temperature; and k is the Boltzmann constant.

This limits the power density expended for evaporation [6]

$$q_v < c_s L \frac{p_a}{kT_b} m, \tag{2}$$

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where c_s is the sound velocity in the vapour. Because of the low liquid velocity, a pulsation regime will be settled in the melt volume, with the average flow velocity determined by the averaged Bernoulli equation. Taking into account expressions (1) and (2), it is easy to derive the expression for the average velocity of this flow

$$\bar{V} = \left[2\left(\frac{q_v}{L}\right)^2 \frac{kT_b}{p_a} \frac{(\tau - t_b)f}{m\rho}\right]^{1/2}, \tag{3}$$

where t_b is the time required to heat the surface to the boiling temperature and ρ is the density of the plate material. Since our concern is the initiation of cutting with a speed (equal to the melt flow velocity), which is practical interest ($V \geqslant 0.5$ mm s^{-1}), and samples with a thickness of over 5 mm, the melt flow will be inviscid, which was assumed in the derivation of expression (3). All the aforesaid applies to the plate region which is not melted all the way through, and therefore we will use these results in the consideration of remote cutting of thick plates. The cutting of thin plates by high-power RP radiation will be studied using the model of a thermally thin plate developed for a laser with a moderate output power.

3. Model of the remote cutting of thick plates

It is *a priori* clear that the situation with the cutting of plates whose thickness is comparable with the characteristic width of the cut is rather complicated because the number of physical processes involved is large and it is difficult to describe them quantitatively in the three-dimensional geometry. However, this situation is interesting from the practical viewpoint, because it is important to know how thick the cut can be for given parameters of laser radiation and a given cutting velocity.

It is evident that the initiation of cutting requires that the plate should melt all the way through and the material should be removed from the melt volume by the end of irradiation time $t_{end} \sim d_b/V$. Both processes can occur simultaneously, resulting in a complex three-dimensional shape of the melt volume. Problems of this kind require time consuming numerical calculations. We will restrict ourselves to a simplified consideration of cutting initiation and in so doing will attempt to elucidate only the qualitative features. Accordingly, the processes of heat and mass transfer will be assumed to go on independently. In this case, we will evidently obtain the peak power required for cutting plates of a given thickness.

To determine the conditions for melting through, we will use the expression for the temperature distribution in a plate approaching a beam with a velocity V (the cutting speed) along the coordinate x [5]:

$$T(x,y,z) = \frac{1}{\varkappa}\left(\frac{\chi}{\pi^3}\right)^{1/2} \bar{P} \int_0^\infty \mathrm{d}\tau \sum_{n=0}^{\infty} \left\{ \exp\left[-\frac{(z+2hn)^2}{4\chi\tau}\right] + \exp\left[-\frac{[z-2h(n+1)]^2}{4\chi\tau}\right] \right\} \left[\tau^{1/2}(r_b^2 + 4\chi\tau)\right]^{-1} \times \exp\left[-\frac{(x+V\tau)^2 + y^2}{r_b^2 + 4\chi\tau}\right], \tag{4}$$

where z is the coordinate directed inward the plate; χ is the thermal diffusivity; $\varkappa$ is the thermal conduction coefficient; $T(x, y, z)$ is the temperature of the plate material; and $\bar{P}$ is the average absorbed laser radiation power.

We should find the coordinate x_0 for which the melting is deepest. In this case, the average power should be so selected that this maximum melting depth is equal to the plate thickness. By doing so we will derive the melting–through conditions depending on the velocity, the plate thickness, and the focal spot dimension. Because expression (4) is cumbersome, there is no way to analytically obtain the expressions for x_0 and the melting–through power even for a minimal number of the series terms. That is why these quantities were obtained numerically. The absorbed power $\tilde{P}_1$ required to melt the bottom of a plate is plotted in Fig. 1.

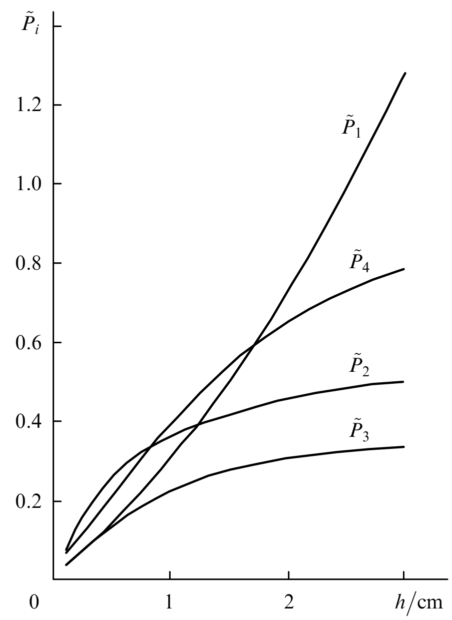

Figure 1. Radiation powers $\tilde{P}_i$ required for the remote cutting of steel plates of different thickness for a cutting speed of 1 mm s^{-1}, $f = 100$ Hz, $\tau = 170$ μs, and $r_b = 1$ cm; $\tilde{P}_i = \bar{P}_i/2\pi^{3/2}\varkappa T_m$ is the normalised absorbed power (T_m is the material melting temperature).

In order for the liquid metal to manage to flow out during the irradiation time d_b/V, the liquid velocity should be no less than the velocity of plate motion, i.e., the cutting velocity. For a low radiation power, we will use expression (3), where the boiling time t_b can be found from the known formula, which determines the surface temperature under pulsed heating [5]:

$$t_b = \frac{\pi^2\varkappa^2\Delta T^2(f\tau)^2 r_b^4}{\bar{P}^2\chi}. \tag{5}$$

In our case, the fluctuation of the surface temperature is $\Delta T = T_b - \bar{T}$, where $\bar{T}$ is the average surface plate temperature in the irradiation region. Let $\bar{P}_2$ denote the average power for which the surface under irradiation is heated to the boiling temperature by the end of every pulse. Putting $t_b = \tau$, we obtain from expression (5)

$$\bar{P}_2 = \pi\varkappa(T_b - \bar{T}) r_b^2 f \left(\frac{\tau}{\chi}\right)^{1/2}. \tag{6}$$

The average surface temperature $\bar{T}$ depends on the plate thickness and other parameters of the problem. When the absorbed laser power exceeds $\bar{P}_2$, all the 'excess' power is spent to vaporise the material:

$$\bar{P}_{\rm v} = \bar{P} - \bar{P}_2 \,. \tag{7}$$

The intensity $q_{\rm v}$ which enters in expressions (1)–(3) is determined by the power $\bar{P}_{\rm v}$:

$$q_{\rm v} = \frac{\bar{P} - \bar{P}_2}{\pi r_{\rm b}^2 (\tau - t_{\rm b}) f} \,. \tag{8}$$

By substituting (8) into (3), we obtain the condition that the liquid melt manages to flow out during the irradiation time. The critical power $\bar{P}_{\rm cr}$ at which the melt is removed is determined from the equation:

$$\frac{V^2 p_{\rm a} m\rho L^2/2}{kT_{\rm b}} = \frac{(\bar{P}_{\rm cr} - \bar{P}_2)^2}{(\pi r_{\rm b}^2)^2 f (\tau - t_{\rm b})} \,. \tag{9}$$

Taking into account (5) and (6), we obtain from Eqn (9) for $h \to 0$ and $\bar{P}_2 \to 0$ the limiting expression for the critical average power:

$$\bar{P}_{\rm cr} = \frac{VL}{2}\,\pi r_{\rm b}^2 (f\tau)^{1/2} \left(\frac{p_{\rm a} m\rho}{kT_{\rm b}}\right)^{1/2} . \tag{10}$$

In the opposite case, when $\bar{P}_{\rm cr} = \bar{P}_2 + \Delta p$, $\Delta p / P_2 < 1$, the power $\bar{P}_{\rm cr}$ is approximately determined from Eqn (9):

$$\bar{P}_{\rm cr} = \bar{P}_2 + \frac{2V^2 (\pi r_{\rm b}^2)^2 f\tau}{\bar{P}_2} \left(\frac{p_{\rm a} m\rho}{kT_{\rm b}}\right) \frac{L^2}{2} \,. \tag{11}$$

Let us return to the expression for the radiation power $\bar{P}_2$ at which the surface begins to boil by the end of the pulse. To derive this expression, we should find the average surface temperature in the focal spot, for which purpose we will use integral (4) for $x = y = z = 0$:

$$\bar{T} = \frac{\bar{P}}{2\pi^{3/2}\varkappa} \frac{I_1(h)}{h} , \tag{12}$$

where

$$I_1(h) = \frac{2\pi^{3/2}\varkappa T_{\rm m} h}{\bar{P}_3}$$

was calculated numerically. It is evident from the structure of expression (4) that the characteristic quantity $I_1(h)$ will depend on two dimensionless parameters: $r_{\rm b}/h$ and $hV/4\chi$. The function

$$\frac{h}{I_1(h)} = \frac{\bar{P}_3}{2\pi^{3/2}\varkappa T_{\rm m}}$$

is shown in Fig. 1. One can see that it is linear for small h and saturates with increasing h. For small h, the surface temperature should be close to the temperature of the bottom of a plate, which is observed in Fig. 1. Therefore, under our conditions, the plate can be considered as a thermally thin one up to $h \leqslant 7$ mm. This value is close to the thickness limitation obtained from simple estimates. Note that there exists an expression for $\bar{P}_1$ and $\bar{P}_3$ in a thermally thin plate [7]

$$\bar{P}_1 = \bar{P}_3 = 2\pi h \varkappa T_{\rm m} \left(\ln\frac{4\chi}{Vr_{\rm b}} - 0.16\right)^{-1} .$$

By substituting expression (12) into (6), we obtain

$$\frac{\bar{P}_2}{\bar{P}_3} = \frac{\pi\varkappa r_{\rm b}^2 (\tau f)(\chi\tau)^{-1/2} T_{\rm b}}{\pi\varkappa r_{\rm b}^2 (\tau f)(\chi\tau)^{-1/2} T_{\rm m} + \bar{P}_3} \,. \tag{13}$$

One can see from Fig. 1 that for our parameters the curve described by expression (13) is approximately 1.5 times higher than the curve representing the power $\bar{P}_3$, at which the average temperature in the focal spot is equal to the melting temperature. According to estimates by expression (11), to remove the melt due to vapour recoil pressure under our conditions, we need only slightly exceed the power $\bar{P}_{\rm cr} \approx \bar{P}_2$, at which the surface in the focal spot begins to boil by the end of a pulse.

4. Effect of the gravity force on the melt removal

If the plate is mounted vertically and the laser beam is horizontal, the gravity force can also participate in the melt transfer. Recall that the gravity force plays a decisive role in this process in the remote cutting of steels by cw laser radiation. To include the effect of gravity, we will use the model approach of Ref. [4], which gives a satisfactory agreement with experiment. We assume that all the melt is removed from a sample when the maximum vertical dimension of the melt region reaches the critical dimension $d_{\rm m}^*$. The magnitude of $d_{\rm m}^*$ was determined in Refs [3, 8]:

$$\frac{d_{\rm m}^*}{R_{\rm c}} = 4.4 \left(\frac{h}{R_{\rm c}}\right)^{1/3} \text{ for } \frac{h}{R_{\rm c}} < 0.75 \,,$$

$$\frac{d_{\rm m}^*}{R_{\rm c}} = 4 \text{ for } \frac{h}{R_{\rm c}} > 0.75 \,, \tag{14}$$

where σ is the surface tension coefficient of the melt; g is the acceleration of gravity; and $R_{\rm c} = (\sigma/\rho g)^{1/2}$ is the capillary radius. For iron, $d_{\rm m}^{*\,\rm max} \approx 1.5$ cm.

To calculate the threshold power at which the width (in the vertical direction) of the melt region reaches $d_{\rm m}^*$, we should find x_0 from Eqn (4), at which the width y_0 of the melt region is maximum, and then calculate this width. By equating it to $d_{\rm m}^*$, it is possible the determine the laser power $\bar{P}_4$ at which the melt will flow out of the interaction region. The curve $\bar{P}_4$ in Fig. 1 shows that the melt removal results in a through cut up to a plate thickness of ~ 1.7 cm. When the laser power is close to $\bar{P}_4$, for $h > 1.7$ cm the cut should be blind, because the melting will not be through by the instant of melt removal. When the power is close to $\bar{P}_1$, the cut should be through.

Therefore, one can see from Fig. 1 that up to $h \simeq 1.2$ cm the power thresholds for the melt removal by gravity and by vapour pressure are close in our conditions. In this case, after the melt removal, a through cut is obtained, because the plate is melted all the way through. For a higher plate thickness, the surface 'boils up', but the plate is not melted all the way through, and therefore $\bar{P} \simeq \bar{P}_2$ and the cut will be blind. By increasing the power to $\bar{P}_1$, one would expect a through cut. Finally, for $h > 1.7$ cm and $\bar{P} \simeq \bar{P}_1$, both melt-removal mechanisms 'operate' and the cut should be through. Because $\bar{P}_1$ increases with h significantly faster than $\bar{P}_2$ and $\bar{P}_4$, the laser radiation power should be significantly (exponentially) increased to make a through cut in one pass.

It is clear from general consideration that all power thresholds will increase with increasing the cutting speed. The power $\bar{P}_1$, at which the bottom of a plate is melted, increases most with increasing cutting speed. Calculations show that, for example, a two-fold increase in the cutting speed raises the curves $\bar{P}_2 - \bar{P}_4$ by 20 % – 30 % and the curve $\bar{P}_1$ by a factor of two. For high speeds, $\bar{P}_4 > \bar{P}_2$, i.e., the cutting threshold under these conditions is determined by the melt removal due to the vapour pressure. It is evident from expressions (14) that remote cutting is easier to perform for a high off-duty ratio and that for equal off-duty ratios it is better to use longer pulse durations.

We considered above the picture of cutting initiation, i.e., the power thresholds of this process as functions of the plate thickness. Below, we will study the dependence of the cutting speed threshold on the focal spot dimension and some features of the cutting process for a thermally thin plate ($h = 7.5$ mm).

5. Thin plates

Because of the large dimensions of the focal spot of an MLTK-50 laser ($d_b > d_m^{*\max}$), we will use the modified model [2]: when the vertical dimension of the melt region exceeds d_m^*, the melt from the edges of a cut will be assumed to be instantly removed. Fig. 2 shows the results of calculations of cuts according to the model [2] for different thicknesses and speeds. The cut width decreases with increasing speed and plate thickness. Calculations of the cutting of a 5-mm thick plate with a speed of 1.3 mm s^{-1} showed that two thirds of the radiation pass through the cut. This radiation can be sufficient to cut simultaneously two more plates of the same type.

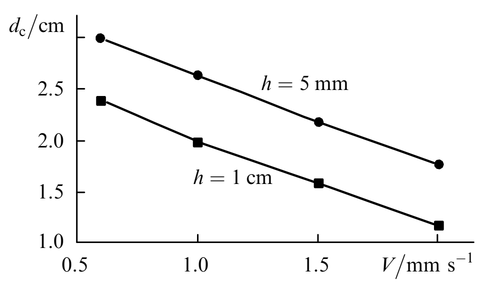

Figure 2. Dependences of the cut width d_c calculated as functions of the cutting speed for plates of different thickness h for an absorbed radiation power of ~ 4.5 kW, $f = 100$ Hz, $\tau = 170$ μs, and $r_b = 1$ cm.

It is interesting to compare the cutting by cw and RP high-power CO_2 lasers. It was shown in Ref. [2] that the RP cutting is more efficient that the continuous one for $P \leqslant 0.5$ kW. Fig. 3 shows the maximum cutting speeds calculated as functions of the focal spot dimension. This formulation of the problem can be quite important, because the focal spot diameter for an MLTK-50 laser setup under the real conditions of remote cutting is estimated as 1 – 3 cm [1]. For example, let the plate thickness be $h = 7.5$ mm, the absorbed power be ~ 4.5 kW, $\tau = 170$ μs, and $f = 100$ Hz. Recall that the critical melting width d_m^* at which the melt flows out under the gravity force in this case is 15 mm (see Section 4). Fig. 3 shows the dependences of maximum cutting speed on the focal spot diameter for RP and cw lasers having the same output power. Calculations revealed that the efficiencies of cutting are close for both lasers. It is likely that the energy expenditures to vaporise the material under these conditions do not result in an appreciable additional melt mass transfer.

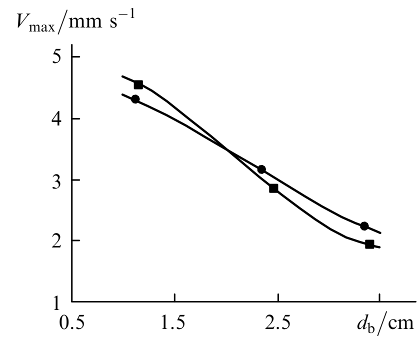

Figure 3. Limiting speeds V_{max} of cutting steel by cw (■) and RP radiation (●) calculated for different focal spot diameters, $h = 7.5$ mm, $f = 100$ Hz, $\tau = 170$ μs, and an absorbed radiation power of ~ 4.5 kW.

Consider the cut shapes in both cutting modes (by cw and RP radiation) for different dimensions of the focal spot. One can see from Fig. 4a that upon continuous irradiation of the plate, the cut shape is typical for this cutting mode [3, 4]. Steel flows out of the melt region after the latter has attained its maximum dimension d_m^*. In this case, the melt temperature at the symmetry axis at the instant of melt removal exceeds the melting temperature by about a factor of 1.5.

The cut width in the case of RP cutting is significantly smaller than for continuous cutting. The melt removal takes place sooner, before the region dimension has attained its limit d_m^* (Fig. 4b). Because of the losses due to evaporation, the maximum average melt temperature in this case is lower than in the continuous mode – it is close to the melting temperature. As the focal spot diameter increases, the radiation intensity lowers, as does the effect of vapour recoil. For this reason, the RP cutting initially resembles the cutting by cw radiation. Then, the plate heats up to increase the dimension of the boiling region, with the effect that the role of vapour pressure grows in importance. The mode of mass removal by gravity is replaced with the mode of mass transfer under the action of vapour recoil pressure. Therefore, the cutting parameters under consideration lie in the region of mode change, so that the limiting speeds of continuous and RP cutting differ insignificantly within the frameworkof our model.

6. Comparison with experiment

Experimental data on the remote cutting of metals using an MLTK-50 laser are scarce and are primarily technical in character due to the applied nature of the problem [9]. As for the scientific aspect of the question, it was reported in Ref. [9] that a 2-mm thick steel plate could be cut at a speed up to 2 mm s^{-1}. According to our model, an absorbed

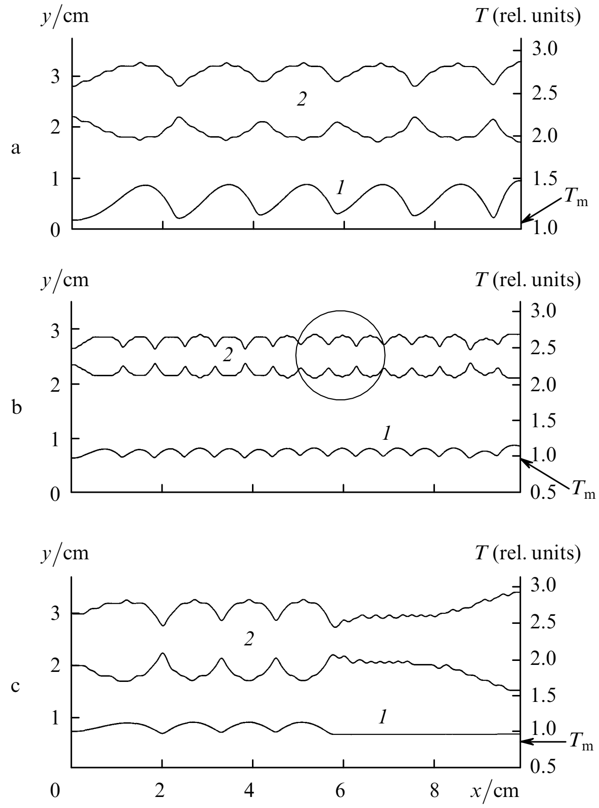

Figure 4. Calculated profiles of the temperature (*1*) at the instant of melt removal and the cut shapes (*2*) in the case of cw (a) and RP (b, c) irradiation for an absorbed radiation power of ~ 4 kW, $h = 7.5$ mm, $d_b = 1.5$ (a, b) and 2.5 cm (c); the remaining conditions correspond to Fig. 3. The circle indicates the focal spot shape.

power of 7 kW is sufficient to cut such a plate with a speed of 2 mm s^{-1} (see Fig. 1 and Section 4). This power value is less than the experimental absorbed power reported in Ref. [9], which indicates that this experimental point lies within the calculated range where cutting is realisable.

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