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Repetitively pulsed gas-jet laser cutting of metals in an oxygen-containing gas

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Abstract. A model of the repetitively pulsed gas-jet laser cutting of thick metals in an oxidising gas is developed. It is shown that the optimal choice of the time-dependent (radiation) and beam-focusing parameters will make it possible to increase the average cutting rate by a factor of 1.5 – 1.8.

Numerous original experimental and theoretical studies (see, for example, the bibliography in Refs [1, 2]) have been made of gas-jet laser cutting (GJLC) of metals. In view of the complexity and wide variety of the physical processes occurring under these conditions, a model of GJLC, permitting the selection of the optimal radiation parameters, has not yet been developed. The simplest physical GJLC models are based on an analysis of thermal processes [3, 4]. The absorbed laser radiation energy is consumed in heating the metal, from the initial temperature to the melting point, and as the latent heat of fusion. The liquid melt formed as a result is removed by an auxiliary gas jet either instantaneously or at a selected constant rate [5].

The GJLC efficiency falls and the required power increases on increase in the thickness of the sheet being cut. GJLC in an atmosphere containing oxidising gases is used to cut thick metal sheets. When air or oxygen is used as the working gas, a considerable proportion of the energy consumed in metal cutting is generated as a result of an exothermic oxidation reaction. This energy is comparable to the contribution made by the laser radiation energy. In addition, the radiation power may be reduced by employing a repetitively pulsed laser. A model of repetitively pulsed cutting based on the postulates formulated in Refs [6, 7] was developed in the present study.

At a sufficient oxygen concentration in the gas, the oxidation reaction rate is determined by the diffusion of oxygen through the oxide film; the rate of heat evolution is then inversely proportional to the thickness of the oxide film on the metal melt. The oxide film thickness depends in turn on the rate of film removal under the influence of thermocapillary forces proportional to the superheating of the melt. Since this is a self-consistent process with nonlinear relationships, one may postulate that the average characteristics of time-dependent repetitively pulsed cutting may differ from those of continuous cutting for identical average laser radiation powers.

We shall use a simplified formulation to consider time-dependent GJLC of steel in an oxidising atmosphere. We shall assume [7] that the melt is transferred only under the influence of thermocapillary forces in the horizontal direction and that it is possible to consider independently the planar problem for an individual horizontal cut section. Earlier estimates indicate that one may assume that the melt film is thin and that the flow in it is planar, and one may disregard the convective terms in the equations of motion and energy. Since the oxide film thickness is usually significantly less than the melt thickness, the rate of removal of the oxide may be determined from the rate of motion of the melt on the surface. The thermal and dynamic processes in the melt film will be considered in the one-dimensional approximation. The results of the calculations made within the framework of the model of continuous cutting in a nonoxidising atmosphere agree satisfactorily with experimental data [7].

We shall formulate time-dependent equations for the velocity and temperature distributions in the melt film and we shall apply the relevant boundary conditions at the bottom and on the surface of the film. To facilitate the numerical solution, we shall introduce a dimensionless coordinate directed across the melt film and equal to the ratio of the dimensional coordinate to the time-dependent thickness of the melt film: $y = y_0/\Delta_{\mathrm{m}}(t)$. The corresponding equations assume the following form:

$$\begin{gathered}\rho_{\mathrm{m}}\left(\frac{\partial u}{\partial t} - y\,\frac{\Delta'_{\mathrm{m}}}{\Delta_{\mathrm{m}}}\frac{\partial u}{\partial y}\right) = \frac{\mu_{\mathrm{m}}}{\Delta^2_{\mathrm{m}}}\frac{\partial^2 u}{\partial y^2}\,, \\ \rho_{\mathrm{m}} c\left(\frac{\partial T}{\partial t} - y\,\frac{\Delta'_{\mathrm{m}}}{\Delta_{\mathrm{m}}}\frac{\partial T}{\partial y}\right) = \frac{\lambda_{\mathrm{m}}}{\Delta^2_{\mathrm{m}}}\frac{\partial^2 T}{\partial y^2}\,,\end{gathered} \tag{1}$$

where $0 \leqslant y \leqslant 1$. The boundary conditions on the metal – melt and melt – oxide interfaces are formulated in the following form:

$$\begin{gathered}u = 0\,, \qquad T = T_{\mathrm{m}}\,, \\ \frac{\lambda_{\mathrm{m}}}{\Delta_{\mathrm{m}}}\frac{\partial T}{\partial y} - \rho_{\mathrm{m}} c (T_{\mathrm{m}} - T_{\infty}) = \rho_{\mathrm{m}} H_{\mathrm{m}} V\end{gathered} \tag{2}$$

for $y = 0$ and

$$\begin{gathered}\frac{\mu_{\mathrm{m}}}{\Delta_{\mathrm{m}}}\frac{\partial u}{\partial y} = \frac{\sigma'_T}{d_0}(T - T_{\mathrm{m}})\,, \\ \frac{\lambda_{\mathrm{m}}}{\Delta_{\mathrm{m}}}\frac{\partial T}{\partial y} = A(\Delta_{\mathrm{ox}})Q_{\mathrm{L}}(t) + Q_{\mathrm{ox}}\end{gathered} \tag{3}$$

for $y = 1$. Here $u(t, y)$ and $T(t, y)$ are the velocity and temperature of the melt; $\Delta_{\mathrm{m}}(t)$ is the melt film thickness;

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$\varDelta'_m = d\varDelta_m/dt$; ρ_m, c, μ_m, and λ_m are the density, heat capacity, viscosity, and thermal diffusivity of the melt; T_m and H_m are the temperature and heat of fusion of the metal; σ'_T is the derivative of the surface tension with respect to temperature; V is the cutting rate; d_0 is the cut width; $Q_L(t)$ is the laser radiation intensity; $\varDelta_{ox}$ is the oxide film thickness; the absorption coefficient $A(\varDelta_{ox})$ was calculated for the laser radiation wavelength $\lambda = 10.6$ μm and a characteristic angle of incidence on the cut surface in the middle section amounting to 0.03 rad, which corresponds, for example, to the cut width $d_0 = 3$ mm when the thickness of the plate being cut is $h_0 = 0.1$ m.

The rate of formation of the oxide on the melt surface $Q_{ox} = H_{ox}\rho_m D_{ox}\delta Y_{ox}/\varDelta_{ox} Y_{ieq}$ is determined from the condition that it is limited by the diffusion of oxygen in the FeO oxide film during cutting in an oxygen atmosphere [7]. Here, H_{ox} and D_{ox} are the heat of the iron oxidation reaction and the diffusion coefficient of oxygen in the oxide at the temperature T_m; $Y_{ieq} \approx 0.23$ and $\delta Y_{ox} \approx 0.06$ are, respectively, the oxygen concentration in the liquid oxide, which is in a state of a local thermodynamic equilibrium with the metal, and the change in the oxygen concentration in the oxide.

The unknowns $\varDelta_m(t)$ and $\varDelta_{ox}(t)$ occur in the system of equations (1) and the boundary conditions are given by expressions (2) and (3). In order to determine them, we shall formulate the balance equations for the masses entering the melt and oxide films, and the equations for their removal under the influence of thermocapillary forces:

$$\frac{d\varDelta_m}{dt} = \frac{K_m}{\varDelta_m}\frac{\partial T(t,0)}{\partial y} - 2\frac{\varDelta_{ox}}{d_0}\int_0^1 u(t,x)\,dx\,,$$

$$\frac{d\varDelta_{ox}}{dt} = \frac{K_{ox}}{\varDelta_{ox}} - 2\frac{\varDelta_{ox}}{d_0}u(t,1)\,, \tag{4}$$

$$K_m = \frac{\lambda_m}{\rho_m}[H_m + c(T_m - T_\infty)]\,, \qquad K_{ox} = \frac{D_{ox}\delta Y_{ox}}{Y_{ieq}}\,.$$

Eqns (1) and (4) and the boundary conditions (2) and (3) form a closed system of equations. We shall write out the steady-state solution for $Q_L = Q_{Ls} = \text{const}$:

$$\varDelta_{ms} = \left(\frac{d_0^2\mu_m K_m}{\sigma'_T}\right)^{1/3},$$

$$\varDelta_{oxs} = \frac{H_{ox}\rho_m K_{ox}}{Q_{Ls}}\left\{\left[2\frac{\mu_m\lambda_m Q_{Ls}}{K_{ox}\sigma'_T}\left(\frac{d_0}{\varDelta_{ms}H_{ox}\rho_m}\right)^2 + 1\right]^{1/2} - 1\right\}, \tag{5}$$

$$V_s = \frac{K_{ox}}{\lambda_m}\left(Q_{Ls} + \frac{H_{ox}\rho_m K_{ox}}{\varDelta_{oxs}}\right).$$

The numerical results for the characteristic situation, analysed for the steady-state case in Ref. [7], are as follows: $Q_{Ls} = 1.5\times10^8$ W m^{-2}, $d_0 = 3$ mm, and cut height $h_0 = 0.1$ m. Under these conditions, we have $\varDelta_{ms} = 6.6\times10^{-5}$ m, $\varDelta_{oxs} = 6.2\times10^{-6}$ m, and $V_s = 1.8\times10^{-2}$ m s^{-1}.

We shall now consider the repetitively pulsed regime. We shall assume that the radiation intensity changes stepwise during a period τ, i.e. during the time $\tau\sigma$ (σ is the off-duty factor) the radiation intensity is Q_{Ls}/σ. Then, it is zero during the time $\tau(1-\sigma)$. Thus, the average radiation intensity during the period is Q_{Ls}, which is the intensity in the steady-state case.

The steady-state solution (5) was adopted as the initial condition for the time-dependent problem defined by the system of equations (1)–(4). We sought a quasi-steady-state solution by the steady-state method for the case when the time-dependent parameters averaged over a period cease to vary. The time-dependent problem (1)–(4) was solved numerically by a semi-implicit method. The system of equations (1) was solved by the sweep method employing a semi-implicit scheme, whereas the quantities $\varDelta_m$ and $\varDelta_{ox}$ occurring in the equations as coefficients were taken from the previous time step in the solution of the system of equations (5).

The ranges of variation of the time-dependent radiation parameters τ and σ were selected on the basis of the following considerations. The nonlinear influence of the transient conditions may result in a change in the heat flux from the oxidation reaction, determined by the oxide film thickness. Since the oxide thickness depends on the rate of motion of the melt on the surface, the characteristic time of the radiation intensity variation should be of the order of magnitude of the characteristic time for the establishment of the rate of movement of the melt in the film, i.e. $\tau\sigma = \rho_m\varDelta_m^2/\mu_m \approx 10^{-3}$ s. The range of periods for a given radiation intensity is limited from below by electric breakdown intensity in air (for the characteristic values adopted here, it is essential to ensure that $\sigma > 0.05$) and from above by the requirements imposed as regards the cleanness of the cut walls (minimal period and depth of surface irregularities).

The results of the calculations are presented in Figs 1–3. Fig. 1 illustrates the characteristic variation of the cutting rate and of the thicknesses of the melt and oxide in the quasi-steady-state regime ($\tau = 3\times10^{-3}$ s, $\sigma = 0.2$). Fig. 2

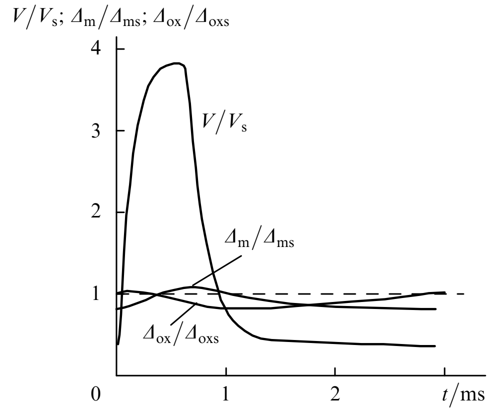

Figure 1.

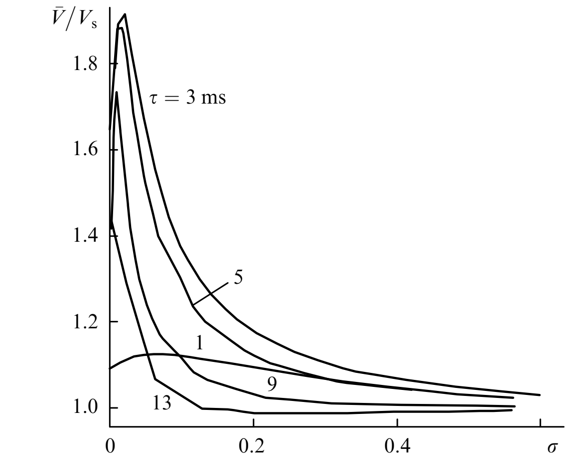

Figure 2.

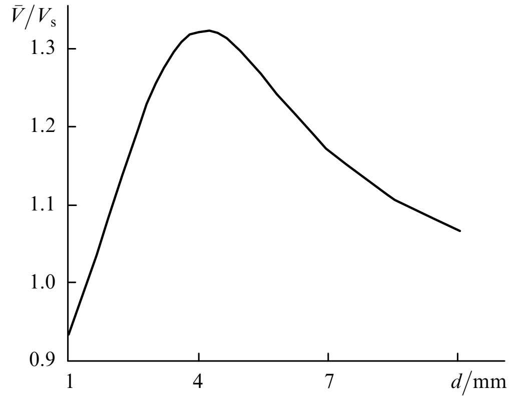

Figure 3.

illustrates the cutting rate, averaged over a period and compared with the cutting rate during continuous operation at the same radiation intensity, as a function of the off-duty factor for different periods. The dependence of the average cutting rate on the cut width d_0, modelling the influence of the radiation focusing, is shown in Fig. 3 for $\tau = 5$ ms and $\sigma = 0.1$.

It can be seen from the results of the calculations presented above that the repetitively pulsed regime may reduce or increase the average cutting rate, compared with the continuous regime. However, one may expect that the optimal selection of the time-dependent and beam-focusing parameters will make it possible to increase the average cutting rate by a factor of 1.5 – 1.8.

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