# MODELING OF METAL LASER CUTTING PROCESSES IN SUPERSONIC JET IN INERT GAS

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Up-to-date $CO_2$– lasers are widely used in laser treatment of materials (drilling, welting, cutting). Technical achievements of laser methods both in Russia and abroad are limited and have been applied only for some types of ferrous metals until now (iron, steel, stainless steel, electrical steel). A number of works reviewed in [1], cannot describe satisfactory the processes of gas-laser metal cutting, and this fact implies consideration of a great number of complex and interrelated processes.

In [2], an analysis of physical processes in the gas-laser cutting of metals was given and the problems of its mathematical simulation were formulated. Solving the problem on interaction of a supersonic gas jet with a plate having a cross-cut is complicated by a slot jet flow with turbulent boundary layers and a shock-wave system. A simplified problem formulation is considered in [2], Fig. 1. If the gas pressure in the cylinder $P_0$ is known and the ambient pressure $P_a$ is set, the gas parameters at the nozzle exit section are calculated by the following isoentropic formulas:

$$P_1 = P_0\left(1-\frac{k_g-1}{k_g+1}\lambda_1^2\right)^{k_g/k_g-1},\ \rho_1 = \rho_0\left(1-\frac{k_g-1}{k_g+1}\lambda_1^2\right)^{1/k_g-1}, \tag{1}$$

$$T_1 = T_0\left(1-\frac{k_g-1}{k_g+1}\lambda_1^2\right),\ \lambda_1^2 = \frac{k_g+1}{k_g-1}\cdot\left(1-\left(\frac{P_a}{P_0}\right)^{k_g-1/k_g}\right),\ V_1 = \lambda_1 a_c,\ a_c = \sqrt{\frac{2k_g}{k_g+1}R_g T_*}.$$

Here $P_1$, $\rho_1$, $T_1$, and $V_1$ are the pressure, density, temperature, and the gas velocity at the nozzle exit section, $k_g$ and $R_g$ is the ratio of specific heats and the gas constant, $\lambda_1$ is the superficial velocity, $a_c$ is the critical speed of sound, and $T_*$ is the stagnation temperature.

At $\lambda_1 > 1$, when the flow is supersonic, a standing shock arises between the nozzle and the plate. The parameters behind this shock are calculated by the formulas

$$\lambda_2 = \frac{1}{\lambda_1},\ P_2 = P_1\left(\frac{\lambda_1^2 - \dfrac{k_g-1}{k_g+1}}{1-\dfrac{k_g-1}{k_g+1}\lambda_1^2}\right),\ \rho_2 = \rho_1\lambda_1^2,\ T_2 = \frac{P_2}{\rho_2 R_g}. \tag{2}$$

In case the pressure gradient $-dP/d\xi = k \approx \Delta P/L = 0,5\rho_2 V_2{}^2/L$ ($L$ is a metal plate thickness) is constant, we obtain:

$$P = P_2 - 0,5\rho_2 V_2^2 \xi/L,\ V_g = V_2\left(1+0,5\xi/L\right),\ \rho = \rho_2/\left(1+0,5\xi/L\right),\ T_g = P/\left(\rho R_g\right). \tag{3}$$

Motion of the melt film is considered in the coordinate system $(\xi,\ \eta)$, connected with a cutting front surface, Fig. 1: $\xi = (x+\omega_0)\cos\alpha + z\sin\alpha,\ \eta = (x+\omega_0)\sin\alpha - z\cos\alpha$.

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**Abstract**

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$$\frac{\partial U}{\partial \xi}+\frac{\partial V}{\partial \eta}=0, \tag{4}$$

$$\rho_m\left(\frac{\partial U}{\partial t}+U\frac{\partial U}{\partial \xi}+V\frac{\partial U}{\partial \eta}\right)=-\frac{dP}{d\xi}+\mu_m\frac{\partial^2 U}{\partial \eta^2}, \tag{5}$$

$$\rho_m\left(\frac{\partial E}{\partial t}+U\frac{\partial E}{\partial \xi}+V\frac{\partial E}{\partial \eta}\right)=U\frac{dP}{d\xi}+\frac{\partial}{\partial \eta}\left(\rho_m\kappa_m\frac{\partial E}{\partial \eta}\right)+\mu_m\left(\frac{\partial U}{\partial \eta}\right)^2. \tag{6}$$

Here $U$, $V$ are the velocity vector components in the $\xi$ and $\eta$ directions, respectively, $E=c_mT$, $T$ is the temperature, $\rho_m$, $c_m$, $\mu_m$ are the density, specific heat capacity and viscosity of the liquid metal, $\kappa_m=\lambda_m/\rho_m c_m$ is the temperature diffusivity.

The moving boundary $\eta=0$, where metal melting occurs, moves along the normal to the cut-front with a velocity $V_n$. The continuity conditions for liquid velocities and the Stefan conditions are satisfied at this boundary

$$U(\xi,\,0)=V_c\cos\alpha,\; V(\xi,\,0)=V_c\sin\alpha, \tag{7}$$

$$\lambda_m\frac{\partial T}{\partial \eta}-\lambda_S\frac{\partial T_S}{\partial \eta}=\rho_m H_m V_n,\; T(\xi,\,0)=T_S(\xi,\,0)=T_m. \tag{8}$$

Here $\lambda_m$, $\lambda_S$ are the thermal conductivity coefficients of the melted and solid metal, $T_m$, $H_m$ are the melting point and phase-transition heat, $V_c$ is the velocity of cutting. At the other moving boundary $\eta=H(\xi,\,t)$ the conditions

$$\eta=H(\xi,\,t):\; \mu_m\frac{\partial U}{\partial \eta}=\tau,\;\; \frac{\partial H}{\partial t}+U\frac{\partial H}{\partial \xi}=V. \tag{9}$$

$$\eta=H(\xi,\,t):\lambda_m\frac{\partial T}{\partial \eta}=\frac{2A(\gamma)W}{\pi\omega_0^2}\frac{\cos(\alpha-\varphi)}{\cos\varphi}\exp\left(-\frac{2\left(\xi\cos\alpha+H(\xi)\sin\alpha-\omega_0\right)^2}{\omega_0^2}\right). \tag{10}$$

are satisfied. Here $\gamma$ is the angle of the beam incidence onto the liquid surface; $A(\gamma)$ is the radiation-absorption factor, $\tau$ is the tangential stress at the liquid-gas interface.

$$\cos\alpha=1\Big/\sqrt{1+(z_m)_x'^2}\,,$$
$$\cos\varphi=1\Big/\sqrt{1+H_\xi'^2}\,,\; \gamma=\alpha-\varphi. \tag{11}$$

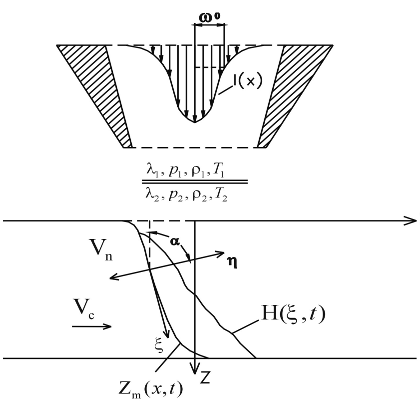

Fig. 1. Interaction of the gas jet and radiation with the metal plate.

The processes accompanied the gas-laser cutting are formulated mathematically in the form of the adjoint problems (1-3), (4-11) with the conditions at the moving bounds (8), (10). At the certain simplified assumptions, it is succeeded to solve these problems analytically [2], that allows to lead the adjoint conditions at the motion bounds to the nonlinear algebraic equations and to solve them using the Newton method. Owing to this, evaluation of the liquid film thickness and its increasing dynamics on the cutting depth in dependence on the cutting velocity was obtained, Fig. 2. The dependence of the inclination angle of the cutting front to the cutting direction was calculated taking into account the melt thickness and the cutting velocity, that is coincided with the experiments qualitatively [2]. It was numerically constructed (in the form of criteria) the dependence of maximal cutting depth on the cutting velocity, thermal-physical properties of metal and the radiation parameters, which had a good agreement with the experimental data for thin plates with thickness up to 0.5 mm [2].

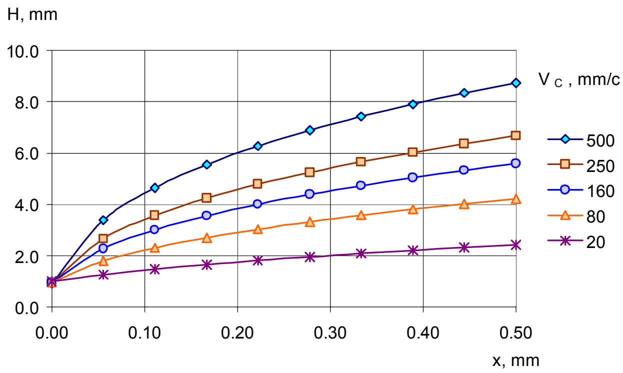


Fig. 2. Influence of the cutting velocity on thickness of the liquid melt layer.

The cutting quality depends on a number of physical parameters [1, 2], the main of which are the radiation polarization and the spatial-energetic beam characteristics. It is characterized by a width, a perpendicular level of the cutting side surfaces to the sheet, the surface roughness and absence of flashes (solidified melting drops at the lower cut). Description of the cut surface form shall be considered in three-dimensional formulation taking into account the peculiarities of the radiation absorption at the cutting front and its side surfaces, that allows to evaluate of the influence effectiveness on the laser radiation material with a different intensity density and the beam polarization. Assuming that by an intensive gas feeding, the hydrodynamic processes inside the cut (melt removing) occurs instantly, and the incident radiation constantly interacts with the solid metal surface. The mathematical problem formulation adds up to solution of the equation of kinematic compatibility of the surface cutting points [2].

$$\frac{\partial z_m}{\partial t} - V_c \frac{\partial z_m}{\partial x} = -V_n \sqrt{1 + \left(\frac{\partial z_m}{\partial x}\right)^2 + \left(\frac{\partial z_m}{\partial y}\right)^2}\ , \ z_m(x, y, 0) = 0 \tag{12}$$

$$\begin{aligned} &\frac{\partial z_m}{\partial x}(-a, y, t) = \frac{\partial z_m}{\partial x}(a, y, t) = 0, -b \le y \le b \\ &\frac{\partial z_m}{\partial y}(x, -b, t) = \frac{\partial z_m}{\partial y}(x, b, t) = 0,\ \ -a \le x \le a \end{aligned} \tag{13}$$

Here $z_m$ is the surface form, $a, b$ are the plate sizes ($a, b >> \omega_0$). For $V_n$ in the assumptions of the thickness smallness of the melting metal layer, the expression [2, 3] were obtained:

$$V_n = \frac{2WA(\gamma)\cos\gamma \exp\left(-2\left(x^2+y^2\right)/\omega_z^2\right)}{\pi\omega_z^2\left(\rho_m H_m + c_s^0 \rho_s^0 \left(T_m - T_0\right)\int\limits_0^1 \nu(t)\,dt\right)},\ \omega_z = \sqrt{\omega_0 + \left(\frac{\left(z - z_f\right)\lambda_0}{\pi\omega_0}\right)^2} \tag{14}$$

where $\lambda_0$ =10.6 μm is a length of the radiation wave; $\rho_m$, $H_m$ are the melting density and metal melt heat; $T_m$, $T_0$ are the melting temperature and the initial temperature; $c_s^0$, $\rho_s^0$ are the specific heat and density of the solid the material; $\omega_z$ is a radius of the laser beam. Interaction of between the radiation and metals is described by the formulas:

$$R_S = \left| \frac{\cos\gamma - (N^2 - \sin^2\gamma)^{1/2}}{\cos\gamma + (N^2 - \sin^2\gamma)^{1/2}} \right|^2, \qquad R_p = \left| \frac{N^2\cos\gamma - (N^2 - \sin^2\gamma)^{1/2}}{N^2\cos\gamma + (N^2 - \sin^2\gamma)^{1/2}} \right|^2,$$

where $R_S, R_p$ are the reflection factors; $N = n_\omega + ik_\omega$ is a complex refraction factor. The absorption factor is calculated by $A(\gamma) = 1 - R_p$ at the parallel polarization, or by $A(\gamma) = 1 - R_S$ at perpendicular one. In case of a circle polarization, the absorption factor is calculated by the formula $A(\gamma) = 1 - 0.5(R_S + R_p)$.

The initial beam structure had the Gauss distribution along the section and accounted the lens focusing. The caustic center could change with respect to the material surface [3]. Only single absorption was considered, the repeated reflection and absorption were not taken into account. The main radiation portion, interacting with the metal, falls onto the cutting surface at large angles. The main peculiarity is a great dependence of the absorption factor on the incident angle, Fig. 3.

Equation (12) was solved numerically by the implicit difference scheme with a pseudoviscosity method. The cutting form in the frame of the formulated problem is described from the upper plane of the metal sheet $z = 0$ up to the limited depth of a material destruction $z < 0$. Figure 4 shows projections of the cutting form in the section $y - z$ for three different cases of the beam polarization. In case of cutting by the $S-$polarized beam the radiation absorption factor at the cutting front is small (see Fig. 3), so the marginal cutting parameters are also small (the cutting depth), (Fig. 4, a). The surface form is smooth because the maximum density of the absorbedpower is found in the center. In case of cutting by the $P-$polarized beam the density maximum of the absorbed power is located at the cut walls, where the beam falls at the angle of $85^\circ - 87^\circ$. By this, the side surface form is evolved to a vertical line, Fig. 4, c. Figure 4, b shows the circle beam polarization usually used in laser technological systems, which gives in computations something averaged between $S-$ and $P-$ polarizations. In all cases, the radiated surface aims to take the form assuring the minimum radiation absorption.

A location of the focal plane of the Gauss beam relatively the upper surface of the cutting material essentially influences on the cutting form. Figure 5 shows the $y - z$ projections of the cutting forms for three peculiar values of position of the beam focal surface: above the plate (+3 mm), small deepening (–1 mm) and large deepening (–3 mm). The peculiar feature is the presence of the plane area with two fractures at the bottom cut. The fractures presence id explained by a strong dependence of the radiation absorption factor on the incident angle, Fig. 3. A high steepness of the cut walls provides the same high radiation absorption, which sharply decreases up to zero by coming of the incident angle to $90^\circ$. By this, the cutting form with a small focus deepening is more preferable by sight.

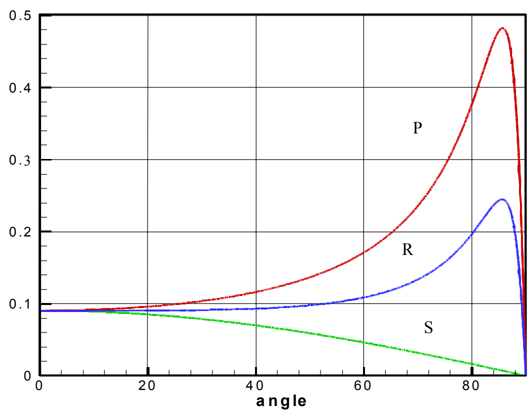


Fig. 3. Dependence of the radiation absorption factor on the incident angle at different polarization ($S$ – perpendicular, $P$ – parallel, $R$ – circle).

Thus, the problem of description of the gas-laser metal cutting is firstly proposed in the form of adjoint problems of mechanics of continuous media with the motion bounds, which had been solved analytically at the certain simplified assumptions, that allows us both to evaluate the integral characteristics and to obtain the three-dimensional cutting structure. The joint solution of the problem of the interphase interaction of the gas jet and melt taking into account the wall flows and radiation propagation in a narrow channel, opens the possibilities to solve the main problem connected with modeling of conditions for the qualitative cut.

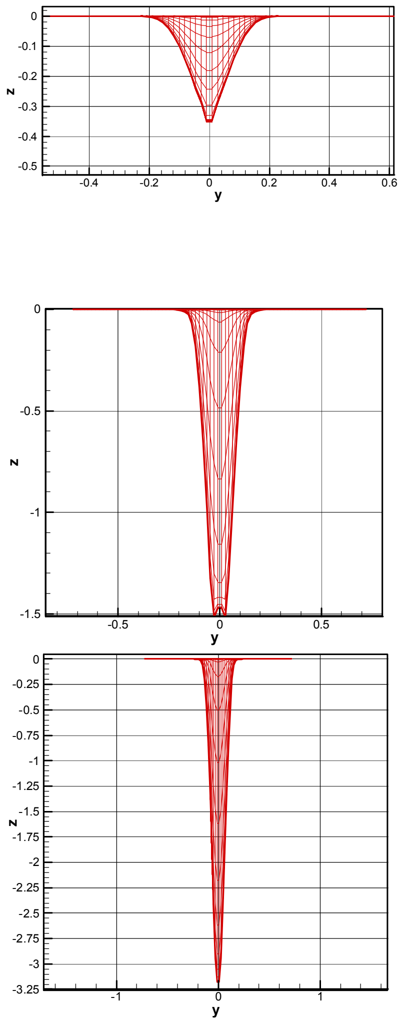


Fig. 4. Influence of the radiation polarization on the cutting depth and form:
a) $S$ – perpendicular ; b) $R$ -circle;
c) $P$ -parallel ( $z_f = 0$).

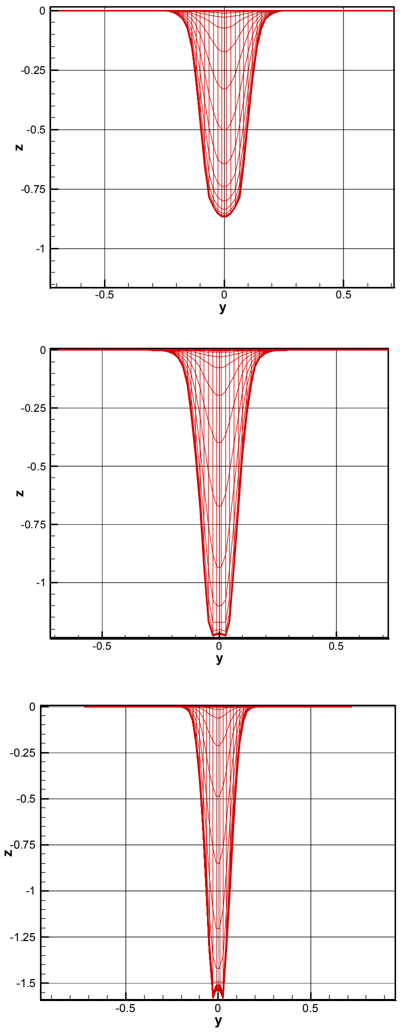


Fig. 5. Influence of the deepening of the focus on the cutting form (circle polarization):
$z_f$ mm: a) +3 mm; b) –1 mm; c) –3 mm.

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