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Experimental optimisation of the gas-assisted laser cutting of thick steel sheets

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***Abstract*. We report on the experimental optimisation of the oxygen-assisted CO_2 laser cutting of low-carbon sheet steel 5 to 25 mm in thickness. It is shown that the cut edge roughness is minimal when the energy input per unit volume of the material removed and the incident beam power per unit sheet thickness remain constant at ~ 20 J mm^{-3} and ~ 200 W mm^{-1}, respectively, over the entire range of sheet thicknesses examined. The corresponding Péclet number is Pe $= 0.5$. These results can be used to determine the optimal beam power and cutting speed for a particular sheet thickness. At sufficiently large thicknesses, the conditions that ensure the minimum roughness can be written in the form of relations between nondimensional parameters.**

Keywords: *laser cutting, cut quality criteria, optimisation, nondimensional parameters.*

1. Introduction

Laser cutting of metals is successfully used in practical applications, and there continues a considerable effort aimed at improving its performance parameters [1, 2]. There are several laser cutting methods [1]. Low-carbon steels are typically laser-cut in a reactive gas (oxygen) atmosphere. Laser cutting offers high processing speed, with focus on high cut quality. The cut quality parameters include the amount of burr (solidified melt droplets on the bottom edge of the cut), cut edge roughness, heat-affected zone width and cut taper.

Despite the many theoretical and experimental studies in this field, a complete, consistent physical picture of the laser cutting process is still lacking [2, 3], and conditions needed to achieve high cut quality have not yet been formulated. This is primarily related to the diversity of and the complex interplay between the physical processes involved in laser cutting. The main processes are beam propagation in the cut, radiation absorption, energy release as a result of an exothermic reaction and metal oxide formation when oxygen is used as the assist gas, heat transport in the material, melting, gas flow in the cut and melt layer motion under the action of the gas flow. The cut edge roughness, one of the basic cut quality criteria, depends on the dynamics of melt front propagation and the flow behaviour of the melt layer [4]. The mechanisms of the development of melt flow instabilities that may have an adverse effect on laser cutting quality were reviewed, e.g., by Golubev [5].

In theoretical modelling of the gas-assisted laser cutting process, the relation between the incident laser beam power and cutting speed is derived from the energy balance (see, e.g., [6, 7]). This approach allows the maximum cutting speed to be evaluated. It is known that the maximum speed is not necessarily optimal in terms of cut quality [8]. Moreover, a number of important parameters that appear in the energy balance, such as the absorption coefficient of the cut zone and the heat of the exothermic reaction of iron oxidation, are intricate functions of cutting conditions and cannot always be evaluated with the required accuracy. As a result, even the maximum cutting speed is difficult to determine with certainty.

In this context, experimental optimisation of cutting conditions in order to improve cut quality is a topic area. To date, a rather large amount of data on laser cutting has been collected, but those data are primarily for thin sheets (less than 10 mm in thickness) [1, 8, 9]. Modern industrial CO_2 lasers enable quality cutting of sheets up to 25 mm in thickness [1]. One of the main approaches to improving the laser cutting performance is to raise the incident beam power, which in addition enables cutting of thicker sheets. Moreover, adequate comparison of data from different sources with the aim of identifying general relationships is not always possible because published experimental results often contain incomplete data sets or were obtained under different conditions. The quality criteria used, which are in general different for each cut quality parameter [10], are not always clearly specified.

The purpose of this work was to experimentally optimise the oxygen-assisted laser cutting conditions for thick low-carbon steel sheets. The blur-free cut edge roughness was used as the cut quality criterion.

2. Experimental

In our cutting experiments, we used a laser machining system created at the Khristianovich Institute of Theoretical and Applied Mechanics, Siberian Branch, Russian Academy of Sciences, which included a cw CO_2 laser with a beam parameter product (the product of the beam waist radius and the far-field beam divergence half-angle) of

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4.7 mm mrad [11]. Cutting was performed with a circularly polarised beam by a standard procedure. The beam was focused by a single ZnSe lens. To adjust the beam waist position relative to the gas nozzle, the lens was fitted with a translation system and readout device. Coaxial with the laser beam, a jet of the assist gas (99.999 %-pure oxygen) was fed to the cutting zone. The assist-gas pressure was measured in the cutting-head chamber with an accuracy of 0.01 bar. During cutting, the gap between the gas nozzle and sheet surface was maintained constant using a capacitive sensing system. The sheets were of ordinary carbon steel (St3ps) 5 to 25 mm in thickness.

Large volumes of data are substantially easier to process when represented in the form of relations between nondimensional combinations of parameters, as is common in similarity analysis of complex physical systems. This allows one to reduce the number of independent variables and to find characteristic parameters of the problem. In determining such parameters, we proceed from the following assumptions: the energy released at the cut front is rather evenly distributed throughout the cut depth, the sheet thickness far exceeds the kerf width, and the molten material is ejected from the cutting zone by the gas jet.

The basic parameters of the laser cutting process are the thickness of the sheet being cut, t; the laser beam power, W; the cutting speed, υ; and the assist-gas pressure at the kerf inlet, p. The kerf width, b, is easy to measure. With these parameters, the following nondimensional combinations can be made up: $W/(\lambda t T_{\mathrm{m}})$, $\upsilon b/\gamma$ and b/t, where λ and T_{m} are, respectively, the thermal conductivity and melting point of the material; $\gamma = \lambda/(\rho c)$ is its thermal diffusivity; and ρ and c are its density and specific heat. The variables $W/(\lambda t T_{\mathrm{m}})$ and $\upsilon b/\gamma$ appear in problems with a moving extended heat source [12]. $W/(\lambda t T_{\mathrm{m}})$ is proportional to the power density of the extended source, and the $\upsilon b/\gamma$ ratio is known as the Péclet number, Pe. The b/t ratio can be thought of as a parameter characterising the forces exerted by the gas flow on the melt layer.

When a gas flows through a pipe of constant cross section at a constant pressure gradient over length t (Poiseuille flow), b/t determines the relationship between the viscous friction force and pressure: $b/t = 4\tau/p$ (where τ is the shear stress) [13]. The W, t, b and υ parameters, which appear in the nondimensional combinations above, can be determined experimentally.

In our experiments, two series of measurements were made for each sheet thickness. In the first series, the focal length of the lens, f, and the oxygen pressure in the cutting-head chamber were selected. To this end, using successive approximations we determined the ranges of W, υ and Δf (beam waist position relative to the sheet surface) corresponding to the highest cut quality. In the second series, the cut edge roughness and kerf width were determined as functions of incident beam power, cutting speed and beam waist position relative to the sheet surface. The initial values of W and υ were taken approximately in the middle of the respective ranges corresponding to high cut quality. The initial beam waist position was adjusted so as to minimise the kerf width. From those data, we determined υ, b and W that ensured the minimum roughness. The sheet thicknesses, p and f values and beam powers at which the measurements were made are listed in Table 1. Increasing the sheet thickness reduces the range of beam powers in which high cut quality can be achieved, which is due to the increase in cutting threshold power. In view of this, the effect of incident power on the cut edge roughness was examined in greater detail for sheet thicknesses below 20 mm. Figure 1 is a photograph of a typical cut surface at a sheet thickness of 25 mm.

Table 1.

t/mm	W/kW	f/mm	p/bar
5	0.37–3.5	127, 190	0.5
10	0.9–3	190	0.5
16	1.2–4	190	0.4
20	3–4.5	190	0.4
25	4–4.5	254	0.35

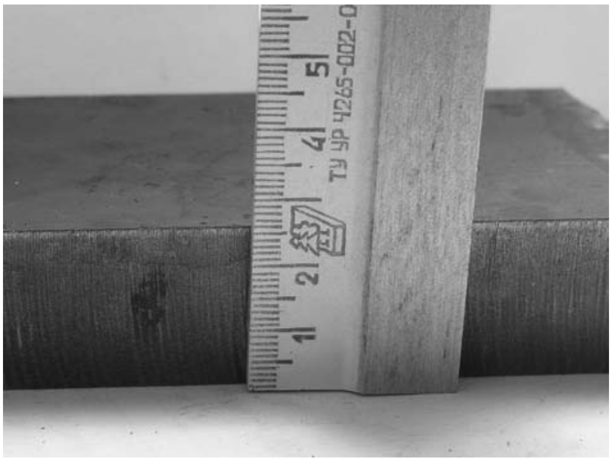

Figure 1. Typical cut surface at $t = 25$ mm, $W = 4.5$ kW and $\upsilon = 0.6$ m min^{-1}.

The cut surface roughness was measured at distances $t/3$ and $2t/3$ from the front edge, using an Olympus LEXT confocal laser scanning microscope, and the specimen was characterised by the largest of the two values. The microscope enables three-dimensional surface imaging through layer-by-layer scanning, with the possibility of determining the roughness value in a specific section.

3. Experimental results and discussion

Using the procedure described above, we obtained a sufficiently large amount of experimental data for the sheet thicknesses and incident beam powers listed in Table 1. Figure 2 plots the cut edge roughness R_z against kerf width at $t = 5$ mm. To obtain these data, we first determined Δf that minimised the kerf width at a given incident power. Next, at this Δf we determined the cutting speed that minimised the roughness and then measured R_z and b as functions of Δf at this speed. The results were used to plot R_z against b.

Figure 3 illustrates the effect of the laser beam power on the cutting speed corresponding to the minimum roughness at $t = 5$ mm. To obtain these data, we determined Δf that minimised R_z at each incident power. Next, at this Δf and the corresponding incident power we measured R_z as a function of cutting speed and determined the speed and kerf width that minimised the roughness. Measurements were then made at other incident powers.

Such data were also obtained at $t = 10$ and 16 mm. The optimisation results for the entire range of thicknesses

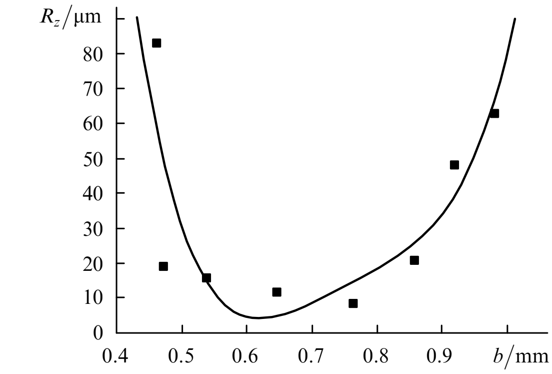

Figure 2. Cut edge roughness versus kerf width at $t = 5$ mm and $W = 2.3$ kW.

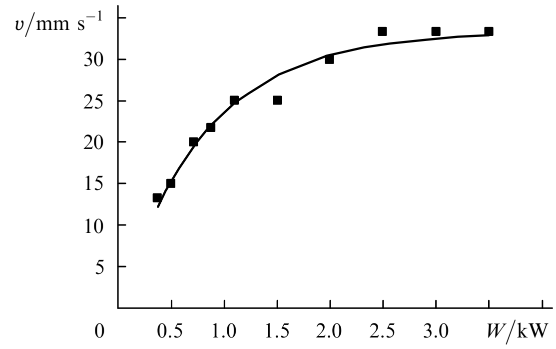

Figure 3. Optimal cutting speed versus beam power at $t = 5$ mm and $f = 190$ mm.

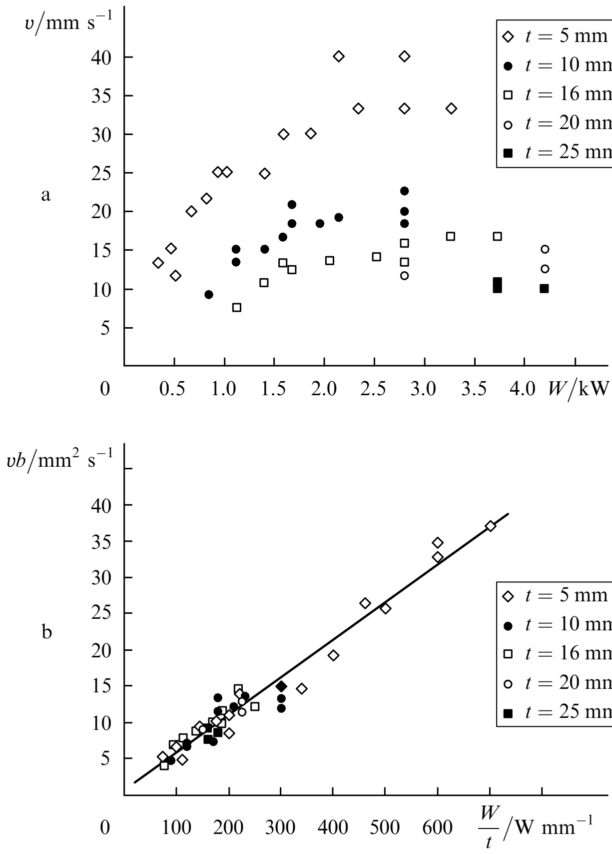

Figure 4. Effect of the beam power on the optimal cutting speed at different sheet thicknesses, t: plots of (a) υ against W and (b) υb against W/t.

examined are presented in Fig. 4a as plots of the optimal cutting speed, υ, against incident power, W (some of the data points were obtained in control experiments). In Fig. 4b, the same data are presented as plots of υb against W/b.

In the plot of υb against W/b in Fig. 4b, all of the data points fall close to a straight line with $W/(\upsilon tb) = 19.4$ W mm^{-3}, which implies that, independent of the sheet thickness and incident power, R_z is minimised at the same energy input per unit volume of material removed. The relation between the nondimensional parameters in question can then be written in the form

$$\frac{W}{\lambda t T_{\mathrm{m}}} = (1 + \mathrm{Sf}\,)\,\frac{W}{\upsilon t b \rho (c T_{\mathrm{m}} + L_{\mathrm{m}})}\,\mathrm{Pe}, \qquad (1)$$

where L_{m} is the latent heat of fusion of the material and $\mathrm{Sf} = L_{\mathrm{m}}/(cT_{\mathrm{m}})$ is the Stefan number.

The line in Fig. 4b indicates the cutting speed that minimises the cut edge roughness at a given sheet thickness and incident power. In addition, the roughness depends on the incident power. At $t = 5$ and 10 mm, R_z as a function of power has a minimum. We failed to detect a minimum at larger thicknesses because of the limited laser output power. Figure 5 plots R_z/t against $W/(\lambda t T_{\mathrm{m}})$ and $\upsilon b/\gamma$. The thermophysical parameters used were those for pure iron under normal conditions.

The W/t values corresponding to the minimum in $R_z(W)$ at sheet thicknesses of 5 and 10 mm are given in Table 2 together with the W/t for the specimens with the minimum roughness at thicknesses above 10 mm. It can be seen that, over the entire range of sheet thicknesses examined, the minimum occurs at nearly the same value of W/t. The average, $W/t = 194$ W mm^{-1}, corresponds to the nondimensional parameter $W/(\lambda t T_{\mathrm{m}}) = 1.6$, which gives a Péclet number $\mathrm{Pe} = 0.5$.

It is known that high-quality laser cutting is possible in a limited range of Péclet numbers [5, 7]. According to Golubev [5], there may be an optimal Péclet number. Here, we determined its exact value, which offers an unambiguous quantitative cut quality criterion.

The kerf width that minimises the cut edge roughness increases with sheet thickness. Figure 6 plots the kerf width against sheet thickness at the W, υ and Δf values that minimise the cut edge roughness. We used a lens with $f = 254$ mm at a sheet thickness of 25 mm and a lens with $f = 190$ mm at smaller thicknesses. The best-fit line is given by $b = 0.35 + 0.02t$. A similar $b(t)$ dependence was obtained by Prusa et al. [7] from experimental data for sheet thicknesses from 1 to 12.7 mm.

The variable parameters of laser cutting are the sheet thickness, incident beam power and cutting speed. Using the optimal values of W/t and υb and the best-fit relation for $b(t)$, we obtain the following relations between the process parameters that minimise the cut edge roughness:

$$W = 190t, \quad \upsilon = \frac{11}{0.35 + 0.02t}, \qquad (2)$$

where W is expressed in watts, υ – in millimetres per second, and t – in millimetres. At large thicknesses, when the first

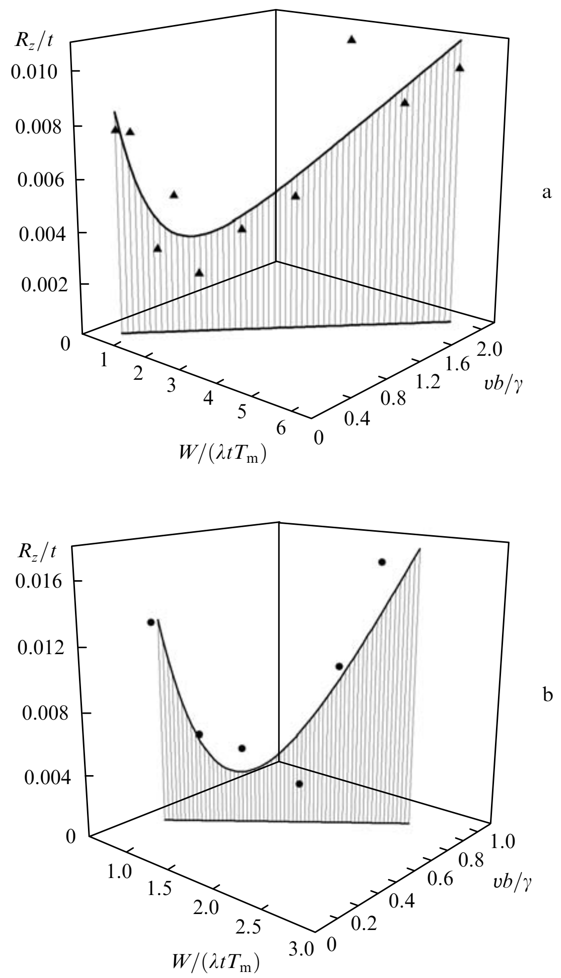

Figure 5. Cut edge roughness as a function of the beam power and cutting speed in nondimensional coordinates at $t = 5$ (a) and 10 mm (b).

Table 2.

t/mm	$\frac{W}{t}$/W mm^{-1}
5	220
10	180
16	190
20	200
25	180

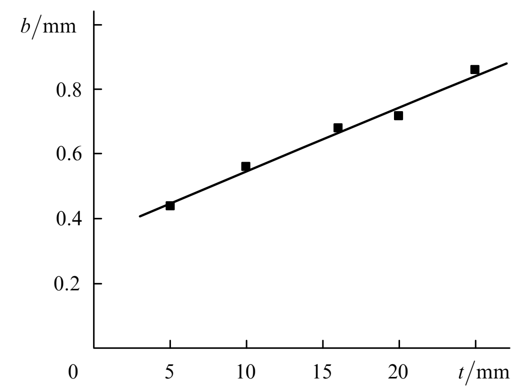

Figure 6. Kerf width corresponding to the minimum roughness as a function of sheet thickness.

term in the denominator in the expression for cutting speed in (2) can be neglected, these relations can be written in nondimensional form:

$$\frac{W}{\lambda t T_{\rm m}} = 1.6, \quad \frac{vt}{\gamma} = 24.$$

One quantity of practical interest is the energy input per unit cut length, W/v. From (2), we obtain

$$\frac{W}{v} = 6t + 0.35t^2. \qquad (3)$$

The energy input during laser cutting can also be estimated from the condition $W/(vt) = \text{const}$, with the kerf width assumed to be constant [8]. It follows from (3) that such estimates are legitimate at small sheet thicknesses, when the second term can be neglected because of the small coefficient of t^2. Relation (3) is consistent with results reported by Black [14], who compiled $W/(vt)$ data from various sources for oxygen-assisted cutting of low-carbon sheet steel up to 20 mm in thickness (most of the data were for thicknesses under 10 mm). All of the data presented by Black [14] fall in the range $W/(vt) = 6$–13 J mm^{-2}, with higher $W/(vt)$ values at larger thicknesses.

4. Conclusions

We studied the effect of cutting parameters on the cut edge roughness in oxygen-assisted laser cutting of low-carbon sheet steel 5 to 25 mm in thickness. Our experimental results show that the roughness is minimal when the energy input per unit volume of material removed and the incident beam power per unit sheet thickness remain constant over the entire range of thicknesses examined. In nondimensional form, these conditions can be written as $W/[vtb\rho(cT_{\rm m} + L_{\rm m})] = \text{const}$ and $W/(\lambda t T_{\rm m}) = \text{const}$. The corresponding Péclet number is $\text{Pe} = 0.5$.

We also obtained a linear relation between the kerf width and the thickness of the sheet being cut. This allowed us to represent our experimental results in the form of relations between the incident beam power and cutting speed that minimise the cut edge roughness at a particular sheet thickness. At sufficiently large thicknesses, these relations can be written in nondimensional form.

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