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Experimental study of laser-oxygen cutting of low-carbon steel using fibre and CO_2 lasers under conditions of minimal roughness

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Abstract. **The results of an experimental study of laser-oxygen cutting of low-carbon steel using fibre and CO_2 lasers are generalised. The dependence of roughness of the cut surface on the cutting parameters is investigated, and the conditions under which the surface roughness is minimal are formulated. It is shown that for both types of lasers these conditions can be expressed in the same way in terms of the dimensionless variables – the Péclet number Pe and the output power Q of laser radiation per unit thickness of the cut sheet – and take the form of the similarity laws: Pe = const, Q = const. The optimal values of Pe and Q are found. We have derived empirical expressions that relate the laser power and cutting speed with the thickness of the cut sheet under the condition of minimal roughness in the case of cutting by means of radiation from fibre and CO_2 lasers.**

Keywords: *laser cutting, CO_2 laser, fibre laser, cutting quality, optimisation, dimensionless criteria.*

1. Introduction

The advantages of laser cutting of materials are high speed and high quality of the processing. In the last decade, cutting with the use of high-power solid-state disk lasers or fibre lasers has been actively investigated and applied in practice. As a result of numerous studies, it was established that there are a number of differences in metal cutting by means of fibre and CO_2 lasers. The fibre laser has an advantage over the CO_2 laser in cutting of thin (less than 4 mm) steel sheets [1]: it provides a much greater cutting speed than the CO_2 laser with a comparable quality of cutting. In the case of thick sheets, the cutting speeds for both lasers are comparable, but the CO_2 laser provides higher quality of the cut.

The reasons for the differences in characteristics of the cuts made using the two types of lasers are not yet formulated clearly. According to most researchers, these differences are of fundamental nature and related to the peculiarities of propagation and absorption of laser radiation with the wavelengths of 1.07 and 10.6 μm in the cut channel [2–4].

The comparative experimental studies allow one to advance in understanding the physical characteristics of laser cutting with the use of radiation at different wavelengths. They were carried out, for example, in papers [5, 6], in which the energy balance of cutting in the inert gas atmosphere was studied.

Laser cutting can be carried out in a certain range of its speeds and for different values of the radiation power. Since the advantage of laser cutting is high quality of the cut, and its most important criterion in many applications is roughness of the cut surface, it is of interest to determine the cutting conditions ensuring minimal roughness. Theoretical solution to the problem of the laser cutting optimisation in accordance with the criterion of the cut quality is presently complicated by the fact that the model of the surface relief formation in the cutting process is not yet elaborated with taking into account all possible mechanisms. The maximum cutting speed that is obtainable on the basis of the energy balance is, generally speaking, not the best in terms of quality of the cut.

In experimental studies, the maximal cutting speed is usually determined for each particular laser, and then the corresponding value of roughness is fixed. Herewith, the criteria that serve to select the initial parameters of cutting are not always clearly formulated. In this paper a different approach is applied. First, cutting parameters are optimised and the minimum achievable roughness for each type of laser is determined. Then, the speed that corresponds to the minimal roughness is selected.

Another feature of this work is the use of dimensionless parameters to compare the cutting performance for fibre and CO_2 lasers. This allows us to present the experimental results in the generalised and compact form. In our previous works [7, 8], the optimisation problem for the CO_2 laser has been solved experimentally. The conditions of the cutting quality in the case of laser-oxygen cutting of steel sheets were formulated in the form of similarity laws – the values of the generalised dimensionless variables ensuring the minimal surface roughness were found. By way of such variables, the dimensionless laser power and Péclet number were used.

In the present work, the in-depth study of the problem of laser cutting optimisation is continued, and for the first time a detailed comparison of the cutting parameters using fibre and CO_2 lasers under the conditions of the minimal surface roughness is conducted. The results are formulated in terms of the dimensionless parameters.

2. Experimental procedures

The cutting was carried out using an IPG/IRE-Polus ytterbium laser with a collimator (IPG, model D5-WC/AC) having the power of 2 kW and the beam parameter product BPP (the product of the beam radius in the near field and the angular radius of the beam in the far field) equal to 3.8 mm mrad.

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The beam diameter at the focusing lens after the collimator was 17 mm at the focal length of the lens of 200 mm; the cutting was performed at the power of 0.5–2 kW. A continuous CO_2 laser with the BPP equal to 4.7 mm mrad was used as well [9]. The cutting was carried out in accordance with the traditional scheme by means of circularly polarised radiation having the power of 0.5–3.5 kW. Radiation was focused by a ZnSe lens with a focal length of 190 mm. The beam diameter on the lens was 25 mm. The fibre laser was used for cutting the sheets of St3ps low-carbon steel of 3, 5 and 10 mm in thickness, while the sheets of 5, 10 and 16 mm in thickness were cut by the CO_2 laser. The jet of oxygen was formed by means of a conical nozzle in the laser cutter chamber: at the gas overpressure of 0.25 MPa in the case of cutting the sheets of 3 mm in thickness, and 0.05 MPa in the case of cutting the sheets of 5, 10 and 16 mm in thickness.

As a measure of roughness (typical height of inhomogeneity) the R_z value was used. The roughness was measured using an Olympus LEXT laser confocal scanning microscope and a Rank Taylor Hobson profilometer (Series Form Talysurf). By means of the layerwise scan method, the microscope allowed one to obtain a three-dimensional picture of the surface and determine the roughness value in a given section. In our case, the R_z value was defined in two sections – at the distances of one-third and two-thirds of thickness of the upper sheet surface. The larger of these two values was chosen to characterise the sample.

Optimal parameters were found in two stages. Initially, a two-parametric optimisation was carried out: the optimal position of the beam waist and the cutting speed (further designated as V_c^*) was determined for a given power value. The beam focus position defines the cutting width, the optimal value b^* of which is determined for each power value. After that, at the second stage, the radiation power was optimised. Of several pairs of V_c^* and b^* values corresponding to different powers, those were selected for which the surface roughness of the cut was minimal. These values are designated as V_{opt} and b_{opt}, and the corresponding laser power was considered optimal.

The relationship between the roughness R_z of the surface cut and the cutting parameters can be represented in the form of the functional dependence

$$R_z = F(W, V_c, h, b, \Delta p, \rho_g, \mu_g, u_g, c_m, \lambda_m, \rho_m, T_m, L_m, f), \quad (1)$$

where W is the radiation power; V_c is the cutting speed; h is the thickness of the cut sheet; b is the cut width; Δp is the pressure difference of the process gas across the sheet thickness; ρ_g, u_g, and μ_g are, respectively, the density, average speed and dynamic viscosity of the process gas; c_m, λ_m, ρ_m, T_m, and L_m are, respectively, specific heat, thermal conductivity, density, melting temperature and specific heat of melting of the material being cut; and f is the focal length of the lens.

It was experimentally shown in previous papers [7, 8] that, for the description of the surface roughness R_z when cutting the low-carbon steel with the use of CO_2 laser radiation with oxygen as the process gas, the function

$$\frac{R_z}{h} = \Phi(\mathrm{Pe}, Q, A_i) \quad (2)$$

can be used instead of (1), with the following dimensionless parameters: $\mathrm{Pe} = V_c b \rho_m c_m / \lambda_m = V_c b / \gamma$ is the Péclet number; $\gamma = \lambda_m / (\rho_m c_m)$ is the material thermal conductivity; and $Q = W / (\lambda_m h T_m)$ is the laser power. The symbol A_i denotes the set of parameters that characterise the system of radiation focusing, the laser beam quality, the properties and chemical composition of the material to be cut. These parameters in our study are constant.

It should be noted that the possibility of existence of function (2) that describes, via these dimensionless parameters, all the diversity of the experimental data for two different lasers with the radiation wavelengths differing by a factor of 10 requires experimental verification. The second fundamental problem of practical importance was to experimentally determine the form of this function and to find out whether it has a minimum similarly to the case of CO_2 lasers. The dimensionless parameters given above correspond to the dimensional combinations W/h, $V_c b$ that can be determined experimentally.

To perform the optimisation, i.e. to determine the minimum of R_z, we varied the thickness h of the cut sheet, laser radiation power W, cutting speed V_c and cutting width b.

3. Experimental results

The maximum amount of data on the cutting by means of both CO_2 and fibre lasers has been obtained for the material thickness of 5 mm. Figure 1 shows the photographs of the cut surface made at the radiation power of 1 kW and optimal cutting speed of 0.8 m min^{-1} for the fibre laser and 1.5 m min^{-1} for the CO_2 laser under the condition of minimal surface roughness. A similarity in the surface structure can be seen for both types of the lasers. Regular strokes are observed in the upper part of the cut surface, while in the bottom those strokes become chaotic. The correlations between the zone depths, groove steps and their angles of inclination in both cases are close.

The results of measuring the surface roughness as a function of the cutting speed for the fibre laser are shown in Fig. 2. It is seen that, in the upper part of the cut surface, the roughness does not virtually depend on the speed, slightly decreasing with increasing speed. In the bottom part of the surface, wherein larger structures are observed, the roughness depends on the cutting speed and possesses a minimum at V_c = 0.8–0.9 m min^{-1}.

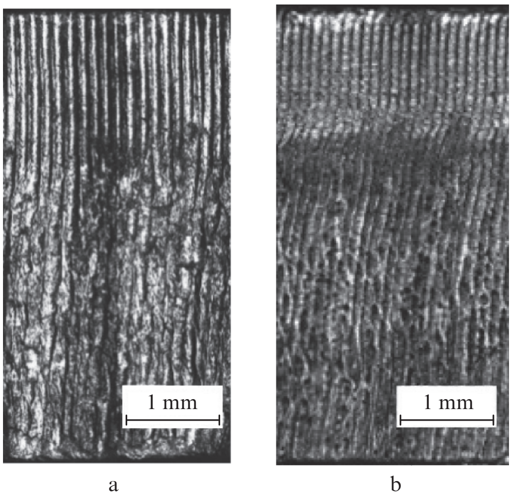

Figure 1. Photographs of the cut surface of the sheet of low-carbon steel with a thickness of 5 mm when cutting with the use of (a) the fibre laser (W = 1 kW, V_c = 0.8 m min^{-1}) and (b) the CO_2 laser (W = 1 kW, V_c = 1.5 m min^{-1}).

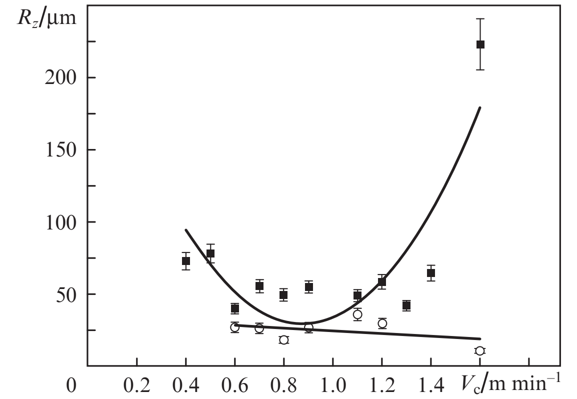

Figure 2. Dependences of roughness on the cutting speed when using the fibre laser with the power of 1 kW and the sheet thickness of 5 mm in the vicinity of the top (○) and lower (■) surfaces of the sample.

In the first-stage experiments, the optimal speed V_c^* and cutting width b^* were found for each laser power. The results of such an optimisation for a thickness of 5 mm, when cutting with the use of the fibre and CO$_2$ lasers, are shown in Figs 3 and 4.

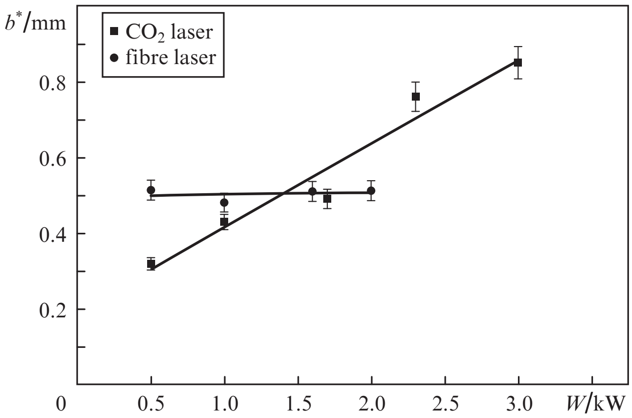

Figure 3. Optimal cutting width vs. radiation power for the fibre and CO$_2$ lasers at $V_c = V_c^*$.

Figure 4 shows the maximal cutting speed V_{max}, above which the cut disappears. Note that, when cutting with oxygen as the process gas, the maximum speed always exceeds the optimal one and does not depend on the laser type within the experimental scatter of values.

The dependences of the optimum cutting width (Fig. 3) and speed (Fig. 4) on the power are fundamentally different for the CO$_2$ and fibre lasers. In case of the CO$_2$ laser, the values of V_c^* and b^* increase linearly with increasing power, while in case of the fibre laser they remain virtually constant ($V_c^* = 0.7 - 0.9$ m min^{-1} and $b^* = 480 - 514$ μm in the power range of 0.5–2 kW).

The generalised data for different sample thicknesses in the cutting optimisation by two parameters – the speed and width of the cut – are shown in Fig. 5 in the form of dependences of the Péclet number $\mathrm{Pe}^* = V_c^* b^* / \gamma$, which is calculated by the optimal speed and optimum cutting width, on the dimensionless laser power $Q = W/(\lambda_m h T_m)$. The thermal characteristics of pure iron were used.

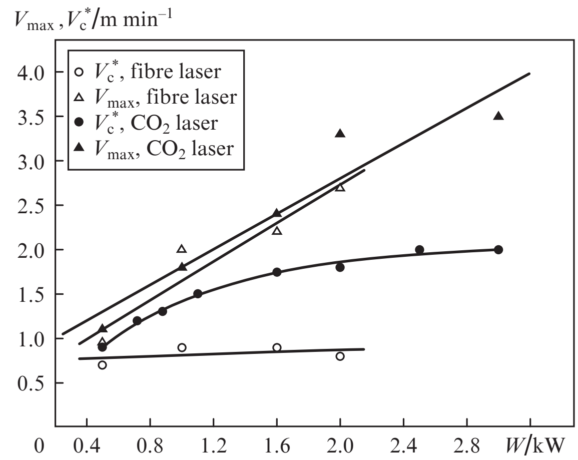

Figure 4. Maximum cutting speed V_{max} and cutting speed V_c^* corresponding to the minimal surface roughness as functions of radiation power for the fibre and CO$_2$ lasers at $h = 5$ mm.

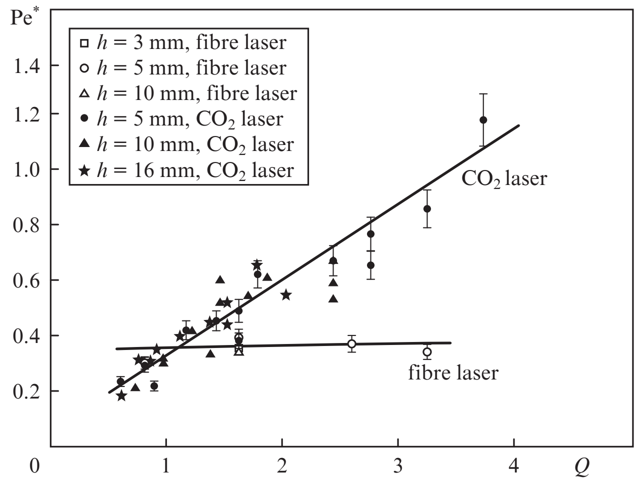

Figure 5. Péclet number corresponding to the minimum roughness as a function of dimensionless radiation power for the metal samples of different thicknesess h.

As can be seen from Fig. 5, the data for different thicknesses are described in the dimensionless coordinates by a linear dependence $\mathrm{Pe}^*(Q)$, whose form is determined by the type of the laser. In the case of the fibre laser, this dependence is 'degenerate' – within the experimental error, different values of the laser power correspond to the same optimum Péclet number. Thus, in the range of parameters under consideration, when cutting with the use of the fibre laser, a minimum surface roughness optimised for the speed and cutting width (focus position) can be achieved if the Péclet number $\mathrm{Pe}^* = 0.35$ is provided, regardless of the thickness of the cut sheet and laser power.

In case of the CO$_2$ laser, different optimal Péclet numbers correspond to different values of the dimensionless power, and the dependence $\mathrm{Pe}^*(Q)$ is close to linear.

The measurements show that the roughness corresponding to the optimal speed and cutting width depends on the power – it changes along the lines in Fig. 5, which represent the dependences $\mathrm{Pe}^*(Q)$. The generalised data derived in the optimisation of cutting with respect to three parameters – the cutting speed, position of focus relative to the surface (cutting

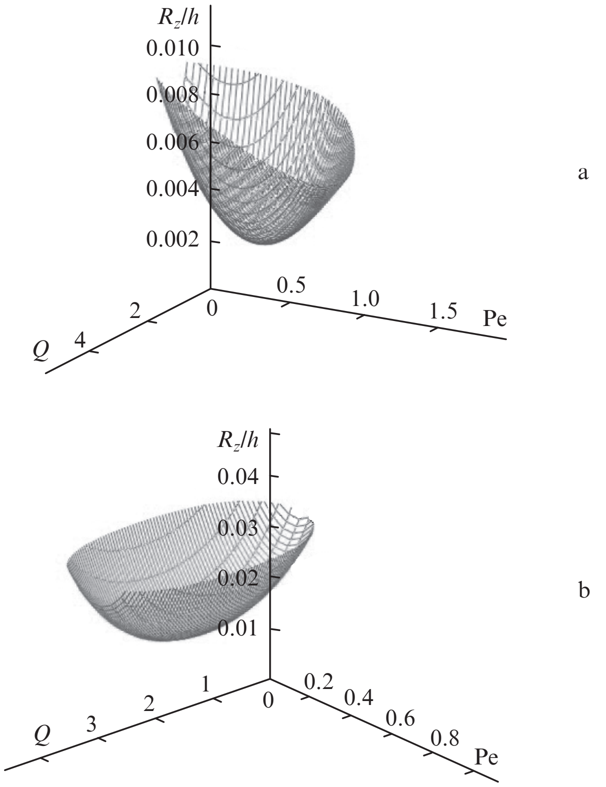

Figure 6. Experimental dependences of the surface roughness R_z/h on the Péclet number $\mathrm{Pe} = V_c b/\gamma$ and the dimensionless power $Q = W/(\lambda_m h T_m)$ when cutting the sheets of 5 mm in thickness by (a) the CO_2 laser and (b) the fibre laser.

width) and laser radiation power – are shown in Fig. 6 in the form of plots of the surface roughness R_z/h as functions of the Péclet number and dimensionless power.

In fact, Fig. 6 presents the experimentally defined functional $R_z/h = \Phi(Q, \mathrm{Pe}^*)$ for both types of the lasers. It can be seen that this function is cup-shaped and possesses a minimum that corresponds to the optimum cutting conditions: $\mathrm{Pe}_{\mathrm{opt}} = \mathrm{const}$, $Q_{\mathrm{opt}} = \mathrm{const}$. Optimal values of the dimensionless parameters are given in Table 1.

Table 1. Optimal dimensionless parameters of cutting.

Parameter	CO_2 laser ($\lambda = 10.6$ μm)	Fibre laser ($\lambda = 1.07$ μm)
$\mathrm{Pe}_{\mathrm{opt}} = V_{\mathrm{opt}} b_{\mathrm{opt}}/\gamma$	0.5	0.35
$Q_{\mathrm{opt}} = W/(\lambda_m h T_m)$	1.6	1.6–2.6

The sections of the cups $R_z/h = \mathrm{const}$ in Fig. 6 are of ellipsoidal form; their large axes coincide with the lines in Fig. 5, being the result of optimisation with respect to two parameters. In the case of the fibre laser, the cup is elongated along the axis of the dimensionless power that corresponds to the condition $\mathrm{Pe} = \mathrm{const}$, while in case of the CO_2 laser the cup is tilted to this axis at a certain angle.

The data show that the similarity law (2) is common to both types of the lasers, but its details, in particular, the form of the dependence $R_z/h = \Phi(Q, \mathrm{Pe})$ and the optimal Péclet numbers are different. In the case of the CO_2 laser, the dependence $R_z/h(Q)$ has a pronounced minimum. When cutting with the use of the fibre laser, there exists a wide range of the Q values with a weak power dependence of the roughness.

The data in Table 1 allow one to present and compare in simple and clear form the conditions for obtaining the minimal roughness of the cut surface by using two types of the lasers. The dimensional dependences are more convenient for practical purposes. To gain the minimal roughness in the case of the CO_2 laser, it is necessary to increase the laser power proportionally to the thickness of the cut sheet, so as to satisfy the condition $W/h = 200 \pm 20$ W mm^{-1}. No significant changes in the surface roughness occur when cutting with the use of the fibre laser in the range $W/h = 200-320$ W mm^{-1}, whilst the power increase does not lead to an increase in optimal velocity at a given sheet thickness (see Fig. 4). It is therefore advisable to use the same power for both lasers, namely 200 W per 1 mm thickness of the cut sheet.

The cutting width does not refer to the adjustable parameters of laser cutting, it represents a characteristic of the cut, which complicates the use of the condition $V_{\mathrm{opt}} b_{\mathrm{opt}} = \mathrm{const}$. For the fibre and CO_2 lasers, the optimal cutting width increases with the thickness of the cut sheet. Herewith, the laser type virtually does not affect the dependence of the cutting width on the thickness (Fig. 7). The data in Fig. 7 are approximated by the dependences $b_{\mathrm{opt}} = 0.35 + 0.02h$ for the CO_2 laser and $b_{\mathrm{opt}} = 0.32 + 0.027h$ for the fibre laser. This allows one to exclude the cutting width from the conditions $V_{\mathrm{opt}} b_{\mathrm{opt}} = \mathrm{const}$ and, within the experimental scatter of $\pm 15\%$, express the optimal cutting speed via the sheet thickness by means of an analytic dependence. The relations for the optimum cutting speed appear as follows: $V_{\mathrm{opt}} = 11/(0.35 + 0.02h)$ for the CO_2 laser and $V_{\mathrm{opt}} = 7/(0.32 + 0.027h)$ for the fibre laser, where b_{opt} and h are taken in millimetres, and V_{opt} – in mm s^{-1}.

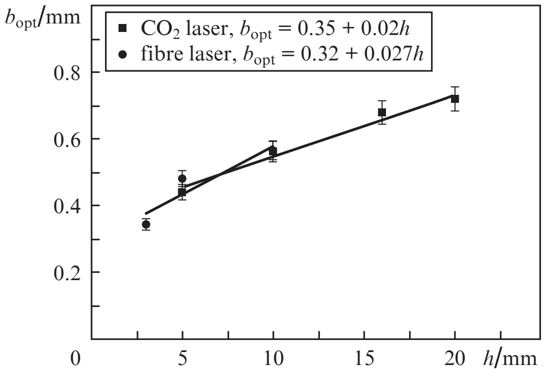

Figure 7. Optimal cutting width at the optimum focus position and optimal radiation power and cutting speed as functions of the sheet thickness for the fibre and CO_2 lasers.

4. Conclusions

We have compared the laser-oxygen cutting of the low-carbon steel with the use of the fibre laser (the wavelength of 1.07 μm) and the CO_2 laser (the wavelength of 10.6 μm). As a result of generalising the experimental data, the conditions under which the surface roughness of the cut is minimal have been obtained. These conditions are expressed in the form of similarity laws in terms of the dimensionless variables, namely the Péclet number $V_c b/\gamma$ and the laser power per unit the sheet thickness $W/(\lambda_m h T_m)$. The conditions are the same for the two types of the lasers: $V_{\mathrm{opt}} b_{\mathrm{opt}}/\gamma = \mathrm{const}$, $W_{\mathrm{opt}}/(\lambda_m h T_m) = \mathrm{const}$.

The values of the dimensionless variables that correspond to the minimal roughness when cutting with the use of the fibre and CO_2 lasers have been found. Simple relations have been derived from the similarity laws, which allow one to determine the basic original parameters of the laser cutting for a given sheet thickness – the laser power and cutting speed corresponding to the minimal roughness.

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