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Energy characteristics of laser-oxygen cutting of steel by CO_2-laser radiation

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Abstract. **The energy balance in the laser-oxygen cutting of steel sheets of thickness 5–16 mm was investigated. The necessary expenditure of energy and the thermal efficiency of the process were determined for cutting parameters that provided minimal roughness (characteristic height of irregularities) of the cut surface. For the minimal roughness, the ratio between the components of the energy balance equation was determined to be independent of the sheet thickness. We also measured the oxidised iron fraction in the melt being removed.**

Keywords: *laser cutting, CO_2 laser, cut quality, energy balance.*

1. Introduction

Laser cutting differs from other material cutting techniques in that it combines a high cutting rate and a high quality of the cut surface. Recent years have seen remarkable progress in the employment of disk and fibre solid-state lasers for cutting metals. In comparison with CO_2 lasers, these lasers enable cutting thin (up to ~5 mm in thickness) sheets with a high rate. However, when cutting thick sheets the efficiency of using solid-state lasers is substantially lower and they are inferior to CO_2 lasers as regards the cut quality. In the opinion of the majority of researchers, the reason lies with the features of the absorption of 1.06–1.08 μm wavelength radiation in the cut channel at oblique radiation incidence and a significant lowering of the absorption coefficient with increase in sheet thickness [1, 2]. At the present time CO_2 lasers are the sole instrument for high-quality laser cutting of metal sheets of different thickness, including thick sheets.

In our previous works [3–5] we formulated a quantitative criterion for the quality of a cut: a minimal surface roughness for the complete absence of burr (solidified drops of the melt on the lower edge of the cut). Proceeding from this criterion, we performed for the first time a complex optimisation of the cutting of steel up to 25 mm in thickness using CO_2-laser radiation and determined dimensionless parameters which serve to minimise the roughness of cut walls.

The present work completes the series of investigations into the laser cutting of thick steel sheets by CO_2-laser radiation, which was commenced in Refs [3–5], and is concerned with determination of the energy efficiency of cutting, proceeding from energy balance measurements under the optimal conditions of minimal roughness. These investigations are required to optimise the expenditure of energy in the cutting, which is especially topical in view of the relatively low CO_2-laser efficiency in comparison with fibre and disk lasers.

2. Formulation of the problem and experiment technique

Laser cutting is accompanied with local material melting and involves melt removal using the jet of an auxiliary gas. The cutting of thick sheets of carbon and low-alloyed steels is made, as a rule, in an oxygen jet (the laser-oxygen cutting). In this case, the exothermal reaction of iron oxidation is also a source of energy comparable to the energy of laser radiation. The entire process is the stimulated combustion of iron in oxygen [6].

The power balance equation in the laser-oxygen cutting may be written in the form [7, 8]

$$AW + W_{\mathrm{ox}} = W_{\mathrm{m}} + W_{\mathrm{cond}}, \tag{1}$$

where W is the power of laser radiation; A is the integral coefficient of radiation absorption in the cut channel; W_{ox} is the power released in the oxidation of iron; W_{m} is the power spent to fuse the metal in the cut zone; and W_{cond} is the power that goes to heat the metal outside of the cut zone. In an expanded form the balance equation assumes the following form:

$$AW + Vbh\rho\delta_{\mathrm{ox}}\Delta H = Vbh\rho(c\Delta T + L_{\mathrm{f}}) + W_{\mathrm{cond}}, \tag{2}$$

where V is the cutting rate; b is the average cut width; h is the sheet thickness; ρ is the material density; c is the specific heat capacity of the material at room temperature; $L_{\mathrm{f}} = 225$ J g^{-1} is the material's specific heat of fusion; δ_{ox} is the oxidised iron fraction in the melt being removed; ΔH is the specific heat of the oxidation reaction (in J kg^{-1}); $T = T_{\mathrm{m}} - T_0$; T_{m} is the material's melting temperature (in °C); and T_0 is the ambient temperature.

The balance equation may be simplified by introducing generalised dimensionless parameters. The authors of Refs [9, 10] calculated the energy loss due to thermal conduction under laser cutting conditions and showed that the expression for the thermal loss can be written in the form $W_{\mathrm{cond}}/(\lambda h\Delta T) = f(\mathrm{Pe})$, where $\mathrm{Pe} = Vb/\chi$ is the Peclet number; $\chi = \lambda/(\rho c)$ is the thermal diffusivity of the material; and λ is its thermal conductivity. The Peclet number may be regarded as the dimensionless cutting rate. On introducing the dimensionless radiation power $Q = W/(\lambda h T_{\mathrm{m}})$ and assuming that $T_0 = 0$ and that the

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melt temperature $T_{mf} = T_m$, the energy balance equation may be written in the dimensionless form [9]:

$$AQ = \mathrm{Pe}\left(1 + \frac{L_f - \delta_{ox}\Delta H}{cT_m}\right) + f(\mathrm{Pe}). \quad (3)$$

Therefore, the balance equation (3) includes the thermal physical material characteristics and only two dimensionless variables (Q and Pe), which are defined by specified cutting parameters W, V, and h as well as the cut width b.

Experiments to measure the optimal values of the generalised variables are described elsewhere [3–5]. According to the resultant data, for a cut sheet thickness $h = 5-25$ mm, the roughness is minimised when the conditions $Q \approx$ const and Pe $\approx$ const are fulfilled. In this case, the optimal values of Q and Pe are the same for all thicknesses: $Q_{opt} \approx 1.6$, $\mathrm{Pe}_{opt} \approx 0.5$. For a sheet thickness $h = 5$ mm, the minimal roughness $R_z = 8-10$ μm, and for $h = 10-24$ mm it grows almost linearly with the sheet thickness.

Measurements of the oxidised iron fraction δ_{ox} and therefore of the contribution of the exothermal oxidation reaction to the total balance poses the greatest difficulty in determining the energy balance (1). That is why the quantities AW, W_m and W_{cond} were measured experimentally and the quantity W_{ox} was calculated from the balance equation.

In experiments we employed a cw CO_2 laser with a self-filtering resonator and a beam perfection parameter BPP = 4.7 mm mrad [11]. The laser generated plane polarised radiation, which was next transformed to circularly polarised radiation using a phase shifting mirror. Cutting was carried out using the circularly polarised radiation in the traditional way – with the use of a lens focusing system, with oxygen at a density of 99.999 % being fed along the axis of the laser beam. We cut low-carbon St.3ps steel sheets of thickness 5, 10, and 16 mm.

For sheets of different thickness, the cutting parameters were selected in accordance with the criteria for minimising the roughness of the cut surface, which were determined in Ref. [3]. The experimental values of W, V, b and the excess oxygen pressure Δp in the prechamber of the cutting head for a sheet of thickness h are given in Table 1.

Table 1. Cutting parameters.

h/mm	W/W	V/mm s^{-1}	b/mm	Δp/MPa
5	1000	24.17	0.530	0.050
10	2000	18.33	0.725	0.050
16	3000	15.0	0.958	0.04

In the calculation of the Peclet number, for a cut width we used the average of its widths measured at the upper and lower sheet surfaces. The power W_m can be determined from the expression

$$W_m = Vhb\rho(c\Delta T_f + L_f), \quad (4)$$

where $c = 0.66$ J g^{-1} K^{-1} is the average specific heat capacity of the metal in the course of cutting; $T_f = T_{mf} - T_0$ is the temperature difference between the melt and ambient medium. According to Ref. [12], for a moderate rate V, the value of T_{mf} may amount to ~1900 K. By substituting in expression (4) the values of the cutting rate and the cut width for sheets of different thickness borrowed from Table 1, we determined the power required for fusing the metal.

To determine the thermal conduction power loss W_{cond}, use was made of a colorimetric technique: a sample of length l was cut from a steel sheet of thickness h during a time τ, following which we found (with the aid of a calorimeter) the energy E_g spent to heat the material during the cutting and the power (from the relation $W_{cond} = 2E_g(V/l) = 2E_g/\tau$). The factor 2 in the relation for W_{cond} takes into account the thermal loss in two directions from the cut. A detailed analysis of this energy measurement technique was made in Ref. [13]. The energy loss due to convective cooling both by the technological gas and by the ambient air was shown to be small provided the samples were not heated above 100 °C.

Nevertheless, to monitor the possible thermal loss in the samples being cut, for instance due to convective heat exchange with the ambient air, the measurements were made for eight samples of different mass to determine the average value of the power W_{cond}.

In the present work the laser radiation absorption coefficients for steel sheets of thickness 5, 10, and 16 mm were measured using a technique described in Ref. [14]. The experimental facility is schematised in Fig. 1.

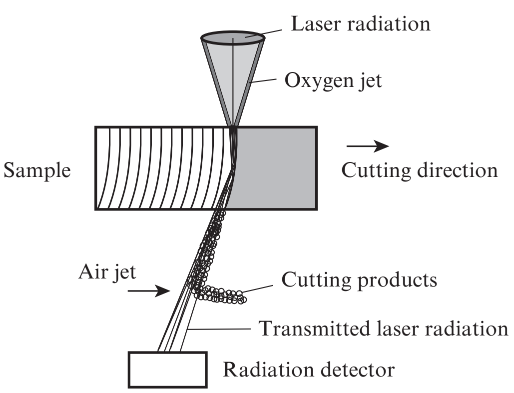

Figure 1. Layout of the measurement of the coefficient of laser radiation absorption in the cut channel.

The substance of this technique is as follows. The radiation transmitted through the cut channel arrived at a detector, in our work an OPHIR 5000W-CAL-SH power meter. In doing this we monitored the diameter and deflection of the beam in the interaction of the radiation with the material in the course of cutting, so that all radiation transmitted through the cutting region found its way into the detector. The products of metal combustion were blown away by an air jet, which prevented them from reaching the detector.

3. Results

The data resulting from our W_{cond} measurements for 5-, 10-, and 16-mm thick samples with strongly varying masses M are collected in Table 2. When calculating E_g we used the specific heat capacity $c = 0.46$ J g^{-1} K^{-1} for the cold metal. Samples of different width and therefore of different mass were cut in the experiment. The data given in Table 2 suggest that a 2–3-fold variation of the sample temperature increase T_g after cutting for a constant thickness h of the steel sheet being cut has only a minor effect on W_{cond}. This leads us to assume that convective cooling affects only slightly on the measured value of W_{cond}. The spread of experimental W_{cond}

Table 2. Results of W_{cond} measurements for different sheet thicknesses.

h/mm	M/g	l/cm	τ/s	W_{cond}/W	ΔT_2/°C
5	186.9	10.4	4.2	873	21.2
	90.6	10.0	4.0	778	37.4
10	95.8	9.5	5.2	1533	90.2
	349.8	9.5	5.2	1749	28.0
16	243.3	9.0	6.0	2697	72.3
	629.8	8.9	6.0	2937	30.2

values did not exceed 6 % in the measurements made for eight samples.

Figure 2 shows the results of measurements of CO_2-laser radiation absorption coefficient in the cutting of samples of different thickness. Table 3 and Fig. 3 show the data on the main energy fluxes in the oxygen-assisted laser cutting of 5-, 10-, and 16-mm thick steel sheets. Also presented in Table 3 are the thermal efficiency of cutting $\eta_{\mathrm{t}} = W_{\mathrm{m}}/(AW + W_{\mathrm{ox}})$ and the oxidation reaction energy fraction $\delta_E = W_{\mathrm{ox}}/(AW + W_{\mathrm{ox}})$ in the total energy input.

One can see from Fig. 3 that all components of the balance equation (1) exhibit an almost linear dependence on the sheet thickness, i.e. the component ratios are independent of the sheet thickness. This permits explaining the fact that the minimum roughness condition $Q_{\mathrm{opt}} = W/(\lambda h T_{\mathrm{m}})$, which was studied in detail earlier [3–5], contains only the power W of laser radiation. Since the minimal roughness is attained for the whole thickness range for approximately the same values of Q_{opt} and $\mathrm{Pe}_{\mathrm{opt}}$ [3], their ratio $E = Q_{\mathrm{opt}}/\mathrm{Pe}_{\mathrm{opt}}$ remains invariable. The quantity E is the dimensionless power of laser radiation deposited in a unit volume of the material being removed. In view of the balance equation (2) and relation (4) for W_{m} we obtain

$$E = \frac{1}{A}(1 + \mathrm{Sf})\left(1 + \frac{W_{\mathrm{cond}}}{W_{\mathrm{m}}} - \frac{W_{\mathrm{ox}}}{W_{\mathrm{m}}}\right), \tag{5}$$

where $\mathrm{Sf} = L_{\mathrm{f}}/(cT_{\mathrm{m}})$ is the Stefan number.

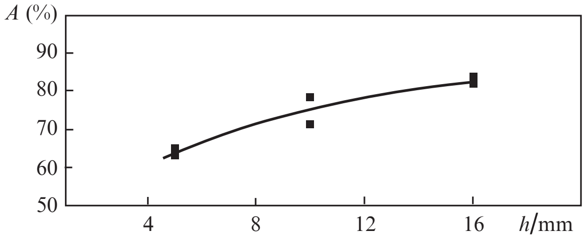

Figure 2. Coefficient A of CO_2-laser radiation absorption in the cut channel for different sheet thicknesses h. The points stand for experimental values and the solid curve is their approximation.

Table 3. Measured values of the components of power balance equation (1).

h/mm	W/W	AW/W	W_{ox}/W	W_{m}/W	W_{cond}/W	δ_E	η_t
5	1000	650	833	664	819.9	0.56	0.43
10	2000	1500	1478	1370	1608	0.5	0.46
16	3000	2490	2724	2377	2837	0.52	0.45

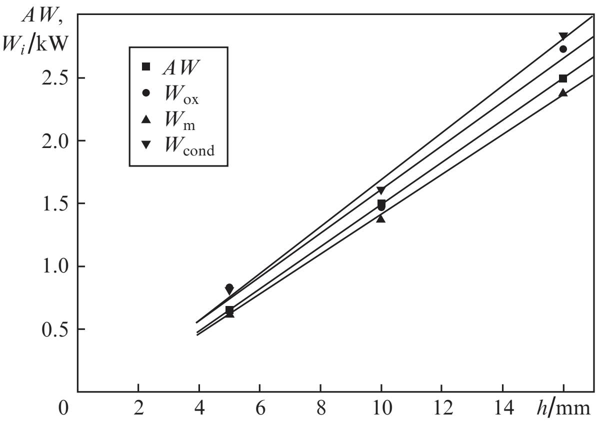

Figure 3. Components of power balance equation (1) measured as functions of sheet thickness.

Under the condition of highest quality (minimised roughness) cutting, in these experiments the ratios of energy balance components entering in expression (5) remain the same for different thicknesses of the sheet being cut. Since $A \approx$ const, from expression (5) there follows the condition $E \approx$ const, which was observed experimentally [3].

The sheet-thickness independence of energy balance components has several implications:

(i) Under the condition of minimal roughness of the cut surface, the thermal efficiency η_{t} of cutting remains constant throughout the thickness range. Approximately 45 % of all inputted energy is spent to fuse the metal, the remaining energy is removed from the cut zone due to thermal conduction and goes to heat the sample.

(ii) The oxidation reaction energy fraction E in the entire energy input is also approximately the same for all sheet thicknesses (Table 3).

(iii) The oxidised iron fraction δ_{Fe} is also the same for different thicknesses. In the laser-oxygen cutting of low-carbon steel, the FeO oxides account for more than 95 % of all oxides [12, 14]. The quantity δ_{Fe} is defined as the ratio $W_{\mathrm{ox}}/W_{\mathrm{ox}}^{\mathrm{tot}}$, where $W_{\mathrm{ox}}^{\mathrm{tot}} = Vhb\rho(E_{O_2}/M_{\mathrm{Fe}})$ is a parameter equal to the power that would be released in the combustion of all removed iron; $M_{\mathrm{Fe}} = 55.8$ g mol^{-1} is the molar mass of iron; $E_{O_2} = 254$ kJ mol^{-1} is the energy of the oxidation reaction $\mathrm{Fe} + {}^1\!/_2 O_2 = \mathrm{FeO} + E_{O_2}$ [7, 12]. The results of δ_{Fe} calculation are given in Table 4, where use is made of the designations of volume ($\mathrm{d}\Omega^{\mathrm{Fe}}/\mathrm{d}\tau$) and mass ($\mathrm{d}M^{\mathrm{Fe}}/\mathrm{d}\tau$) metal consumption rates in the laser cutting. The data of Table 4 suggest that only 30 %–35 % of iron is oxidised and makes a contribution to the overall energy balance of laser cutting. A part of the metal may additionally oxidise, for instance, when moving in the form of droplets in the flow of oxygen, but this process does not exert effect on the heating of the sheet being cut.

Table 4. Rates of oxygen and metal consumption during cutting.

h/mm	$\frac{\mathrm{d}\Omega^{\mathrm{Fe}}}{\mathrm{d}\tau}$/mm^3 s^{-1}	$\frac{\mathrm{d}M^{\mathrm{Fe}}}{\mathrm{d}\tau}$/g s^{-1}	$W_{\mathrm{ox}}^{\mathrm{tot}}$/W	δ_{Fe} (%)	$\frac{\mathrm{d}M^{O_2}}{\mathrm{d}\tau}$/g s^{-1}	$\frac{\mathrm{d}M_{\mathrm{gas}}^{O_2}}{\mathrm{d}\tau}$/g s^{-1}
5	64.0	0.500	2304	36	0.051	0.07
10	132.7	1.035	4777	30	0.088	0.13
16	229.9	1.790	8276	33	0.168	0.23

We also estimate what amount of oxygen is required to oxidise 30 % of the removed metal. To oxidise the amount of iron equal to 1 mol requires 0.5 mol of molecular oxygen.

The oxygen mass consumption rate $\mathrm{d}M^{O_2}/\mathrm{d}\tau$ required for oxidising iron may be found from the expression

$$\frac{\mathrm{d}M^{O_2}}{\mathrm{d}\tau} = 0.5\delta_{\mathrm{Fe}}\frac{\mathrm{d}M^{\mathrm{Fe}}}{\mathrm{d}\tau}\frac{M_{O_2}}{M_{\mathrm{Fe}}},$$

where M_{O_2} =32 g mol^{-1} is the molar mass of oxygen. The results of calculation are collected in Table 4. Also given in the Table are the calculated values of $\mathrm{d}M^{O_2}_{\mathrm{gas}}/\mathrm{d}\tau$ (the amount of oxygen delivered to the cutting zone), which was estimated from the following expressions:

$$\frac{\mathrm{d}M^{O_2}_{\mathrm{gas}}}{\mathrm{d}\tau} \approx \frac{\pi b^2}{4}\rho_{\mathrm{gas}}V_{\mathrm{gas}},$$

$$V^2_{\mathrm{gas}} = \frac{2C_0^2}{k-1}\left[1 - \left(\frac{p_{\mathrm{atm}}}{p_{\mathrm{atm}} + \Delta p}\right)^{(k-1)/k}\right].$$

Here, V_{gas} is the oxygen flow velocity in the cut channel determined with the help of Bernoulli equation; ρ_{gas} is the oxygen density; C_0 is the velocity of sound in oxygen; k is the adiabatic exponent; and p_{atm} is the ambient pressure.

Under the conditions of our experiment (see Table 1) for $\rho_{\mathrm{gas}} = 1.4\times10^{-6}$ g mm^{-3} we obtain $V_{\mathrm{gas}} = 2.40\times10^5$ mm s^{-1} and the values of $\mathrm{d}M^{O_2}_{\mathrm{gas}}/\mathrm{d}\tau$ given in Table 4. These data suggest that the amount of oxygen passing through a section of area $\pi b^2/4$ is only 1.5 times greater than the amount of oxygen spent to oxidise iron. Since the real oxygen flow in the cut channel and its interaction with the surface is not taken into account in this estimate, the calculation gives an upper estimate, and it may be assumed that it is precisely the amount of oxygen delivered to the sample that limits the oxidised iron mass.

4. Diskussion of results

One can see from Fig. 3 that both the absorbed laser power and the power released in the oxidation reaction grow linearly with sheet thickness under minimised-roughness conditions. In this case, the oxidised iron fraction remains invariable. As suggested by the estimates given above, for thicknesses of 5–15 mm and an oxygen pressure of 0.05 MPa the consumption of oxygen is only 1.5 times the consumption required to produce the iron oxidation degree observed in the experiment. For sheet thicknesses greater than 15–20 mm the oxygen pressure has to be lowered [3, 4]. This is done to prevent the overheating of material in the upper part of the cut and the transition of the cutting process to an uncontrollable mode with a large roughness [8]. Therefore, with increasing thickness the chemical reaction energy fraction in the overall energy balance becomes smaller and the energy condition for a high-quality cut is violated. Furthermore, when the oxidised metal fraction becomes smaller, viscosity and the surface tension coefficient increase [15], which hampers the removal of melt and may be responsible for an increase of roughness and the emergence of burr. Both of these circumstances may limit the maximum thickness of sheets cut with a high quality.

A significant difference between the laser cutting of thick and thin sheets (less than 3–5 mm in thickness) consists in that the cutting rate, the shape of the cut surface and its roughness are largely determined by the processes of melt removal from the cut channel. The physics of these processes is complicated and is not yet perfectly understood [16, 17]. The character of melt flow has a substantial effect on relief formation [16]. The flow mode (laminar or turbulent) is characterised by the Reynolds number Re, which is the ratio between the forces of inertia and the forces of viscous friction. The melt flow at the cut front may be treated as a voluntary flow through a rectangular tube. For a voluntary flow the Reynolds number is defined in the following way [18]:

$$\mathrm{Re} = RV_{\mathrm{m}}/\nu, \tag{6}$$

where R is the hydraulic radius; V_{m} and ν are the flow velocity and the kinematic viscosity of the melt. The hydraulic radius is defined as the ratio between the flow section area and the wetted perimeter [18]: $R = h_{\mathrm{m}}/(1 + 2h_{\mathrm{m}}/b)$, where h_{m} is the thickness of the melt film.

According to the results of the present work, the oxidised iron fraction for the minimal roughness remains invariable throughout the thickness range and is equal to 0.3–0.35. More than 95% of oxides are the FeO oxides. The cutting rates whereby the energy balance was measured and the surface roughness was minimal ranged between 15 and 24.2 mm s^{-1}. For cutting rates below ~33 mm s^{-1} the temperature of the melt film depends only slightly on the rate: it varied in the 1900–1940 K range [11]. In this case, the melt viscosity variation does not exceed 10% and the average viscosity values in the indicated temperature range are equal to 1.1×10^{-6} m^2 s^{-1} for Fe and 10^{-6} m^2 s^{-1} for FeO [15].

To determine the melt flow velocity we assume, like is done in estimates of this kind, that the melt is removed under the force of auxiliary gas pressure [16]: $\rho_{\mathrm{m}}V_{\mathrm{m}}^2/2 \approx \Delta p$, where ρ_{m} is the density of the melt substance and Δp is the pressure difference across the channel length. We also take advantage of the mass conservation law to make a crude estimate of h_{m}: $V_{\mathrm{m}}h_{\mathrm{m}} = Vh$. As a result we obtain estimates for Reynolds numbers: Re ≈ 100–260 for Fe and 90–220 for FeO.

A voluntary flow is laminar when the Reynolds number does not exceed 580 [18]. Considering that the pressure difference Δp and hence the gas velocity may only decrease with increase in sheet thickness, it is safe to assume that the Reynolds numbers do not amount to the critical values in the conditions of highest-quality laser cutting.

Among the criteria for cut quality in our work, along with minimal roughness, is the absence of burr. When the forces of melt surface tension are strong enough, a part of the melt is not carried away from the sheet edge and remains in the form of solidified droplets and makes up the burr. The ratio between the forces of surface tension and the forces of melt inertia is characterised by the Weber number

$$\mathrm{We} = \frac{h_{\mathrm{m}}\rho_{\mathrm{m}}V_{\mathrm{m}}^2}{\sigma}, \tag{7}$$

where σ is the surface tension coefficient of the melt substance [19].

In view of the estimative relations given above for the melt film parameters, the Weber number may be related to the experimentally measured parameters in the following way:

$$\mathrm{We} = \frac{Vh\sqrt{2\rho_{\mathrm{m}}\Delta p}}{\sigma}. \tag{8}$$

Estimates made using formula (8) yield We ≈ 5–11 for Fe and 2–4 for FeO for h = 5–16 mm.

For the melt to be reliably removed from the cut channel and from the sheet edge, the Weber number should exceed some critical value, which is equal to 2.2 in the conditions of laser cutting [18]. As is clear from the foregoing estimate, the conditions for the removal of melt from the sheet edge are fulfilled in our experiment.

Mention should also be made of the following circumstance. One can see from Fig. 3 that all specific, i.e. divided by the sheet thickness, powers are approximately equal. It is not unlikely that this energy equilibrium of the laser cutting of steel with the help of oxygen is among the conditions for obtaining minimal surface roughness.

5. Conclusions

Our work is the first complex investigation into the power balance in the laser-oxygen cutting of thick steel sheets for the optimal parameter W/h = 200 W mm^{-1} and a Peclet number $\mathrm{Pe}_{\mathrm{opt}} = 0.5$, which correspond to the minimal roughness of the cut surface. The following results were obtained for the first time in our experiments:

(i) The coefficient of CO_2-laser radiation absorption was measured in the cutting of 5–16 mm thick steel sheets.

(ii) The oxidised iron fraction was shown to be equal to 30%–36% in the cutting with a minimal roughness, the minimal roughness being independent of the metal thickness to within experimental error.

(iii) In the laser cutting of steel, all components of the power balance equation (the absorbed laser power AW, the power W_{ox} of the exothermal reaction of iron oxidation by oxygen, the power W_{m} spent to fuse the metal in the cut zone, the power W_{cond} spent to heat the metal beyond the cut zone) divided by the sheet thickness were found to be independent of h.

(iv) The specific powers (AW/h, W_{m}/h, W_{cond}/h, W_{ox}/h) for sheets of thickness 5, 10 and 16 mm were shown to have close values. The spread of experimental values of these quantities is within an interval of 130–170 W mm^{-1}. It may be suggested that this result is due to the selected cutting modes [3, 4] corresponding to the minimal roughness of the cut surface. Departures from the optimal value of the ratio between balance equation components and prevalence of some single factor, for instance an excess of the power of the exothermal reaction of iron oxidation by oxygen or an increase in W_{cond}, may impair the surface quality owing to an overheating of the cut zone and emergence of uncontrollable combustion.

(v) We performed a qualitative analysis of the data obtained. The resultant estimates of Reynolds and Weber numbers made for the conditions of our experiment showed that cutting with a minimal roughness and without burr formation is attended with a laminar mode of melt flow at the cut front and that the condition for the removal of melt from the lower cut edge is fulfilled, with the effect that no burr is formed on the edge.

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