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SLOVAK REPUBLIC

INTERNATIONAL CONFERENCE of SCIENTIFIC PAPER
AFASES 2013
Brasov, 23-25 May 2013

ASPECTS OF THE POWER BALANCE FOR LASER CUTTING PROCESS

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Abstract:.*Oxidation of iron in oxygen is an important power source for cutting steel through thermal processes.For oxygen-assisted laser cutting of steel plates energy to melt the material is given by the oxidation reaction and the laser beam radiation.It provides a way to assess the contribution to material melting of two physical phenomena.The material is removed in the molten state.On the basis of the cut shape are calculated power consumed to start the oxidation reaction and power given by reaction.The efficiency of the cutting process is expressed as dimensionless fractions.*
Keywords: *laser oxygen cutting,steel, specific energy.*

1. INTRODUCTION

The cutting of materials by a thermal process can be helped by the presence of reactive gas which together with material removal effect support a chemical exotherm reaction which brings energy to the erosion front [1],[2]. Using oxygen to cutting by melting of iron base materials is due to a favorable conjuncture of situations that make this possible. Thus the combustion of iron from steel in oxygen liberates sufficient calories to compensate heat losses by conduction, convection and radiation and heated the reaction products so as to keep the local temperature of workpiece to iron ignition.
Temperature for ignition of the reaction should be close to the melting temperature of the metal. Also, the melting temperature of the formed oxides` should be close to the melting temperature of the metal so that all the reaction products are liquid and can be removed by the kinetic effect of the gas as they are formed.

At forming temperature oxides can be, solid, liquid or gas. For solid oxides forms a layer which prevents contact between oxygen and metal stops metal burning. This is the case of alumina is formed on the surface of the aluminum for thermal cutting of aluminum. The formation of a reaction product gas, such as carbon monoxide, is an obstacle. Gas layer produced adheres to the melt metal surface by absorption and hinder the access of oxygen.

Contaminate the oxygen which will slow down the combustion. Liquid oxide formation is favorable to reaction propagation. They have a catalytic role. The liquid oxides can be removed simultaneously with liquid molten metal. To maintain the oxidation reaction is important contact between the reactants at the molecular level.

2. OXIDATION REACTION

Metals and gases that satisfy these conditions to enable the use of a reactive gas for machining are limited:

- iron in oxygen:

$2Fe+2O_2 = Fe_3O_4 +270.8$ Btu; (1)

- copper in chloro:

$2Cu +2\ Cl = Cu_2Cl_2 + 70.8$ Btu (2)

(Cu_2Cl_2 melts at 420^oC);
- tin in chloro:
$Sn + 4Cl = SnCl_4 + 129.6$ Btu (3)
($SnCl_4$ is liquid at ambient temperature).

Cutting copper and tin with chloro in the role of reactive gas may not be made because chloro is a toxic gas.

In the presence of oxygen and iron from the steel oxidizes slowly to ambient temperature. As the temperature increases the oxidation is accelerated. For temperature of 1300^oC reaction becomes quasi-instantaneously. This temperature is called the ignition temperature.The ignition temperature depends also on the material. It is known that over the temperature of1000^oC and the oxidation reaction becomes significant at temperatures of 1350^oC or 1400^oC is almost instantaneous [5] [6] .In some cases it is considered the temperature of 1200^oC[5]. Following iron oxides are formed FeO, Fe_2O_3, Fe_3O_4. All these oxides are formed by a strong exothermic reaction while reaction is fast. For each atom of oxygen fixed in the form of iron oxidation emit 66 calories.

The chemical reactions of oxidation of iron have the following form: [6]:

$$Fe + O \rightarrow FeO + 267kJ \quad (4)$$

$$3Fe + 2O_2 \rightarrow Fe_3O_4 + 1120kJ \quad (5)$$

$$2Fe + 1{,}5O_2 \rightarrow Fe_2O_3 + 825kJ \quad (6)$$

For laser cutting showed that importance has only formation of FeO. It is estimated that the temperature of cutting front is between the 1950-2250^oC. The oxidation reaction for 1mol of Fe requires a temperature of 1400^oC to initiate the reaction and the heat to boot reaction is 275 J/g. It is noted that this is much lower than that obtained from the chemical reactions. These values are given relative to amount expressed in moles of reactants. The chemical oxidation reaction of iron takes place with both reactants in excess.

In reality, the quantities of reactants vary because iron can burn faster than laser source heat the material.

From the existing alloy elements especially in alloy steels and stainless steel which give additional heat at erosion front by oxidation noted:[6]

$$Cr + 3O_2 \rightarrow 2Cr_2O_3 + 1163.67\,kJ \quad (7)$$

$$Ni + 1.5O_2 \rightarrow NiO + 248kJ \quad (8)$$

3. EXPERIMENTS

In experiments was used a CO_2 laser MAZAC 1500. Maximum average power emitted is 1500 W. In experiments using carbon steel sheet cold rolled SR EN 10025 (OL 37 - STAS 500/2, S235), with a thickness of 3 mm [3], [4].

In the experiments have varied the following parameters:

-Oxygen pressure pO_2 [bar]. Oxygen pressure is a process parameter that was measured at the outlet of the gas tank. It has a direct influence on the gas speed in the cut and as result in chemical reaction of burning material.

- Average power P[W]. Average power is the energy emitted by the laser oscillator in a long time. Average power is directly adjustable on the machine control.
- Cutting speed v [mm/min]. Cutting speed is the relative speed of movement between the laser head and the workpiece. Its influence is considerable both in general cutting process and particularly for irradiation conditions. Cutting speed is adjustable directly on the machine control.
- Pulse frequency f [Hz]. Pulse frequency is the number of pulses per unit time. Pulse frequency is adjustable directly on the machine control.
- Cycle η [%] cycle (or duty cycle) is the ratio of pulse duration (or pulse time) and total duration of the between two pulses (period). Cycle is adjustable directly on a machine command.

Upper and lower levels influence factors are given in Table 1.Was measured cut width on top of workpiece w_s [mm] and bottom of workpiece w_i[mm]. The top piece is considered that direct irradiated by laser beam. In the calculations was used the average cut width:

$$w_m = \frac{w_s + w_i}{2}\,[\text{mm}] \quad (9)$$

Energy evaluation of laser cutting process was done by identifying a type power size a associated with physical phenomenon. Thus, similar to the average power of the laser beam material is considered power necessary to melt the material a power consumed to start oxidation reaction and power released as a result of oxidation. These were calculated by the ratio of energy and time.

Table 1: Levels of influence factors

influence factor	Lower level	Higher level
Average power *P [W]*	800	1500
Cutting speed *v [mm/min]*	1300	3000
Cycle η [%]	50	85
Frequency *f [Hz]*	150	400
Oxygen pressure pO_2 *[bar]*	0.8	2

As a general assumption is considered that the shape of the cut is kept constant during the process and the material is removed only in the molten state at the melting temperature.Cross section of the cut is considered the shape of a trapezoid. It neglects the removal of material as vapors. The process of cutting is uniformly and stable.

To appreciate the area in which the oxidation takes place was considered cutting front surface. This is slightly larger than the cross-section area through cut. Material removal in laser cutting process is considered relative to the cross-section area of cut.

2. SPECIFIC ENERGY

The specific energy to material removal of in molten state Q is defined as the ratio of the linear energy E_l consumed in the process and cut cross section area A_s.

$$Q = \frac{linear\,energy}{cut\,cross\,section} = \frac{E_l}{w_m\, e}\left[\frac{J}{mm^3}\right] (10)$$

Where:
e –sheet thickness, e= 3mm.
- linear energy $E_l = \frac{P}{v}$ [J/mm](11)

Specific energy to removing material characterized cutting process relative to change of influence factors. Although the calculations are based on values for a cut already achieved efficiency helps when you want to determine the linear energy for other processes of laser cutting. From the technological point of view, it is intended situation that the specific energyf or material removal is to minimal value.

Minimum specific energy expressed as minimum energy consumption as a quantity expressed in J to remove the maximum of material expressed in mm^3.

The reduction in the values specific energy may be associated with the oxidation reaction contribution. The oxidation reaction increases cut cros-section area through without changing the linear energy.

Figure 1 shows the Pareto diagram for specific energy Q. Decreased specific energy Q means lower energy consumption to remove unit volume of material. It is observed that the higher effect is the speed, followed by the power effect. Speed effect is a decreasing effect and the power is increasing effect.

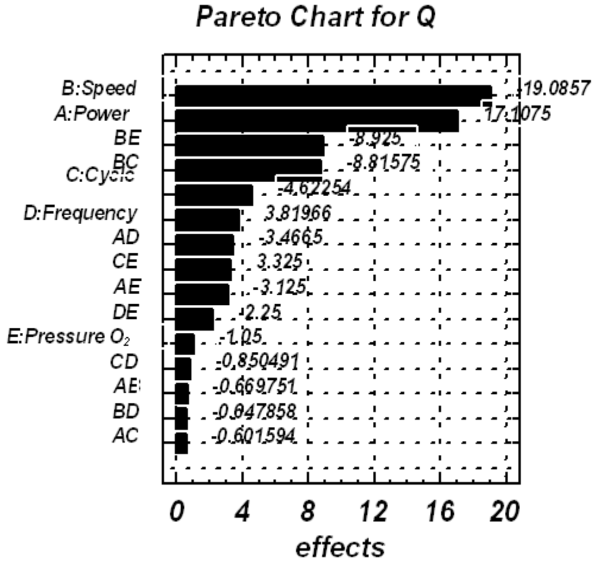

Figure 1 Pareto chart for specific energy

The following effects are cycle and frequency efects. It is noted that the oxygen pressure and its interactions have little effect. Increasing energy put to workpiece by increasing power level increase specific energy Q.

It shows that some additional energy is used for vaporization and not in useful physical phenomenon of melting material.

3. POWER FOR MELTING AND OXIDATION

In the following we will analyze the cutting process in terms of energy, using experimental results. It is considered that cutting takes place continuously and the process is stable. It is characterized by the following powers:

- *P*– time average power of the laser beam;
- P_u–useful power; the power needed to ensure the material melting;
- P_{in}–the power needed to provide the necessary heat to initiate the oxidation reaction;
- P_{out}–power resulting from the oxidation reaction.

The useful power is determined by the relation:

$$P_u = \frac{energy\ for\ melting}{time} = \rho \cdot A_s \cdot v \cdot L_0\,[\mathrm{W}] \quad (12)$$

where :

- ρ=7.85 g/cm^3, density of the material;
- L_0 –the heat required to bring the material to the melting temperature and to melt the material to be processed. $L_0 = 2396\,J/g$
- cut cross-section area

$$A_s = \frac{w_s + w_i}{2} e = w_m \cdot e\,[\mathrm{mm}^2] \quad (13)$$

Based on the similar reasoning, the calculated power required to initiate the oxidation reaction. is:

$$P_{in} = \frac{energy\ \ for\ preheating}{time}\,[\mathrm{W}] = \rho \cdot A_f \cdot v \cdot L_{in} \quad (14)$$

- where the cutting front area is:

$$A_f = \frac{1}{2}\frac{w_s + w_i}{2}\pi \cdot \sqrt{\left(\frac{w_s - w_i}{2}\right)^2 + e^2}\,[\mathrm{mm}^2] \quad (15)$$

Heating occurs at the front of erosion. In order to activate the oxidation reaction is necessary to heat the material more than1000^{o}C. Was considered to L_{in}=550J/g value.

At the cutting front takes place a heat release after oxidation:

$$P_{out} = \frac{energy\ from\ oxydation}{time} = \rho \cdot A_f \cdot v \cdot L_{out}\ [\mathrm{W}] \quad (16)$$

L_{out} value was considered: L_{out}=4600J/g

Figure 2 shows the Pareto chart for useful power. It is noted that for this highest effect is speed effect. This effect is increasing effect. Thus, it is shown that the increase in speed favors melting and reduces vaporization of the material. Continuous irradiation given by cycle favors the melting and discontinuous irradiation given by frequency favors vaporization losses of heat by conduction. Power has significant effects by its interactions. Highest effects have parameters that control the interaction time between laser radiation and material. Oxygen pressure has little effect.

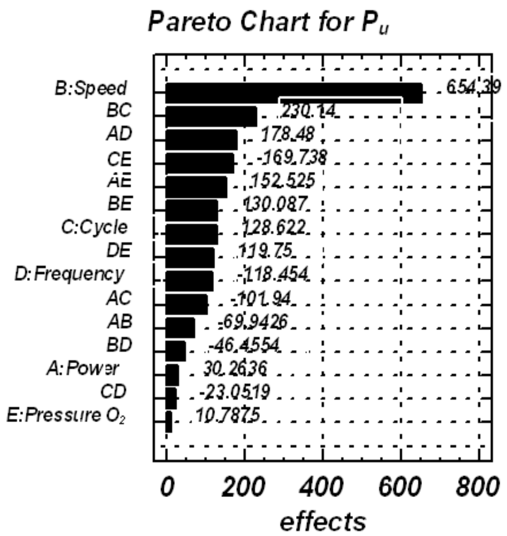

Figure 2 Pareto chart for useful power

Figure 3 shows the Pareto chart for the power required to initiate the oxidation reaction.

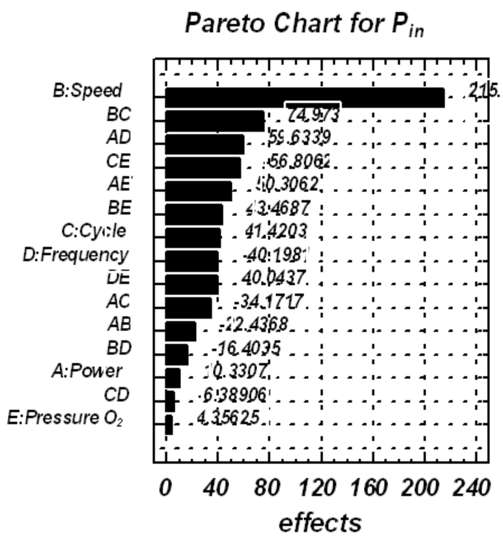

Figure 3 Pareto chart for the power required to initiate the oxidation reaction

The highest effect is speed effect. This a increasing effect is. The second effect is the interaction between the speed and cycle. The interaction between cycle and oxygen pressure has high effect.

Figure 4 shows the Pareto chart for the power given by the oxidation reaction. It is noted that the highest effect is the speed effect.

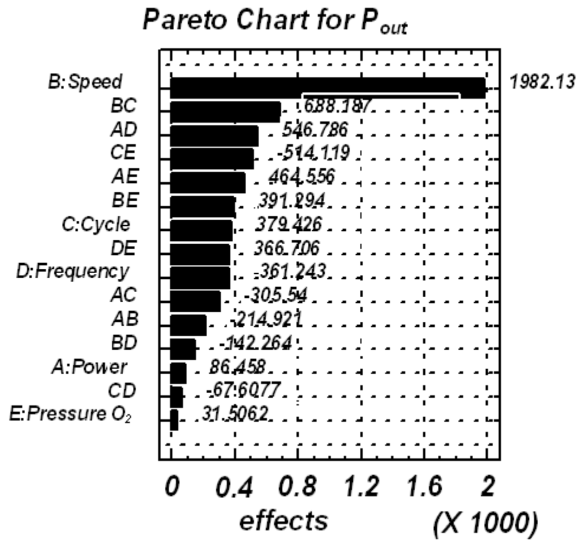

Figure 4 Pareto chart for the power given by the oxidation reaction

Hierarchy of factors influence for three powers considered is similar because the difference that appears in calculus formula is only for amount of latent heat.

4. ENERGY EFFICIENCY

Are defined the following cutting process yields:

a) ***efficiency for erosion front*** ε_1

$$\varepsilon_1 = \frac{power\ for\ melting}{average\ laser\ power} = \frac{P_u}{P} [\%] \quad (17)$$

The yield for the erosion front shows the cut obtained by melting with laser beam irradiation and ignore presence of the oxidation reaction. Yield ε_1 can have supraunitary values just due to oxidation reactions.

b) **efficiency for initiation of the oxidation reaction** ε_2

$$\varepsilon_2 = \frac{power\ to\ intiate\ oxidation}{average\ laser\ power} = \frac{P_{in}}{P} [\%] \quad (18)$$

In defining for this ratio was considered that the laser beam have one role that of initiation the oxidation reaction.

c) **overall efficiency of the process** ε_3

$$\varepsilon_3 = \frac{power\ for\ melting}{laser\ power + power\ from\ oxidation} [\%] \quad (19)$$

The efficiency of the cutting process ε3 takes into account the energy given by the laser beam energy and the oxidation reaction**.**

Figure 5 shows the Pareto chart for efficiency e1. It is observed that the speed effect is the highest.

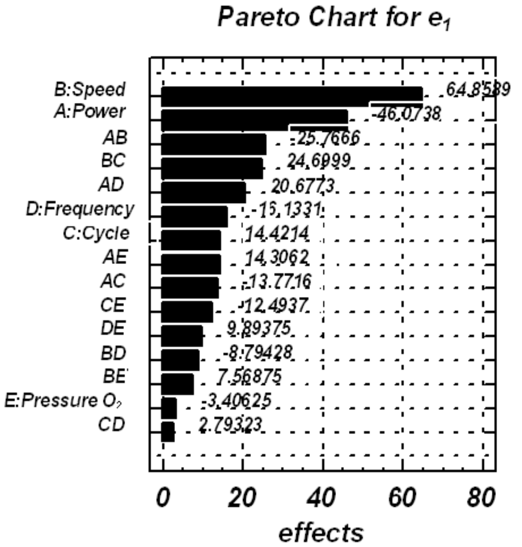

Figure 5 Pareto chart for efficiency for erosion front

This effect is increasing effect. The second effect is the power effect. This effect is a decreasing effect. Thus, it shows that increasing speed has a positive effect for material melting while increasing power favoring vaporization. The effects of the higher are the parameters that control the irradiation. Under thats are located effect of oxygen pressure and interactions in which it participates.

Figure 6 shows the Pareto chart for efficiency e2. It is noted that the highest effects are speed and power effects.The hierarchy of effects is similar to that for fraction e1 due to the calculation method.It shows that the main energy balance is between power and speed.

Figure 7 shows the Pareto chart for efficiency e3.It shows that highest effect is the speed effect. This effect is a increasing effect. The second effect is that of power effect. This effect is a decreasing effect. The difference between the two effects is reduced compared to previous cases.

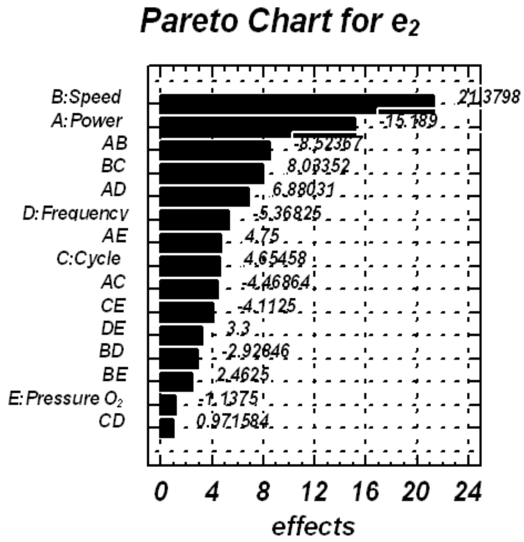

Figure 6 Pareto chart for initiation of the oxidation reaction efficiency

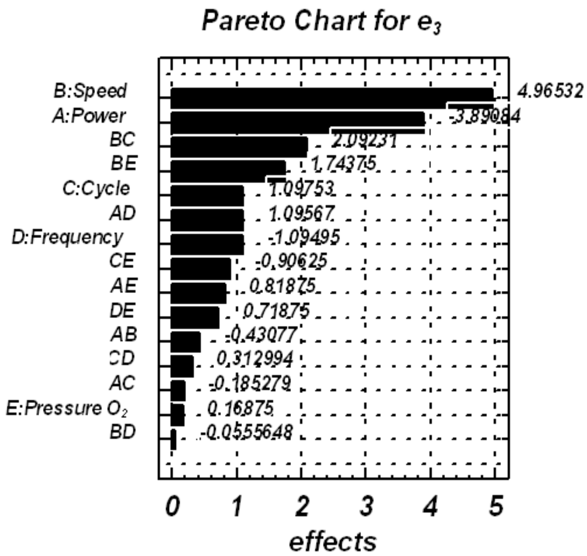

Figure 7 Pareto chart for overall efficiency of the process

We notice the high effects of speed, cycle and interactions between speed and oxygen pressure. It shows increasing the oxygen pressure effect for overall efficiency of laser cutting process.

5. CONCLUSIONS

Modeling performed on quantities which characterize energy for laser cutting process showed that:

- Cutting speed has a high effect on the analyzed quantities.

On the experimental field studied, cutting process optimization is possible by increasing the cutting speed. This means lower energy transmitted to the workpiece to get the same volume of material eroded.

Power and cutting speed provides the main energy balance of laser cutting process.

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