Experimental research methods for CO2 laser cutting of HARDOX400 steel

Constantin Cristinel Girdu
Department of Manufacturing Engineering
Transilvania University of Brasov
Brasov, Romania
girdu.constantin.cristinel@unitbv.ro

Badea Lepădătescu
Department of Manufacturing Engineering
Transilvania University of Brasov
Brasov, Romania
lepadatescu@unitbv.ro

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Abstract— The laser beam is a source of radiation with concentrated energy. The characteristics of the laser beam (spot energy, focal spot diameter, spot temperature) are aspects theoretically researched in this paper. The intensity of the laser beam transmitted to the surface of the part has a Gaussian shape. A CO2 laser was used in the processing of parts from a HARDOX400 steel sheet with a thickness g = 8mm. The values of the cutting parameters were established by sample tests. An experimental design with 27 observations was analyzed. The width of the cutting slot at the straight profile was measured. Physical quantities derived from the cutting parameters and working parameters used were calculated. Spot energy, cost and interaction time were determined and evaluated using the mathematical model given by GRAPH. The research findings show that the best values of the factors studied converge to average values in minimizing Kerf.

Keywords— laser cutting, CO2 laser, Hardox steel, laser cutting parameters

I. Introduction

The laser spot has a special place in the technological processes of laser processing of industrial products. There are few studies that address this important component of the laser beam. For these reasons, we proposed to first treat the laser spot as a small sphere, observable with the naked eye. It consists of a cone of light from a convex lens. The parallel beams of the laser beam enter the lens and are then tightened and focused by it in the focus. It can be described that the laser spot is a bright sphere with enormous energy and very high temperature of the order of 106 K. The laser focus can be positioned relative to the blank by emitting the laser jet that melts the material and separates it into two: piece and waste plate. In the case of CO2 laser experiments, the laser spot is set using the computer in the ByVison interface to a diameter of 0.2 mm. From the spot starts a laser beam with a divergence of less than 2 mrad, conical shape that heats and melts the metallic material. The auxiliary gas helps to eliminate the melt and to form the cutting joint.

The section of the cut has the shape of a normal or inverted trapezoid. If the upper cutting width Ws is larger than the lower width Wi we can estimate that the laser spot is very close to the material, so that the heat flux is stronger at the entrance to the material than below (Wi <Ws). In the case of Wi> Ws it results that the oxidation reaction burns better down, and the pressure of the assistant gas stabilizes the combustion process and pushes the material towards the bottom widening the slit. When Wi = Ws, very rarely, we have perpendicular, parallel walls, there is no deviation from rectilinearity. The laser spot travels on the path set by the cutting plane of the parts. The laser spot cuts the part according to the drawing projected in CAD. There is a functional link through certain computational relationships in the literature of laser radiation, between the diameter D of the beam before entering the lens and the diameter d of the focused spot. The heat flux emitted by the spot is unstable through the material due to the gradient on the Z axis.

This causes the cut, so there is a permanent variation in the cut width. Laser heat ignites the exothermic Fe combustion reaction. The cutting joint is obtained by laser melting and the oxidation reaction that causes the local melting to form the melt. The assistant gas jet eliminates the melt and destroys it by forming incandescent drops, sparks that are removed from the slit. Thin materials are cut with small spots. Thick metal materials are cut with large spots. Small spot means great depth of parallelism. High spot means a small depth of parallelism z. The melt has dimensions of the order of microns on the Z axis. On the X axis the dimensions of the melt are of the order of tenths of mm. The heated portion under the meniscus-concave melt is of the order of mm. There are temperature differences between the walls of the piece, the sheet compared to the melt. The heat through the material is propagated by thermal conduction given by Laplace's law. The phenomenon of heat transmission between the surface of the walls and the melt is convective, but also inside the melt, governed by Newton's relationship.

The cut surfaces are suddenly cooled and thermally hardened to depths of the order of micrometers. The hot drops end up in a state of sparks that are subjected to vaporization. The heat in this case is dissipated by thermal radiation given by the Stefan-Boltzmann relationship. A small slot means minimal laser energy, ie low energy consumption. The technological cutting process is generally environmentally friendly. Oxides and CO monoxide emissions occur after the cutting operation. The laser spot also generates thermal radiation with ϒ and X photons which are radiations with very short wavelengths for which protection is required. For research it is useful to know that the laser spot consists of a focal spot whose dimensions have been determined for geometric and optical reasons. The mathematical relationship we recommend is:

(1)

where dp is the diameter of the focal spot [μm], f-the focal length of the lens [cm], λ-the wavelength of the CO2 laser [μm], and D - is the diameter of the laser beam before entering the lens. For our case, the laser beam is collimated with the help of the lens with f = 19.5 cm, laser beam diameter D = 20 mm, with the value of the wavelength given by the amplified light emission between the excited level 4 and level 3 of the laser energy levels diagram with carbon dioxide, λ = 10.6 [μm]. From the calculation it results that

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the diameter of the focal spot is 66 [μm], the agreement being reasonable with the researched works from the current stage. At this distance the incident intensity of the CO2 laser remains constant. In conclusion, the laser spot has stored energy that does not exist anywhere on Earth. Inside is its nucleus formed by the focal spot of micron dimensions.

A secondary goal of research is to find the temperature of the laser spot. For this we can start from Stefan-Boltzmann's law, considering the spot energy of 3200 J, the spot surface of π mm2, and the laser transition time 1 ps. Taking into account the value of the σ constant of Stefan-Boltzmann, a temperature of approximately 3.17x107K is reached.

(2)

where Eem-emissivity of the laser spot, and T is the temperature

II. Mathematical Modeling

The laser spot has energy and consequently has a certain high temperature. We proposed an easy way to estimate the spot temperature taking into account notions of thermodynamics. The temperature characterizes the degree of heating of the spot. The temperature is related to the laser energy of the spot. This energy is supplied by contact or non-contact to the material by energy transfer to which the conservation law applies. The laser spot is made up of light particles. The energy of a photon is 18.55x10-21 J. The number of photons in the laser spot is about 1023. The temperature must be so high that it melts the metals quickly. The temperature is maximum in the focal spot. It decreases in distance, radially, resulting in a gradient to the edge of the laser spot. There is a heat transfer through the plate without transport of substance given by Fourier's law:

(3)

where dQ is the amount of heat [J] passing through the surface element dS [m2] oriented perpendicular to the direction of the axis oX during dt [s], the plate having the thermal conductivity kT [W / mK].

It is important to define the mathematical relationships that drive research in knowing what laser energy you need to operate with. Thus we proposed the relationships known in the literature: as interaction time:

(4)

where d is the diameter of the spot and v its travel speed.

Laser power density:

(5)

where P represents the power of the laser, and S the area of the laser spot. From the bibliographic researches it can be deduced that the power density is equal to the incident intensity of the laser radiation.

III. Experimental Method

An 8 mm thick H400 plate was prepared to be cut and processed by laser technology. We prepared a robust experiment with a DOE design according to a complete factorial plan with 27 pieces. The parts were cut after selecting the cutting parameters (laser power, auxiliary gas pressure and cutting speed). The central level was established, and subsequently due to the experience gained and the studies, the minimum and maximum levels of the input parameters for which the cutting is performed were established. The scheme of a piece is a square with a side of 20 mm, where one side has been cut semicircularly. The following cutting parameters are set in Table I:

TABLE I. CUTTING PARAMETERS USED IN THE FULL FACTORIAL EXPERIMENT

Cutting parameters	**Level**			**Unit. SI**
	Min	***Med***	***Max***	
Laser power	4900	5000	5100	W
Gas pressure	0.45	0.50	0.55	bar
Cutting speed	1700	1800	1900	mm/min

Experimental research in laser cutting of H400 steel involves the development of heat treatment under controlled conditions of the technological process with the objective of determining the cutting width-Kerf. Technological research on laser cutting consists in selecting the input variables called influence factors and the level of each. The objective function pursued is the Kerf response. The experimental research is based on the development of the complete factorial experimental plan with 27 independent references. The main objective of the study is to look at how the cutting width varies depending on the energy of the laser, as well as to establish the functional connection between them.

The laser device used is from Bystronic, a CO2 laser with a power of 6 KW. It was established that the focus level (point) is located at + 1mm above the sheet, as shown in Fig. 1.

Fig.1. CO2 laser

The slot was measured at the straight profile with the Unior 701 lera. The lera for thickness has many steel blades to measure the cut through the material, being an instrument that ensures precision and quality certified according to standards (Fig. 2).

Fig. 2. Slot measuring instrument by exploring -Lera

The following values of cutting width were found - Kerf, as shwon in Table II:

TABLE II. EXPERIMENTAL RESULTS AFTER LASER CUTTING

Laser power	**Gas pressure**	**Cutting speed**	**Cutting width-Kerf**
W	bar	mm/min	mm
4900	0.45	1700	0.40
4900	0.55	1900	0.30
5000	0.45	1700	0.35
5000	0.50	1800	0.30
5000	0.55	1900	0.35
5100	0.45	1700	0.40
5100	0.50	1800	0.35
5100	0.55	1900	0.35

Considering that the piece was cut in a time of approximately 2.5 s we can calculate another physical quantity relevant to the processing process, the irradiation time:

(6)

Where l it represents the length of the cut contour, the perimeter of the piece. The effects of the CO2 laser action are characterized by the destruction of H400 steel surfaces which is achieved by dislocating material and forming a cut. H400 steel is exposed to CO2 laser radiation for a certain amount of time to penetrate the material and another time to cut the contour of the part. The perforation of the material is performed in a certain time interval under 1s called penetration time or interaction time.

The processing of a part corresponds to an irradiation time. The experimental research methodology consists in the selection of the material, the analysis of its surface. Sample research is done in order to select the cutting parameters. The complete robust factorial plan is designed indicating the matrix of the input parameters with their established values between minimum and maximum. The CAD file is uploaded to the laser installation computer. The input parameters are set according to the cutting plan and each part is independently executed of the H400. These are then measured qualitatively resulting in Kerf responses. With the help of Graph, Kerf's dependence on the energy of the laser spot, the cost coefficient, the heat released in the slot, the interaction time are determined.

IV. RESULTS

The power density exerted by the laser spot on the H400 material is an important quantity that expresses the incident intensity of the I0 laser radiation. The intensity of the laser beam varies according to a Gaussian function as a function of the radial radius r on the X axis. The mathematical relation of the intensity was discovered by A.M. Prokhorov and Konov after the discovery of the laser. It was used by Romanian researchers Ursu et al. in 1986 which contributed to the theoretical development of the CO2 laser. For these reasons, it is worth recalling the relationship of the intensity of the laser beam I:

(7)

where I0 is the incident intensity given by the height of the Gaussian bell or the arithmetic mean of the intensities on the Gaussian curve, r - radial radius, r = r (x, y), r0-laser spot radius. It is observed that the laser intensity at a certain moment decreases after an exponential function of the type e-x ^ 2. The focal spot has a minimum diameter. The intensity of the laser beam focused on the surface of the material is maximum. By focusing inside the material the intensity of the laser beam will decrease exponentially.

Using the values of the laser input-power parameter we calculated the power densities according to Table III:

TABLE III. POWER DENSITY VALUES USED IN THE EXPERIMENT

Input variable	Laser power	P1=4900 W	P2=5000W	P3=5100W
Calculated size	Power density	ρ1=1560 W/cm2	ρ2=1592 W/cm2	ρ1=1624 W/cm2

The interaction time between the laser spot and the H400 material is an important physical quantity that defines the penetration of the blank by the focused laser radiation. The calculation took into account the different speeds, the levels in each case used in the cutting experiments. Thus, it was possible to determine another physical quantity that develops the research in the field of laser spot energy. In Table IV we calculated the times due to the very short interactions between the laser spot and the metal sheet:

TABLE IV. INTERACTION TIME VALUES RESULTING FROM H400 IRRADIATION

Input variable	Cutting speed	v1=1700 mm/min	v2=1800 mm/min	v3=1900 mm/min
Calc. size	Interaction time	τ1(i)=0.705s	τ2(i)=0.666 s	τ3(i)=0.631s

As the cutting speed increases, the interaction time decreases. This result indicates that less laser energy is supplied to the material needed for melting. As a result, the local heat is smaller, the heat flow decreases and the process becomes more economical in the sense that the cutting width improves.

The physical quantities calculated above are useful in calculating the energy density, ie how many Joules are needed to melt an area of 1 cm2, as shown in Table V. If we accurately estimate these physical quantities we can calculate the energy of the laser spot, which is particularly important in the process. melting of the portion of material.

TABLE V. ENERGY DENSITY VALUES PROVIDED BY THE H400 MATERIAL SPOT

Physical size	Spot diameter	d=0.2 mm	Spot area	S=π cm2
Calculated size	Energy density	ρ1(E)=1090 J/ cm2	ρ2(E)=1060 J/ cm2	ρ3(E)=1024 J/ cm2

It is observed that when the laser power becomes maximum and the cutting speed reaches its maximum, the energy density has the best value in the sense that the processing process becomes economical. Thus, the decision can be made to cut parts at laser power and maximum cutting speed in order to be productive and efficient. It is known that in laser cutting the pressure of the assist gas can increase the cutting speed by fast burning of Fe. Therefore, there are a number of independently controllable parameters that determine the energy of the laser spot, as shwon in Table VI. The mathematical relationship of the focus energy is proportional to the product between the energy density and the focus area of the laser spot. In the case of using a CO_2 laser with a wavelength of 10.6 µm, circular polarization, in cutting the HARDOX 400 steel sheet, the mathematical calculation correctly reproduces the focused energy required to melt the material:

TABLE VI. LASER SPOT ENERGY AND MELTING ENERGY

Calc. size	Spot energy laser	E1=3422.6 0 J	E2=3328.4 0 J	E3=3215.36 J
Estimated size	Separation energy	E1(s)=3.60 J/mm2	E2(s)=3.47 J/mm2	E3(s)=3.35 J/mm2

Steen calculated the melt removal energy as the laser power divided by the product between the cutting speed and the thickness of the material.

J. Pocorni estimated the cutting efficiency as the inverse of the elimination energy (vxg / P). A possible cost coefficient came from the laser power ratio divided by the cutting speed, as shown in Table VII.

TABLE VII. CUTTING EFFICIENCY AND COST FACTOR

Calc. size	Cutting efficiency	σ1=0.277 mm2/J	σ2=0.288 mm2/J	σ2=0.298 mm2/J
Estimated size	Coeff (cost)	c1=172.94 J/mm	c2=166.66 J/mm	c3=161.05 J/mm

Powell showed that the heat from the laser is released in the slot plus the heat from the combustion of Fe in the presence of oxygen, ie the heat released from the oxidation reaction which is approximately equal to that given by the laser.

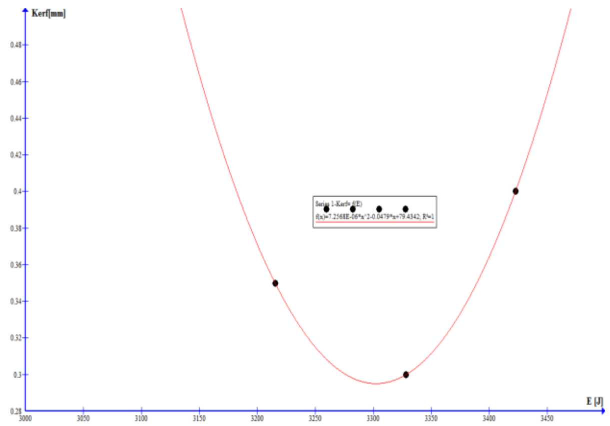

Fig. 3. Kerf's dependence on laser spot energy

(8)

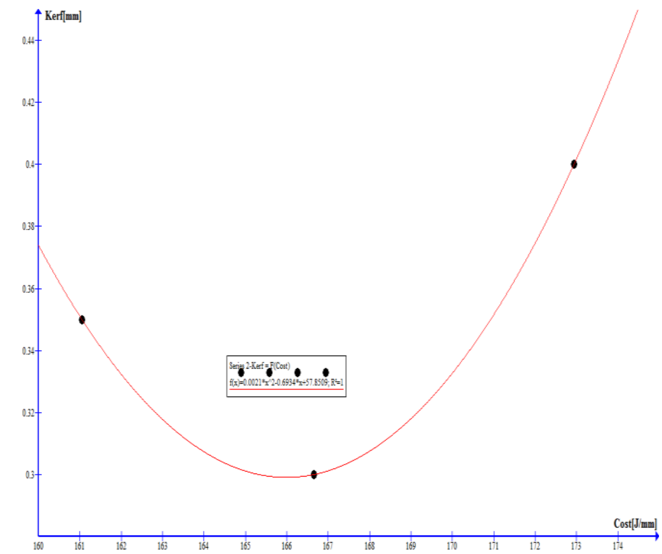

Fig. 4. Impact of cost on cutting width

(9)

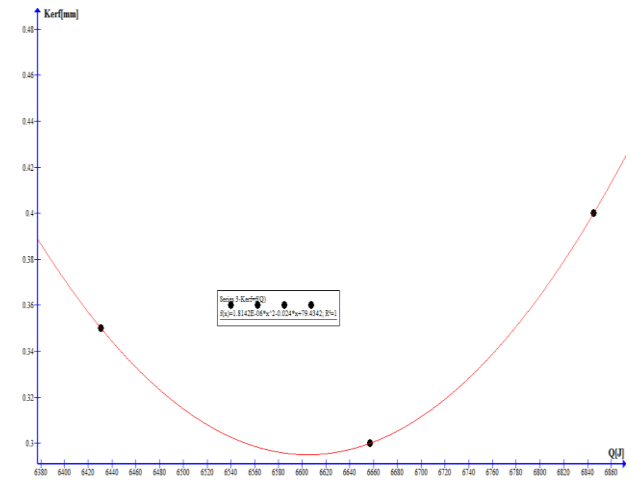

Fig. 5. The influence of the heat released in the slot on the cutting width-Kerf

(10)

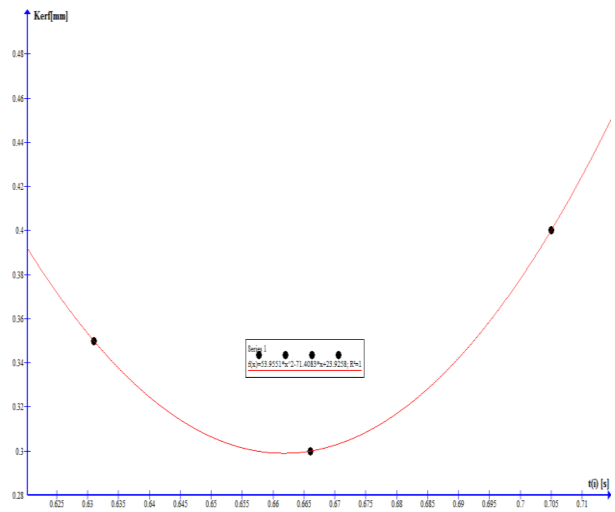

Fig. 6. Kerf cutting width as a function of laser pulse duration (CW)

(11)

Figure 3, 4, 5 and 6 show the Kerf cutting width. The effect of the laser spot energy on Kerf is quadratic. The best value of the energy provided by the spot material for absorption, heating and melting is around 3300J. It turns out that an average laser energy provides an improved Kerf. Also in the mathematical relation the linear coefficient is higher than the quadratic one, so the linear influence is stronger than the quadratic one. The coefficient of determination R2 = 1, results that there is a strong link between the influencing factors and Kerf.

The interaction time as an influencing factor shows that in medium drilling conditions it ensures a minimum Kerf. These trends of the influence factors derived from the laser cutting parameters show that average values have the best effects on the Kerf width. The graphs indicate that the factors influencing Cost and Heat released Q due to the laser and the oxidation reaction have an independent influence on the cutting process. The mathematical model is represented by the duvrice polynomials that describe the functional relationship with each influencing factor considered separately.

The mathematical model provides more accurate information on the effects of interactions. The mathematical model is suitable for analyzing variations in cutting width and estimating the values of input parameters used in the experiment.

V. CONCLUSIONS

The characteristics of CO2 laser radiation can be appreciated:

1. The focused diameter of the focal spot is dependent on the focusing lens.

2. The focused diameter of the focal spot is determined by the diameter before focusing D.

3. In the focal spot the temperature and intensity of the laser (power density) is the highest (T = 107K), I0 = 105W / cm2.

4. 5000 W laser power and 1800 mm / min cutting speed ensure Kerf minimization.

5. Kerf's dependence on the energy of the laser spot, the heat in the slot and the interaction time is quadratic. The Kerf minimum is ensured at average values of the calculated parameters.

6. The mathematical model established by Graph is suitable for finding the values of working parameters.

7. With small laser spots you quickly cut thin sheets, and with large spots you cut thick sheets.

8. In order to ensure the industrial process, the laser power P = 5000 W, the maximum cutting speed v = 1900mm / min at low pressures of the auxiliary gas are recommended.

9. The study improves the research by analyzing the derived parameters involved in the removal of the material (laser spot energy, heat produced in the slit, interaction time, cost coefficient) and the conditions under which Kerf is improved.

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