MODELING AND STUDY OF LASER CUTTING OF SOFT STEEL IN INDUSTRIAL PARTS MANUFACTURING

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ABSTRACT: Soft steels are used in the processing and fabrication of parts due to corrosion and wear resistance. In the manufacturing technology of these products, a circular cutting experiment was designed where disks were obtained at various values of the laser input parameters, cutting speed, gas pressure, laser power, focal position. The present study is based on the circular cutting of the parts made of OL 37 material. The measurements of the discs indicate different and close values from one reference to another, respectively the conicity of the made parts. It is proposed to treat the theoretical aspects related to the stationary and dynamic piercing speed of the laser, the geometry of the piece, the geometric flexibility in determining the deviation from the circularity, the simulation of the addition of melting x depending on the melting angle α, of the geometry of the molten front of the laser leaving from the tip of the laser spot. The method of determining the laser speed in the cutting process is calculated and discussed, the deviation from the circularity, the angle of deviation, the problem of variation of the deviation x from the rectangular dimensional accuracy of the slit due to the laser laser CO_2 melting.

KEY WORDS: laser cutting, laser cutting parameters, CO_2 laser, laser melting, circular laser cutting, laser piercing

1. INTRODUCTION

Laser cutting is one of the most important applications in the field of parts manufacturing using the laser beam. The paper deals with a relevant parameter of the cutting, namely the speed of the laser cutting machine which can be varied in the processing industry of pieces cut from 10mm thick steel sheets. After laser cutting the piece has a Kerf cutting width at the upper surface different from the lower surface, a result which indicates a taper of the piece. The conicity was studied, the deviation from the circularity was calculated, the Kerf deviation and the extreme conditions under which the piece has the smallest material loss in order to increase the production chain. An adequate mathematical support has been obtained to

complete with new theoretical researches the laser cutting technology as a result of the dimensional measurement of each piece. To reduce the geometry of the cutting slice means to obtain the most optimal cutting times in manufacture and production. Thus the function was established in which the Kerf deviation depends on the melting angle resulting from the impact of the laser beam with the studied material. Mathematically we studied the ovalization because the circular cut piece has a shape of the laser cut contour, elliptical, which shows a number of disadvantages as in order to obtain circularity you have to use other processes that require additional processing times. Case studies can be attached to any laser cutting research, with the interesting scientific approaches of Pocorni, Sharma, Powell, Adelman, Thombasen and others who have opened up new theories and methods, both scientifically and technically. The most recent articles published and supporting this work were highlighted by Schwanekamp and collaborators discuss the technology of additive manufacturing, the technique of building parts by melting and adding layers of material through LBM [1]; Chen et al. it treats the porosity of the remodeled layer with welding of Argon, Nitrogen, Oxygen, Air [2]; Seong et al. shows that the stainless steel is cut with a 6KW fiber laser using the stand-off distance between the nozzle and the material [3]; Rutkowski et al. directly measured the thermal diffusivity and specific heat of the polycrystalline materials of Ti-Al-C under laser flash analysis [4]; Garcia et al. addresses the dependence between piercing and cutting process parameters for sheets made of soft steel, stainless steel and Al [5]; Saini et al. investigates laser holes in ZTA to optimize surface roughness [6]; Sharma et al. used SSM in the cutting of zinc-plated steel with fiber laser to determine the Kerf deviation, the melt removal rate according to the laser input parameters [7]; Chatterjee et al. I use a Nd: YAG laser to drill the Ti-Al-V alloy, using Taguchi's method to find the circularity at the entrance and exit of the material [8]; Darwish et al. highlight the high pressure of the assistant gas, as one of the most important process parameters applying the theory of gas dynamics [9]; Zhang et al. used SLM for TiAlN film deposited on stainless steel tools [10].

1. MATHEMATICAL MODELING

1.1. Cutting speed.

The piercing speed is. The OL37 penetration takes place within 0.5 s for a thickness. The piercing speed can be oriented perpendicular to the piece or oblique. The tangential cutting speed at the trajectory is the advancement of the laser will. The two speeds will and are composed vectorially resulting in the laser cutting speed through the material, with the physical significance of the intervening sizes, fig.1, v_o - horizontal speed, v_s - piercing speed, v - resulting oblique speed, v_a - laser feed rate, v_t - cutting speed.

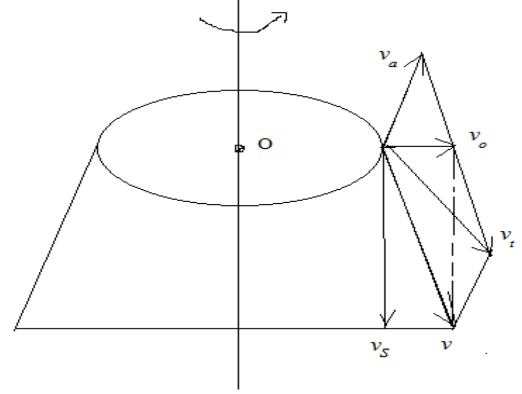

Fig.1. Determination of speeds

Cutting speed is given by the relationship:

$$\vec{v}_t = \vec{v}_s + \vec{v}_0 + \vec{v}_a \qquad 1.1$$

and $$v_t^2 = v_s^2 + v_0^2 + v_a^2 \qquad 1.2$$

The case presented above is the simplest and ideal.

If $\sphericalangle(v_s, v_0) = \alpha$,

then: $$v^2 = v_s^2 + v_0^2 + 2v_0 v_s \cos\alpha \qquad 1.3$$

If $\sphericalangle(v, v_a) = \beta$,

then $$v_t^2 = v^2 + v_a^2 + 2 v v_a \cos\beta \qquad 1.4$$

$$v_t^2 = v_s^2 + v_0^2 + v_a^2 + 2\sqrt{v_s^2 + v_0^2 + 2v_0 v_s \cos\alpha} \cdot v_a \cos\beta \qquad 1.5$$

1.2. The deviation from the circularity. Angular deviation of OL37 disks.

From measurements results in a deviation from the circularity of the disks that are described by a flattened circle at the ends fig. 2, where it was taken into account to find the deviation from the circularity and the angular deviation between the rope that supports the circle arc and the rope that supports the ellipse.

By convention we note with a, b the semiaxes of the ellipse, with the radius of the circular disk, with c the deviation from the circularity.

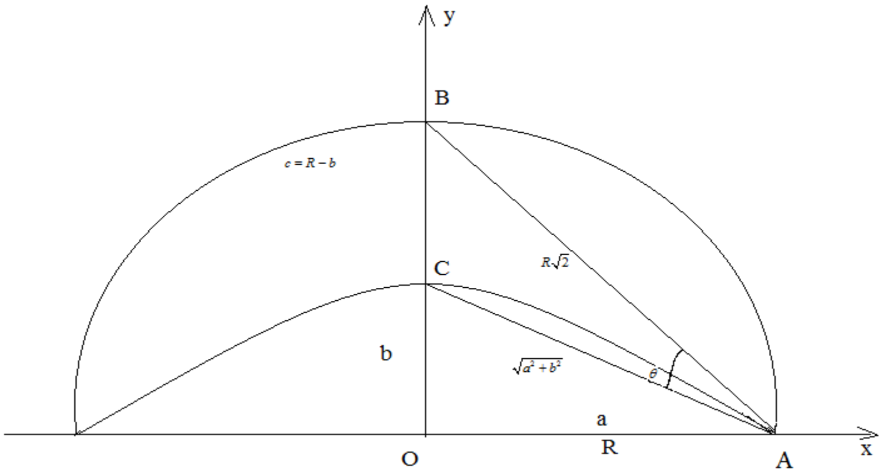

Fig.2. The deviation from the circularity

The angle represents the angular deviation of the oval shaped disk, assimilated with an ellipse to the circle that describes the circularity of the piece.

$$c^2=\left(\sqrt{a^2+b^2}\right)^2+\left(R\sqrt{2}\right)^2-2\sqrt{a^2+b^2}\cdot R\sqrt{2}\cdot\cos\theta \quad 1.6$$

$$\cos\theta=\frac{c^2-(a^2+b^2+2R^2)}{2R\sqrt{2(a^2+b^2)}} \quad 1.7$$

$$c=R-b, \quad 1.8$$

For the case where a and b (ellipse semiaxes) is different from R, we can write, fig. 3:

$$a+\varepsilon_2=R$$

$$b+\varepsilon_1=R$$

$$a-b=\varepsilon_1-\varepsilon_2 \quad 1.9$$

Thus, for the parts resulting from the OL 37 disk experiment, the position deviation and the angular deviation between the circular shape of the disk and its oval shape were calculated.

All these data have taken into account that the distance and angular changes are very small and that they are calculated with a near perfect calculation.

Performing the calculations for the parts of OL 37 with no. 1, 5, 15 obtained the data in table 1.

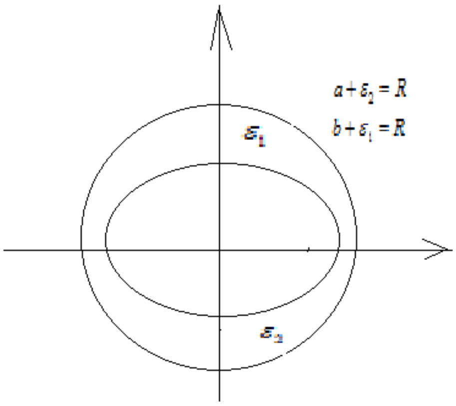

Fig. 3 The differences between the oval and the circular piece

The table shows:

- at piece 1 the big axis and the small axis are on the ellipse.
- track 5 and track 15 have an axis on the circle and one on the ellipse. The angular deviation approaches of 1.

1.3. Debiting piece of material OL37.

With the help of a CO2 laser, we rotate a piece of OL37 steel with a circular profile and the shape of a cone trunk. For the piece of OL37 the diameters are d_1=29,69mm, d_2=29,76mm and the thickness h=10mm. Speed v_1 is 2m/min.

Table 1. Angular deviation - The deviation from the circularity

nr.	D circle (mm)	radius circle R(mm)	D_X (mm)	D_Y (mm)	ε_1 mm	ε_2 (mm)	a (mm)	b (mm)	c=R-b mm	AB (mm)	AC mm	cosθ
1.	30	15	29.97	30.18	0.02	0.09	14.98	15.09	0.09	21.21	21.26	0.9386
5.	30	15	30.00	29.98	0.00	0.01	15.00	14.99	0.01	21.21	21.20	0.9993
15.	30	15	29.98	30.00	0.01	0.00	14.99	15.00	0.00	21.21	21.20	0.9940

What is the speed v_2, what is the speed of the cutting front v and the length processed by turning?

We note - the throughput speed and we will have:

$$\begin{cases} h = v_1 \cdot t \\ \dfrac{d_2 - d_1}{2} = v_2 \cdot t \end{cases} \quad 1.10$$

$$\Rightarrow v_2 = \frac{d_2 - d_1}{2t} = \frac{d_2 - d_1}{2g} \cdot v_1 \quad 1.11$$

$$\Rightarrow v_2 = 7mm/min$$

$$v = \sqrt{v_1^2 + v_2^2} = 2.000012 \frac{m}{\min} \quad 1.12$$

The length processed by turning is:

$$L^2 = h^2 + \left(\frac{D-d}{2}\right)^2 \quad 1.13$$

$$L = \sqrt{10^2 + \left(\frac{0{,}07}{2}\right)^2} = \left(\sqrt{100 + 0{,}0012}\right)mm = \sqrt{100{,}0012} \simeq 10{,}000059mm$$

d. Modeling the function for which the slot has a minimum melting surface due to laser cutting .

The section of the cutting slot between the part obtained from a cutting designed and programmed with the laser beam obtained from a CO2 cutting plant is a trapeze with the following technical characteristics: large base B - is the width of the cut on the lower surface, small base b - is the width of the cut to the upper surface, g is the thickness of the piece, α - is the angle between the extension of the laser cut surfaces, α / 2 is the angle between the inclination of the cut surface and the height of the piece h. We aim to optimize the cutting process so as to melt less material, the cut surfaces between the piece and the plate tend towards parallelism, the melted area in the slot will come from a rectangle, and the trapezoid will be minimized to the smallest area with the section of the shape of a parallelogram or rectangle depending on the cutting parameters. of the laser that are varied according to certain rules with a small objective processing time to reduce production costs and increase cutting efficiency, respectively the productivity of parts.

Thus we note with x the deviation from the flatness, we construct a large triangle, fig.4,

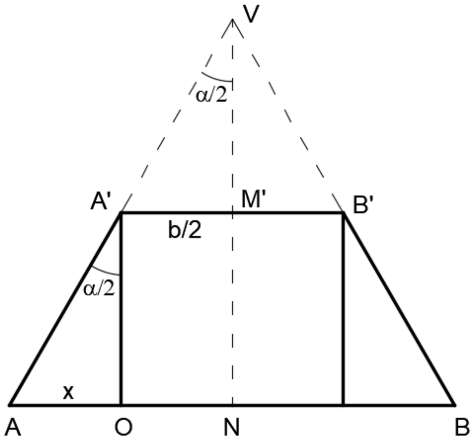

Fig. 4 The geometry of the melting front under the action of the laser spot.

VAB and $\Delta VA'B'$ formed by the bases of the trapezoid, which by constructing the heights of the trapezoid and the triangle VAB, result in similar triangles in which Thales' theorem can be applied.$\Delta AOA' \sim \Delta ANV$ where $OA' \parallel VN$are heights,

$$\frac{AO}{AN} = \frac{A'O}{VN} \quad 1.14$$

$$x = \frac{2Bhtg\dfrac{\alpha}{2}}{2htg\dfrac{\alpha}{2} + b} \cdot \frac{1}{2} \quad 1.15$$

In order to determine the extremes of the function, that is to say the critical points we will carry out the derivation of the first order:

$$\frac{dx}{d\alpha} = 0 \quad 1.16$$

$$\frac{dx}{d\alpha} = \frac{\left(2h - 4Bh^2\right)tg^3\dfrac{\alpha}{2} + btg^2\dfrac{\alpha}{2} + 2Bbh\left(1 - tg\dfrac{\alpha}{2}\right)}{\left(2htg\dfrac{\alpha}{2} + b\right)^2} \cdot \frac{1}{2}$$

it is obvious that the equation leads only to practical solutions:

$$h = \frac{1}{2B}, \quad 1.17$$

$$tg\frac{\alpha}{2} = 0 \Rightarrow \alpha = 0, \quad 1.18$$

$$1 - tg\frac{\alpha}{2} = 0 \Rightarrow tg\frac{\alpha}{2} = 1 \Rightarrow \alpha = \frac{\pi}{2}$$

Result: $\alpha = 0, \alpha = \frac{\pi}{2}$ are extreme points for which x is minimum or maximum. To determine the nature of the extreme, the second derivative is calculated, $\frac{d^2x}{d\alpha^2} \Rightarrow$ in points 0 and $\frac{\pi}{2}$, and if $\frac{d^2x}{d\alpha^2} < 0$ result x has a maximum, and if $\frac{d^2x}{d\alpha^2} > 0$, result x has a minimum.

2. INTERPRETATION OF RESULTS

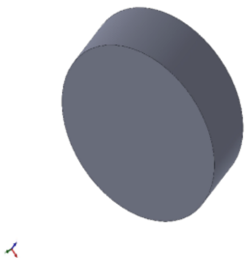

Fig.5 The shape of the cut piece, material OL37.

The cut and cut piece from the Ol 37 soft steel plate has a diameter of 30mm and a thickness of g = 10mm, fig 5. From the measurements it is found that the piece has a conical structure with a radius of 15mm at the top and 15.5mm at the bottom. The volume of the piece was calculated and it was found that it has a value of 7.30cm^3. The width of the slot / channel was determined K_{sup}=0,40mm and K_{inf}=0,35mm, thus an average Kerf

$$K_m = \frac{K_s + K_i}{2} \tag{1.19}$$

calculated gives us a value of 0.37mm.

Consequently, we can calculate the volume of the melt

$$V_t = 2\pi \bar{R} \cdot K_m \cdot g \tag{1.20}$$

which calculated has the value of 354,34mm^3. The density of the steel is 7,85*10^{3}Kg/m^3, thus, the mass of the melt is 2,78g.

The conicity of the piece is due to the laser melting evaluated in the plane and the advancement speed of the laser which describes an elliptical contour deviated from the circularity to the upper and lower surface of the soft steel sheet. The velocity being a vector was expressed with the help of the assembly of vectors and the generalized Pythagorean theorem.

The ellipse perfectly approximates the conicity on both surfaces of the piece. We cannot discuss perfect circularity, a result that requires another processing to arrive at the order of micrometers in error of measurements. The minimum processing time condition is fulfilled when the section of the cutting slit is no longer a trapezoid but a rectangular situation encountered only in the mathematical conditions imposed at 0 and 90 degrees the values of the alpha angle.

The focus position influences the cut and the quality of the piece. The most valuable values are obtained in the case f = one, ie with the focal position on the surface of steel sheets. In other cases it results in high roughness, melting on the surface of the sheet and of the piece, larger striations of the cutting surface, decrease no. of strata, steep channels, with greater depths of penetration, surface oxidation. The cutting process can be carefully monitored using the cutting parameters that indicate the best values for the Kerf width, roughness, hardness. Mathematical calculation helps model and optimize process parameters without using a data processing program, such as the Mini TAB used in California. Through rigorous design, mathematical model calculation, precision measurements we can complete laser beam cutting research. Under the conditions of radiation dependence and material mathematical calculation, programming becomes more complex which can be restricted due to the variation of the laser input parameters.

3. CONCLUSIONS

- Differential calculus expresses critical / extreme points and turning points.
- The deviation from the circularity is shown exactly by the algebraic calculation.
- From measurements we can correctly choose the values of the input parameters that give us the best output parameters.
- Laser cutting is more complete by performing calculations that indicate our prediction, accuracy in measurements.

- The focal position f is a parameter that can be varied above the piece, on the piece, inside the piece, on the lower edge of the piece and below the piece.
- Depending on the level chosen for the focal position we obtain quality of the cut surfaces.
- The cutting speed is a variable parameter being the result of the linear penetration and feed rate.
- In cutting the pieces the angular deviation θ and c the deviation from the circularity were calculated.
- The measurement error is small with respect to lengths, radii of 0.01-0.09mm.
- The cutting is done by laser beam cutting, respectively by melting and blowing with O_2 assistant gas.
- The cutting is asymmetrical being induced by laser thermal cutting between the plate and the piece.
- The cutting width at the top of the piece is different from the lower level due to the melting and expulsion of the material, and in calculations we can estimate the average value of the two measurements.
-The model is reproduced by the variation of the addition x depending on the angle between the cutting edges, which by derivative 1 indicates the critical points, so the function is x = f (α).
-The area of the cut section and the dimensions of the circularly cut pieces of laser differ from one piece to another.
-The effect of laser melting on the taper of the workpiece is analyzed and accurately described the geometry of the workpiece.
-The laser cut is not straight, the slit geometry is conical due to the Fe-O combustion.
-The boundary conditions impose h = 1 / 2B, melting angle being 0 degrees or 90 degrees.
-The angular deviation depends on the semiaxes of the ellipse a and b and the radius R of the cut disk

7. REFERENCE

1. Schwanekamp, T; Marginean; Reuber, M., 2019, Laser beam melting of Cr3C2-NiCr, *INTERNATIONAL JOURNAL OF REFRACTORY METALS & HARD MATERIALS*, Volume: 85, DOI: 10.1016/j.ijrmhm.2019.105069

2. Chen, C; Gao, M; Mu, HY; Zeng, X.Y., 2019, Effect of kerf characteristics on weld porosity of laser cutting-welding of AA2219 aluminum alloy, *APPLIED SURFACE SCIENCE*, Volume: 494, Pages: 1036-1043, DOI: 10.1016/j.apsusc.2019.07.259

3. Oh, Seong Y.; Shin, J.S.; Kim, T.S.; Park, H.; Lee, L.; Chung, CM; Lee, J. - 2019, Effect of nozzle types on the laser cutting performance for 60-mm-thick stainless steel, *OPTICS AND LASER TECHNOLOGY*, Volume: 119, Article Number: 105607, DOI: 10.1016/j.optlastec.2019.105607

4. Rutkowski, P.; Huebner, J.; Kata, D.; Chlubny, L.; Lis, J.; Witulska, K.; 2019, Thermal properties and laser processing of hot-pressed materials from Ti-Al-C system, *JOURNAL OF THERMAL ANALYSIS AND CALORIMETRY*, Volume: 137, Pages: 1891-1902, DOI: 10.1007/s10973-019-08107-w

5. Garcia, SM; Ramos, J.; Lamikiz, A; Figueras, J.; 2019, Influence of Process Parameters in Laser Piercing, *APPLIED SCIENCES-BASEL*, Volume: 9, Article Number: 3231, DOI: 10.3390/app9163231

6. Saini, SK; Dubey, A.K.; Upadhyay, B.N., 2019, Study and optimization of recast layer thickness and surface quality in laser trepan drilling of ZTA, *INTERNATIONAL JOURNAL OF ADVANCED MANUFACTURING TECHNOLOGY*, Volume: 103,Pages: 2977-2989, DOI: 10.1007/s00170-019-03704-3

7. Sharma, V.K.; Kumar, V.; 2019, Study on material transfer and surface properties during fiber laser cutting of A653 galvanized steel sheet, *JOURNAL OF THE BRAZILIAN SOCIETY OF MECHANICAL SCIENCES AND ENGINEERING*, Vol.: 41, Article Nr: UNSP 341, DOI: 10.1007/s40430-019-1842-4

8. Chatterjee, S.; Mahapatra, S.S; Bharadwaj, V; Choubey, A.; Upadhyay, B.N.; Bindra, K.S., 2019, Drilling of micro-holes on titanium alloy using pulsed Nd:YAG laser: Parametric appraisal and prediction of performance characteristics, *PROCEEDINGS OF THE INSTITUTION OF MECHANICAL ENGINEERS PART B-JOURNAL OF ENGINEERING MANUFACTURE*, Volume: 233, Pages: 1872-1889, DOI: 10.1177/0954405418805604

9. Darwish, M.; Orazi, L.; Angeli, D., 2019, Simulation and analysis of the jet flow patterns from supersonic nozzles of laser cutting using Open FOAM, *INTERNATIONAL JOURNAL OF ADVANCED MANUFACTURING TECHNOLOGY*, Volume: 102, Pages: 3229-3242, DOI: 10.1007/s00170-019-03346-5

10. Zhang, K.D.; Guo, X.H.; Sun, L.N.; Meng, X.F.; Xing, Y.Q., 2019, Fabrication of coated tool with femtosecond laser pretreatment and its cutting performance in dry machining SLM-produced stainless steel, *JOURNAL OF MANUFACTURING PROCESSES*, Volume: 42, Pages: 28-40, DOI: 10.1016/j.jmapro.2019.04.009.