Mathematical modeling for soft laser beam processing

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Abstract:- A recent study on the circular cutting of soft steel with CO_2 laser was made on two 600x400mm steel plates of thickness g = 10mm, where 225 references were obtained. The laser power input, lens focal length, low O_2 aspiration gas pressure and cutting speeds were varied to achieve various measurements and research by optimizing the resulting cutting parameters: circularity, dimensional precision, roughness, hardness, etc. Thus, with the help of this paper I managed to correlate the characteristics of the laser radiation according to the physical properties of the steel 37 made on a Bystronic laser plant.

In order to achieve the measurements, the properties and characteristics of the laser beam and control over its propagation must be known to the operator in order to increase the quality of the parts and the industrial productivity.

Key - words: - laser cutting, CO_2 laser, laser piercing, laser drilling.

1 Introduction

In the paper [1] we discuss the incident intensity I_0 that penetrates the surface of the material, the intensity absorbed by I_{abs} steel, the heat received from the laser.

The incident intensity on the surface of the piece depends on the power of the laser beam P and the radius of the radial spot of the beam r:

$$I_o = 2P / \pi r^2$$

$$I_{abs} = A(\alpha)\cos\alpha \cdot I_0 \left[\frac{W}{cm^2}\right]$$

where the physical sizes involved are:

$A(\alpha)$ - absorption coefficient, α - angle between metal surface and laser radiation, - I_0 incident beam intensity $(\frac{W}{cm^2})$.

The processing and control aspects of the laser beam were treated by [GLO 14] to determine the focal spot radius and the interaction area where the radiation has constant intensity,

$$r_f = \frac{\lambda \cdot f}{\pi \cdot r}$$

r is the beam radius before focusing.

The area of parallelism of the beam where it retains its intensity is:

$$z = \frac{2\lambda}{\pi}\sqrt{\rho^2 - 1 \times \frac{f}{d}}$$

where ρ is the tolerance factor, ρ = 1.1 and D = 20mm the uncoated CO_2 laser beam diameter. [Ryk 78] introduces an approximate formula for calculating the I_o intensity at the center of the laser spot:

$$I_0 = \frac{\pi \cdot D^2}{4\lambda^2 \cdot f^2} \cdot P$$

where f is the focal length of the lens and P is the power of the laser. The laser beam diameter D = 20mm for the CO_2 laser can be focused by means of a convergent lens at a focal point whose diameter is comparable to the incident wavelength λ of the incident radiation, is [1-10.6] μm [Donțu].

Fig. 1 focus on parallel incident radiation

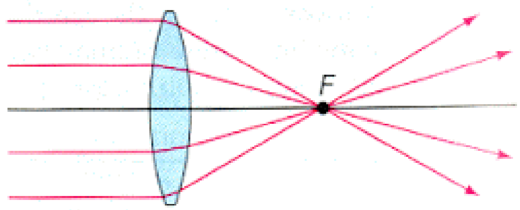

Fig.1 Convergent lenses.

The CO_2 laser has the power output from the laser source P between [2700-3600] W and the focal point diameter:

$$d=1{,}22\,\frac{\lambda f}{D}$$

where, f is the focal length of the lens, for the 50% intensity / waist level. In the experiment, the wavelength λ = 10.6 μm was used, the convergent lens with f_1 = +5 mm, f_2 = +10 mm, f_3 = -3 mm, and laser beam diameter D = 20 mm, wavelength and beam diameter, the frequency $\nu_{CO_2} = 2{,}8 \cdot 10^{13}\,Hz$ are the constant physical quantities of the radiation used.

2 Mathematical modeling

The angle of laser radiation opening (divergence) can be brought to the lowest value by the light diffraction phenomenon. It is clear that the ratio θ of the wavelength λ of laser radiation to the diameter of the aperture of the light beam [10].

If it measures λ in microns 10^{-6} m, and the diameter of the beam in mm, it results from Fig.2, angle $\theta \approx 10^{-3}$.

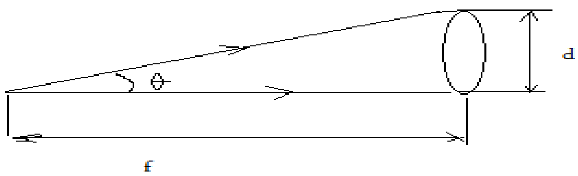

Fig.2 The angle of divergence.

The angle of divergence θ is defined as the ratio of the wavelength $\lambda = 10{,}6\mu m$ to the diameter of the light beam aperture (aperture):

$$\theta = \frac{\lambda}{d}$$

The solid angle is: $\Omega = \pi \cdot \theta^2$.

Focal spot radius is: $r_f = f \cdot \theta$

Spot center temperature: the temperature T_m of the surface of the soft steel material at the center of the spot in the area affected by the laser in interval [6, 10] s is calculated according to [3} formula:

$$T_{\max} = \frac{2I_0}{k}\sqrt{\frac{d \cdot \tau}{\pi}}$$

where k - is the thermal conductivity ($\frac{W}{m \cdot k}$), I_0 - the incident intensity of the laser beam ($\frac{W}{cm^2}$), d - the thermal diffusion ($\frac{cm^2}{s}$), - τ is the continuous laser pulse CW (s)

If the spot is spherical with the spot size of d_f = 0.5mm in the lens focal point, the volume can be calculated:

$$V = \frac{4}{3}\pi d_f{}^3 = 0{,}52 mm^3,$$

and the spot area:

$$A_{spot} = 4\pi (d_f / 2)^2 = 3{,}14 mm^2 = \pi mm^2$$

The volume heated by the laser beam is calculated using the formula:

$$V = \frac{\pi \cdot D_S{}^2}{2}\sqrt{d \cdot \tau_p} = S_S \cdot z$$

where D_S - spot diameter = 0.50 mm, d - thermal diffusion (d = 0.15), τ_p - is the duration of the laser pulse.

The depth of penetration of heat into the material is:

$$z_c = 2\sqrt{d \cdot \tau_p}$$

For a 10s pulse we have:

$$z_c = 2\sqrt{0{,}15 cm^2 / s \cdot 10 s} = 2{,}44 cm$$

The speed with which heat penetrates into the soft steel material is given by:

$$v = 2\sqrt{\frac{d}{\tau_p}} = 2\sqrt{\frac{0{,}15 cm^2 / s}{10 s}} = 0{,}24\,\frac{cm}{s}$$

The depth of the melted layer is calculated by:

$$Z_m = 1{,}2\,\frac{k_T}{A \cdot I_0}\left(T_v - T_m\right)$$

where k_T is the thermal conductivity, $0,5\frac{W}{cm\cdot^{\circ} C}$
A is the absorption coefficient = [0,2-0,3], I_0 - incident laser, T_v - is the vaporization temperature, T_m - is the melting temperature.

In Table 1 are shown the following values of the focal point diameter d_2=3, 23 µm, d_3=6, 46 µm, d_4=1, 93 µm ∈ [1,10,6] µm were obtained.

Table 1. Parameters of experiment.

Focal lengthf(mm)	f_2=+5 mm	f_3=+10 mm	f_4=-3 mm	Divergence $\theta(rad)$
Laser diameter	D=20 mm	D=20 mm	D=20 mm	53x10^{-3}
Focal point diameter	d_2=3,23	d_3=6,46 µm,	d_4=1,93 µm	53x10^{-3}
The wavelengthλ-CO_2	10,6 µm	10,6 µm	10,6 µm	53x10^{-3}

I used the formula [1] in the calculations, for the lens case the spot diameter is 0.2 mm and the radius 0.1 mm. A power of 2800 W was obtained at a rate of 17,8X10^5 W/cm^2/cm^2, and for a 3600 W power a laser incident intensity of 22,9X10^5 W/cm^2. In the case of a lens without lens the diameter of the spot is equal to the nozzle diameter of 0.4 mm and the instrument radius is 0.2 mm (Table 3).

Table 3. Experimental test results.

Laser CO_2	**Lens**		**Without Lens f=0**		**I$_{abs}$** $\left(\frac{W}{cm^2}\right)$ $\alpha = 85^{\circ}$	**Solid angle** $\Omega(sr)$
Power P	2800W	3600W	2800W	3600W	2800W	9.86x10^{-3}
Incident intensity I_0 $\left(\frac{W}{cm^2}\right)$	17,8X10^6	22,9X10^6	11,2X10^5	14,4 X10^5	11,2X10^5	9.86x10^{-3}
Temperature In the spotcenter	5,12X10^{7}C	6,58 X10^{7}C	2,5X10^{6}C	3,21 X10^{6}C	3,2x10^3	9.86x10^{-3}

Temperature increases with laser duration. The Circular Cutting Experiment used the non-lens case on the first day, and the next day cutting with a focal lens with f = 5 mm, 10 mm, -3 mm. So we could calculate the lens focal diameter (Table 4):

Table 4. Elements of laser machine.

Laser CO_2	**Focal length f(mm)**	**Diameter D(mm) Laser O_2unfocused**	**Focal spot radius r_f(µm)**	**Diameter focal spot d(µm)**
Plant laser Bystronic	5mm	20mm	0,84	1,68
	10mm	20mm	1,68	2,36
	3mm	20mm	0,5	1,00

The calculation for the CO_2 laser beam having a diameter of 20 mm and a lens focal length of 5, 10, 3 mm, the focal spot radius will be 0.00084 mm, 0.00168 mm, 0.0005 mm and the diameter of 1.68 , 2.36, 1.00 (µm) will double (Table 5).

The calculation is superior to that formulated by [5].

Table 5. Parameters experimental testes.

<table>
<tr><th>Laser CO_2 plant laser Bystronic</th><th>Depth of heat penetration z_c (cm)</th><th>Heat speed in material v_c(cm/s)</th><th>Heated volume V(cm^3)</th><th>Depth of the melt layer Z_m(mm)</th><th>Area of interaction z(μm)</th></tr>
<tr><td>Laser duration CW τ=6s</td><td>1.89</td><td>0.31</td><td>0.059</td><td>0.26</td><td rowspan="2">7.24</td></tr>
<tr><td>Laser duration CW τ=10s</td><td>2,44</td><td>0,24</td><td>0.076</td><td>0.20</td></tr>
</table>

3 Conclusions

After these experimental tests the next conclusions arise:

- At focal point F the intensity of laser has maximum value,

- Using radiation focus, the radiation intensity can be increased to I_0,

- Breakthrough intensity is approximately $3{,}2\text{x}10^3\left(\frac{W}{cm^2}\right)$,

- Laser radiation uniformly illuminates the lens (light intensity is the same in all directions), and for the CO_2 laser the lens diameter is larger than the diameter of the laser beam D.

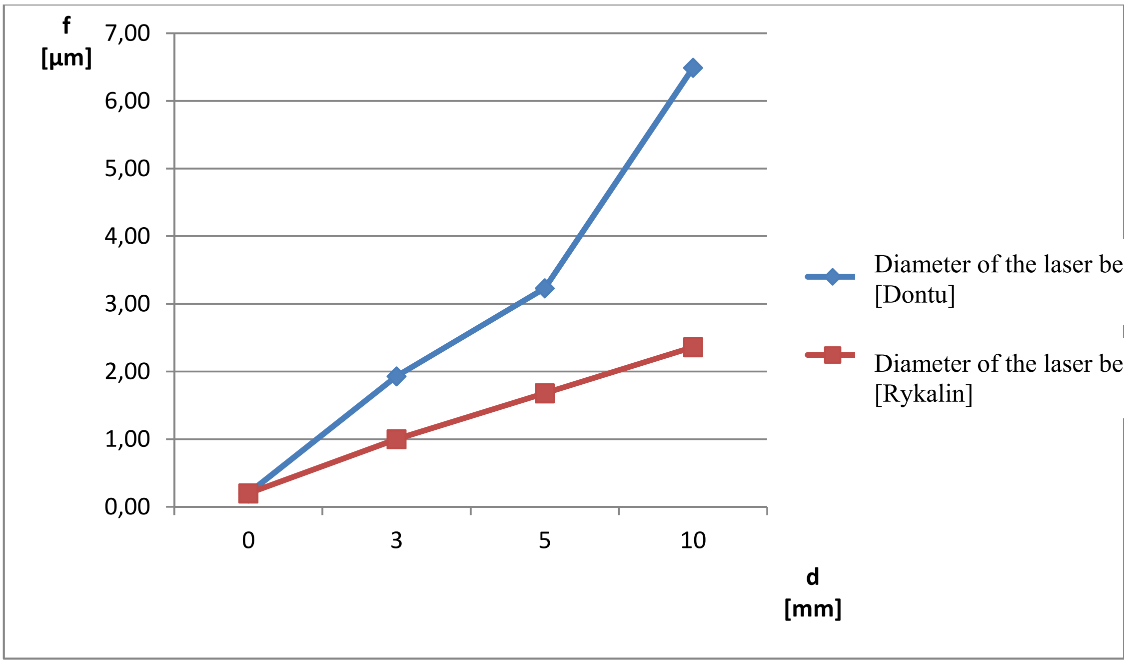

Fig.2 Diametres of the laser beam.

Rykalin's calculation is more accurate.

-The focal point diameter increases with the lens focal distance f decreases.

-The focal point diameter increases when the beam diameter increases.

-If the wavelength decreases, it results in an increase in the focal spot size.

-The focal point is the equivalent of a lighter in the material.

-Temperature focal point is higher in thin sections.

-The focal point diameter changes with the type of lasers, the type of lens, the diameter of the beam.
- Focal point size is based on standard laser radiation parameters.
- In very small dimensions (micrometers), an enormous energy is concentrated.
- Small footprint means very low laser beam divergence.
-The focal point has a very high temperature of the order of 10^5K-10^7K, which is in a micron range.
-The point consists of the focal point surrounded by the sphere due to the oxygen burning in air having the size of the order of mm.
-The sphere has a spherical shape that focuses center point, spark - laser light.
- By performing the cutting operation, two cutting edges are located on either side of the laser light spot
-The spot energy is equal to the focal point energy plus the O_2 asynchronous gas energy.
-The laser beam focussed in the material has a larger diameter at the entrance to Kerf. The laser beam heats the material on each surface of the slit at the initiation temperature of the oxidation, about $1200\,°C$, which is lower than the melting temperature $1535\,°C$.
- We can conclude that the focal point is the source of heat from the laser and the burning of O_2 gives rise to a bright spot of the order of mm.
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- For the CO_2 laser, the spot diameter used in the experiment is 0.2 mm.
- A spot of small diameter is a more intense spot.
-The laser beam is focused to produce an intense focal spot.
-For the CO_2 laser, the angle of divergence is $\theta = [1-60]\,mrad$, and the solid angle from which the beam is $\Omega = [3{,}14-9860]\cdot 10^{-6}\,sr$.
- It is forbidden to look at the spot produced by the laser beam even with goggles as the retina may be affected.
-The focal point has a very small diameter in the order of the microns in which Q_{laser} laser heat is received, which is enormous compared to the heat developed by igniting Q (O_2) oxygen.
-Oil is cut by melting the surface that at a certain temperature in liquid state begins to be expelled from the Kerf under the oxygen jet.
- It is born the idea that the laser spot consists of the focal point (spot) and the sphere that arises from the oxidation reaction between Fe and O.
- As a consequence, laser cutting means metal smelting (melt) and oxygen jet blowing which, due to the spot, warms and melts, and the oxygen removes the melt, giving rise to slag and rivulent surfaces of the slit.
-This miracle of spherical shape is doing its job having a center-point smashing point that perforates and cuts anything, being surrounded by a sphere resulting from the burning of Fe with O_2.
- So there are many aspects to be taken into account in the appearance of this star guided by the mind and human intelligence.
- So far, there is no place in this world that has such energy.
-The spot is centered on the greatest energy in the universe, and it is owned by the TiSa laser at the University of Michigan.
-In the defense strategy, the CO_2 laser and the Titan -Safir laser are successfully used because they locate the targets ultra-fast, heat them, and then destroy them by explosion. The same technique can be used successfully at UFOs. It is not excluded that the human mind identifies such UFO objects and communicates with them through the laser beam. This creation is the human mind that by intelligence will at any moment overcome artificial intelligence only through this technique that accumulates energy inside the resonator and is discharged through a very narrow gigantic beam of magnitude that produces miracles.

References:
[1] E.H. Amara , A. Bendib, *Modelling of vapour flow in deep penetration laser welding* ,J. Phys. D: Appl. Phys. 35 (2002).

[2] E.H. Amara, T. Aoudjit, K. Kheloufi, T. Tamsaout, S. Aggoune, A. Ahmanache, F. Hamadi, K. Bougherara, *Simulation by temperature gradient adaptionof wavelength effect in metal laser cutting,* Centre de Développement des Technologies AvancéesCDTA - Laser Material Processing Team, PO. BOX 17 Baba-Hassen, Algiers, 16303, Algeria, JOURNAL OF LASER APPLICATIONS, (2017)

[3] V. Bujor, R. Boboescu, *Formulation of Modeling Problems in Laser Welding*, Reliability and Durability - Fiability & Durability nr.2 / 2009 "Academica Brâncuşi" Publishing House, Târgu Jiu.

[4] Bocksrocker, O. , Berger, P., Regaard, B., Graf, T "*Characterization of the melt flow direction and cut front geometry in oxygen cutting with a solid state laser*", JOURNAL OF LASER APPLICATIONS, Published: MAY 2017.

[5] M. Chalian, Doctoral thesis, "*Studies on the interaction of laser radiation with metallic substance"* Library of the Polytechnic University of Bucharest, 2003.

[6] S. Dinu, Doctoral Thesis, *Researches on physical phenomena occurring at the interaction of thin titanium dioxide laser radiation deposited on glass*, Library of Polytechnic University of Bucharest, 2006.

[7] O. Donţu, *Laser Processing Technologies,* Technical Publishing House, 1985.

[8] P. V, Glod, PhD thesis "*Industrial optimization of laser cutting of steel sheets",* Polytechnic University Library, Politehnica Publishing House, 2010

[9] Petru-Valentin Glod, Remus Boboescu, *Methods of experimental research applied for laser cutting of steels,* Timisoara, Eurostampa, 2014.

[10] C. Oros, Doctoral Thesis "*Studies on Material Structure Changes in the Interaction of Laser Radiation with the Substance,"* Library of Polytechnic University of Bucharest, 2001.

[11] Parthiban, A., Sathish, S., Ravikumar, R., *"Optimization of CO_2 laser cutting parameters on Austenitic type Stainless steel sheet,* INTERNATIONAL CONFERENCE ON EMERGING TRENDS IN ENGINEERING RESEARCH, Published: 2017.

[12] "*The effect of laser type and power on the efficiency of industrial cutting of mild and stainless steels*", Journal of manufactuting Science and Engineering.

[13] Powell, J., Frostevarg, J., Alexander F. H., *"Dynamic laser piercing of thick section metals",* OPTICS AND LASERS IN ENGINEERING, Published: JAN 2018.

[14] I. M. Popescu, *Physics and Laser Engineering*, Technical Publishing House, 2000.

[15] N. Puscaş, *Lasers,* Academica Publishing House, 2007.

[16] Sharma, V., Kumar, V., "*Investigating the quality characteristics of Al5052/SiC metal matrix composites machined by CO2 laser curve cutting",*), PROCEEDINGS OF THE INSTITUTION OF MECHANICAL ENGINEERS PART L-JOURNAL OF MATERIALS-DESIGN AND APPLICATIONS, Published: JAN 2018.

[17] Gh. Savii - *Lasers,* Facla Publishing House, 1981.

[18] Rajamani, D., Tamilarasan, A., *"Multi-response optimization of Nd:YAG laser cutting parameters of Ti-6Al-4V superalloy sheet"*, JOURNAL OF MECHANICAL SCIENCE AND TECHNOLOGY, Published: FEB 2017.

[19] L.V. Tarasov, *Lasers, Reality and Hopes*, Technical Publishing House, 1990.