Laser Spot as a Tool for Physical and Technological Processing Processes

GÎRDU CONSTANTIN CRISTINEL, BADEA LEPĂDĂTESCU, FLAVIA FECHETE
Department of Manufacturing Engineering
Transylvania University of Braşov
500036 Bvd. Eroilor nr.29, Braşov
ROMÂNIA

Abstract: - The theory and practice of laser applications in material processing highlight the role of the laser spot defined as a cutting tool for efficiency. The main objective of the research is to calculate the spot correction radius, energy density, power density, specific energy resulting from the emission of laser light by CO_2 and Fiber installations with wavelengths of 10.6 µm and 1.06 µm. The Kerf cutting width measured on Hardox400 steel, thickness g=10 mm, output variable, in power laser processing processes is an important technological parameter that validates the correction radius and specific energy. The spot diameter is a working parameter that enters the estimation of mathematical relationships that was established manually, CO_2 laser (0.30 mm) and automatically set with sensors, Fiber laser (0.38 mm). The results obtained were compared and discussed to comment on the correction radius, so that the mathematical model ($r_{correction} = 0,21\ mm$) reconfirms the experimental model ($r_{correction}$ =0.25mm), it results that the two analyzed models confirm each other. The specific energy ∈_s=2080,25 J/mm2 obtained by the CO_2 laser and the specific $\in_s$=1892,4 J/mm^2 obtained by the Fiber laser, justify at this point that for thick sheets the carbon dioxide laser ensures quality when cutting the samples.

Key-Words: - Laser spot, correction beam, CO_2 laser, fiber laser, specific energy.

Received: May 19, 2025. Revised: July 27, 2025. Accepted: August 19, 2025. Published: January 12, 2026.

1 Introduction

Laser cutting is the most common technological process encountered in the automotive and aerospace industries. From previous studies there are many definitions addressed by researchers regarding cutting, we present cutting as a complex physical and mechanical phenomenon, of heating and blowing the molten material with an assistant gas jet. We considered that the parts obtained by cutting have a very high dimensional accuracy if we adjust the laser spot radius with the correction radius. By summing the two characteristic sizes of the laser spots we ensure that we do not erode the parts thermally and to accurately determine that they are Kerf/2. This skill from practical research will be applied in laser manufacturing processes.

Historically, there is a limited number of researches in the world that comment on the radius and diameter of the laser spot or other characteristic sizes. For these reasons, we predicted that clarifications are needed regarding the synergy of laser spots. Volker Neumann, 2012, decided that in the field of laser processing of materials, knowledge of the distribution of incident intensity in the processed volume is of great importance [1]. Binh Xian Cao et al. used an automated focus inspection system for laser processing in order to reach the working surface. The authors use an intelligent system based on three lenses in which the lens L1, divergent, f<0, mobile, the lens L2, fixed, 2f>0, the laser beam is collimated and passes through the lens L3, f>0, which focuses the radiation into an elementary spot, inspected by the image sensor [2]. Oscar Amaro et al., 2021 in a particle accelerator, present the collisions of a laser beam with an electron beam leading to the generation of electron-positrons. The laser has an incident intensity $I_0 = 10^{21}$ W/cm^2, pulsed PW mode, spot diameter d<10 µm [3]. Tang H. et al., 2024, calculated the laser spot size for an unconventional system with a high-energy pulse, the duration of 10^{-12}s when it accelerates relativistic electrons resulting in an energy gain [4]. Jelena Stanojković, Madici Milos, 2022, present the results of research on cutting AISI304 alloy steel, where they indicate that the laser spot focus position has a dominant influence over the other input parameters [5]. Jinglong Tang et al., used in the welding process, a fiber laser with the spot focus position located inside, on Aluminum sheets, for optimal forming [6]. Boboescu Remus, 2014, discusses and formulates the laser spot, through the parallelism zone, where the incident intensity remains constant in laser processing processes [7]. Viet Hoang Dinh, 2023, presents the role of focusing in high-precision material processing. Laser systems use autofocus (AF) based on several focus detection techniques [8]. Levai Ștefan, 2002, highlights that coherent and directional waves can obtain a strong concentration of useful energy in applications [9]. Ursu I, Prokhorov Al et al., treat the interaction of radiation with the substance, the notion of finite spot and infinite spot for the analytical determination of physical quantities such as temperature, melting depth [10].

Basov academician shows that the laser is a very powerful thermal source capable of heating the irradiated portion in such a short time that the heat fails to dissipate from the given place. The heated portion can be melted or vaporized. By adjusting the laser power with the duration of the laser pulse, any temperature regime for different processing results. Academician Prokhorov developed gas jet cutting with a laser, in which the cutting process is obtained due to the laser attack that induces melting and ignites the thermoenergetic reaction between the metal and oxygen. The oxygen jet, the length and power of which is regulated by the nozzle, removes particles of molten metal and cools the processed area, resulting in a clean cut [12].

2 Experimental description

The cutting width is defined by the relationship:

$$Kerf = d_f + r_{correction}, \quad (1)$$

Where:

$Kerf$ = width of the cut [mm]

d_f = focused spot diameter [mm]

$r_{correction}$ = correction radius [mm]

In laser machining processes, Kerf is measured with various instruments: digital caliper, micrometer, microscope. The diameter of the focused spot is set from the laser system program [5]. The correction radius is set before machining the parts to avoid thermal erosion as much as possible. We propose to calculate the correction radius that will be taken into account by the research team. The estimated mathematical relationship:

$$Kerf - r_{correction} = d_f \quad (2)$$

In the situation where the incident intensity [2] of the laser beam decreases by half for the diameter of the focused spot, we can apply the formula:

$$d_f = 2{,}44 \times \frac{\lambda}{D} \times F, \quad (3)$$

Where:

λ = wavelength of laser radiation [µm]

D = diameter of the radiation before entering the lens [mm]

F = focal length of the converging lens [mm]

This results in an analytical relationship for calculating the correction radius of the cutting tool:

$$r_{correction} = Kerf - d_f = kerf - 2{,}44 \times \frac{\lambda}{D} \times F, \quad (4)$$

It is found that the correction element can be estimated using physical quantities characteristic of the laser system, which are constant for the radiation and the lens.

The authors cut different Hardox 400 semi-finished products with carbon dioxide lasers (figure 1), Hardox 450.

Fig.1 Carbon dioxide laser cutting Hardox 400 samples

Therefore, in table 1, following the correction of the cutting technological process, we obtained the correction radius from the experimental data:

Table 1. Correction radius, focused diameter, CO2 laser kerf

Working parameters	Kerf	F	D	λ	$r_{correction}$
SI	mm	mm	mm	µm	mm
Values	0,5	195	20	10,6	0,25

A confidence interval value for the correction radius is established by the approximation relationship:

$$\widehat{r_{correction}} = r_{correction} + 0{,}05, \quad (5)$$

In this case, Kerf = represents the cutting width [mm], focused spot diameter = df, [mm], r correction = the distance resulting from the burning of the metal

[mm], Δr = correction radius [mm]. Kerf will be taken into account in setting the diameter of the focused laser spot and in the dimensional accuracy of the part and not the diameter of the laser beam, the diameter of the focused beam. The correction radius ensures the non-thermal corrosion of the part being of the order of hundredths of mm in the case of Hardox 400 steel. The radius of the cutting tool is Kerf/2 which is composed of the focusing radius, the burning distance/2 minus the correction radius

3 Mathematical modeling

A question regarding a global value of the correction radius becomes a subject of interest for mathematical approximation. We propose that depending on the response variable Kerf and a working parameter focused spot diameter we identify a new relationship. We start from the definition relationship of the correction radius:

$$r_{correction} = Kerf - d_f, \quad (6)$$

The developed quadratic relationship leads us to a better approximation, just like errors [7].

$$r_{correction}{}^2 = (\,Kerf - d_f)^2, \quad (7)$$

$$r_{correction}\left(Kerf + d_f\right) = Kerf^2 - d_f{}^2, \quad (8)$$

$$\frac{Kerf + d_f}{2} \geq \sqrt{Kerf \times d_f}\text{m}, \quad (9)$$

$$r_{correction} \times \frac{Kerf + d_f}{2} = \frac{Kerf^2 - d_f{}^2}{2}, \quad (10)$$

$$r_{correction} \times \sqrt{Kerf \times d_f} \leq \frac{Kerf^2 - d_f{}^2}{2}, \quad (11)$$

$$r_{correction} = \frac{Kerf^2 - d_f{}^2}{2 \times \sqrt{Kerf \times d_f}}, \quad (12)$$

In table 2 we will present the mathematical value of the correction radius:

Table 2. Correction radius, focused diameter, CO2 laser kerf

Working parameters	Kerf	d_f	$r_{correction}$
SI	mm	mm	mm
Values	0,5	0,3	0,21

Correction radius deviation:

$$\Delta r = r_{correction}^{experiments} - r_{correction}^{mathematic} = 0{,}25 - 0{,}21 = 0{,}04, \quad (13)$$

The two methods of calculating the correction radius confirm each other, it results that the studied models ensure stability of the dynamic cutting process.

In the industrial field, the most important characteristics of laser radiation are intensity and directionality. Focusing several laser beams in a confined space can generate high temperatures or initiate thermonuclear reactions. The mode of propagation of laser waves called vibration modes under TEM0, TEM00, TEM000 will produce ionization in the air that initiates a plasma (a spark). The power of this focus called laser spot depends on the focusing parameters of the lens and the degree of collimation of the laser beam. Concentrating a quantity of energy on an elementary surface creates very high temperatures. Cutting materials can be done quickly and precisely by focusing laser radiation. Cutting, drilling, welding operations can be performed with concentrated laser light beams, due to the high temperature, as well as the possibility of working in an inert gas, nitrogen, argon, helium or assisted by oxygen. The qualities of laser light (wavelength, degree of collimation = divergence, intensity, energy) make it useful for the processing of metallic materials. The diameter of the laser spot can vary by the order of tenths of millimeters when cutting Hardox400, H450, H500 sheets. It can be adjusted by moving the waveguide closer or further away [11].

4 Results and discussion

The laser spot step in technological operations is an important processing size. With the spot you melt the material and perform the cutting. There is not much research in this regard and for these reasons I proposed this topic. The laser spot has a circular shape in which an enormous energy is concentrated. It is the tool that helps to make the cut. A characteristic size is the diameter d, and in some studies the radius of the laser spot w.

If we position the laser radiation on the surface of the material, it results that at 1 laser spot cutting is $l_1 = d$, 2 overlapping laser spots result in the cut length

$$l_2 = d + \frac{d}{2} = \frac{3}{2}d, \quad (14)$$

The step of the laser spot is $\frac{d}{2}$. With the 4 edges, extremes of the circular spot, the cutting is

performed. The edges cut, and these will make the cut.
With three overlapping laser spots, the cut length results

$$l_3 = 2d, \tag{15}$$

With three overlapping spots we will cut a length of 2d. For a 100 mm cut we will apply the 3 simple rule:
3 spot . . . . .2d=2x0,30 mm=0,60 mm
X spot . . . . .100 mm

$$X = \frac{3\times100mm}{0{,}60mm} = 500, \tag{16}$$

In practice with n=500 spots we will cut 100 mm.
Checking:

$$L = \frac{2n}{3} \times d = \frac{2\times500}{3} \times 0{,}30 = 100\ mm, \tag{17}$$

Here we have expressed the calculation relationship of the length of a cut depending on the total number of spots and the diameter of the laser spot.
The comb-style cuts each have a certain length. They can be used for testing in order to establish the adjustment parameters. In physics and industry, energy density is a frequently used quantity in cutting [3]. It is defined as the energy emitted per unit volume by the laser spot:

$$\rho_E = \frac{E}{\frac{4}{3}\pi r^3}, \tag{18}$$

Where:
ρ_E = energy density $[\frac{J}{m^3}]$,
E= laser energy [J],
r = spot radius [mm]
The relationship for laser energy was established [4]:

$$E = \frac{P\times d}{v}, \tag{19}$$

Energy density provided by the spot to the part

$$\rho_E = \frac{E}{\frac{4}{3}\pi r^3} = \frac{E}{\frac{4}{3}\pi\times\frac{d^3}{8}} = \frac{6E}{\pi d^3} = \frac{6P}{\pi v d^2}, \tag{20}$$

where P is the laser power [W], d = laser spot diameter [mm], v = feed rate [mm/min]
Power density is another physical quantity used in cutting. It is defined as the power emitted as radiation per unit area [1]. In practice, these studied quantities are frequently used.

$$\rho_P = \frac{P}{S} = \frac{P}{4\pi r^2} = \frac{P}{4\pi\frac{d^2}{4}} = \frac{P}{\pi d^2}, \tag{21}$$

where ρ_P is the measured power density $[\frac{W}{m^2}]$.

The relationship between densities leads us to:

$$\frac{\rho_E}{\rho_P} = \frac{\frac{6P}{\pi v d^2}}{\frac{P}{\pi d^2}} = \frac{6}{v}, \tag{22}$$

Here we will obtain that the density ratio of a circular laser spot depends on the cutting speed:

$$\frac{\rho_P}{\rho_E} = \frac{v}{6}, \tag{23}$$

It is also found that at a minimum energy density, the cutting speed is maximized. In this case, we are efficient when we run the cutting at a maximum speed.
The energy density of the focal spot at normal incidence (i=0) will ensure the superficial melting of the part [8]. The influence of the irradiation spot size on the samples will be taken into account. Reducing the spot diameter has the effect of strongly increasing the incident intensity. The dimensions of the laser spot have an effect on the absorption of laser radiation. In the case of carbon dioxide lasers, the spot sizes are small, on the order of tenths of mm at normal incidence. A large number of consecutive pulses to the same spot leads to an increase in surface roughness. Heating a metal with a radiation pulse, monopulse, is performed with a non-contact laser spot that has a spatial structure on the surface of Gaussian shape. Rectangular pulses are long pulses of the order of microseconds. Gaussian pulses are short pulses of the order of nanoseconds. The energy of the incident laser radiation is instantly distributed in a Gaussian spot. Reducing the duration of the laser pulse has positive effects on local melting. The laser spot moves at a constant speed over the sample where it cuts the part by irradiating it. The laser spot is a thermal source that heats an infinitesimal portion and melts it almost instantly. Steels with a thickness greater than 10 mm are cut with large laser spots that have low penetration capacity. Thin metals are cut with small spots that are characterized by very high penetration capacity.

Fig. 2 Fiber Laser and Hardox400 steel plate

Following the processing of Hardox steel, g=10 mm, with carbon dioxide laser and fiber laser [6], figure no. 2, the following results were obtained for energy density, table 3:

Table 3. Parameters and physical quantities determined analytically CO2 Laser and Fiber Laser

Laser system	Max. speed [mm/min]	Spot Diameter [mm]	Interaction time [ms]	Energy density [J/mm^3]	Power density [W/cm^2]
CO_2 Laser	1600	0,30	11,25	4060,50	7,28x10^6
Fiber Laser	1350	0,38	16,88	3154,38	4,83x10^6

The CO_2 laser has a laser spot with a higher incident intensity, which proves that it is more efficient than the fiber laser for thick sheets. It is also deduced that laser spots concentrated with a higher energy at the same volume have a better melting capacity. In a volume V = 1 mm^3 of a spot, the carbon dioxide laser has a higher brightness, which makes it have important physical properties when evaluating cutting.

The specific point load is another factor that influences the cutting [9]. The specific energy can be approximated as a function of the cutting width Kerf and the energy density. In this way the connection between the laser radiation and the material is made. The mathematical relationship that develops Table 4:

$$\epsilon_s = Kerf \times \rho_E, \quad (24)$$

Table 4 Kerf and laser spot capabilities

Laser system	Kerf [mm]	Energy density [J/mm^3]	Specific energy ϵ_s [J/mm^2]
CO_2 Laser	0,5	4060,50	2080,25
Fiber Laser	0,6	3154,38	1892,4

When cutting, the carbon dioxide laser gives a better cutting quality than the fiber laser. The fiber laser is recommended for thin sheets, under 4 mm. The specific energy can also be interpreted as the energy received from the laser spot on the molten surface [10]. The practical result is that by moving the laser spot on the material we continuously provide the target with the specific energy in order to make the cut.

For sheets over 5 mm thick, the carbon dioxide laser is more efficient in cutting parts. The energy density of carbon dioxide 4060 [J/mm3] is higher than that of the fiber laser 3154.38 [J/mm3], which results in the laser beam emitted by CO2 being more intense. The use of strong electric fields produces different effects on matter. It is known that laser intensity is proportional to the square of the electric field intensity. Another conclusive result that leads to the concentration of light is the focal diameter. In the case of the carbon dioxide laser, the focal diameter is 0.30 mm, and in the fiber 0.38 mm. These aspects lead to qualitative parts obtained with the gas laser [12]. The ByFiber, BySpeed3015, ByAutonome4020 laser systems were used for cutting and drilling hard Hardox sheets. Copper nozzles were used in the cutting head to concentrate the cutting gas. Their diameter was 1.5 mm for the carbon dioxide installation and 1.8 mm for the fiber installation. The nozzle-part distance was adjustable between 0.8 - 1.5 mm. The stand-off ensured the circular piercing. The laser power was selected between [3800, 5200] W. The parts are manufactured with 2D, 3D technology. The straight cutting profile was cut in continuous CW mode, and the circular piercing in pulsed PW mode. With the help of BYSoft, the input parameters, working parameters, stand-off distance, beam polarization were selected. The role of the laser nozzle is to regulate the gas flow rate where the turbulent gas jet from the cutting head becomes a laminar gas jet when passing through the nozzle. The assistant gas surrounds and protects the laser beam in the cutting head, in the nozzle and at the exit from it. An important role of the laser nozzle is to increase the cutting capacity of the gas when it encounters the part [13]. Another role is to control the gas pressure, set at 0.4 - 0.6 bar.

The error committed in determining the correction radius with the experimental model and the mathematical approximation model is 0.04 mm, which demonstrates a very small error < 5%. It follows that the studied models are reliable. The correction radius at the dioxide laser installation was chosen by the operator depending on the Kerf, while at the fiber the sensor system imposed the radius depending on the material. Nine measurements were made at Kerf, from which the average of 0.5 mm emerged in the case of the gas system. The deviation of each experiment is the modulus between the measured value and the average value. The squared deviation increases the accuracy of the error calculation, calculation of the MSE average. The standard error is the radical of MSE/9. The confidence interval is the average Kerf ± 2 standard error. The measured Kerf varied between 0.30 and 0.64 mm. From the statistical calculation based on the input parameters and Kerf values, the effect of each parameter on Kerf can be calculated. In the future, we will propose a study based on Kerf measurements from fiber and CO2 to demonstrate the influencing factors.

4 Conclusion

Following scientific research in the field of processing Hardox 400 steel with power lasers, the following conclusions can be drawn:

1. The laser spot is a heating source that provides power densities necessary to perform certain cutting operations, CO_2 = $7{,}28 \times 10^6$ W/cm^2, Fiber = $4{,}83 \times 10^6$ W/cm^2
2. A quantity of interest is the spot correction radius which is determined using the kerf and the focused spot radius.
3. Another quantity of interest is the specific energy radiated over the entire surface of the focal spot.
4. For practical uses, the following physical quantities of interest are retained: interaction time, energy density, Kerf, power density.
5. In practice, the laser spot moves on the sample surface to process some operations.
6. Reducing interaction time $t_i = 11{,}25\ ms$ for CO_2 laser compared to Fiber laser $t_i = 16{,}88\ ms$ leads to lower energy costs for laser heating of Hardox400 metal samples to melting.
7. The incident laser energy is distributed instantaneously in a laser spot of diameter d, characterized by an incident energy density at the origin of the Gaussian bell, $E_0 = 4060{,}50 \frac{J}{mm^3}$ in the case of the CO_2 installation and $E_0 = 3154{,}38 \frac{J}{mm^3}$ for Fiber installation, which demonstrates more effective melting depth at CO_2.

Acknowledgement: Many words of thanks to SC BYSTRONIC SA BRAȘOV, SC IRUM SA Reghin.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy) The authors equally contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself
No funding was received for conducting this study.

Conflict of Interest
The authors have no conflicts of interest to declare that are relevant to the content of this article.