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# Fiber Laser Intensity when Cutting SICROMAL Steel

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**Abstract**
Alloy steel for the thermal energy industry was cut with a 10 kW fiber laser. The input parameters used in the cutting experiments were the laser power, cutting speed and focus position, at a focus diameter d = 0.38 mm. The output parameter studied was the number of peaks on the side of the sample. Through mathematical and physical modelling, the intensity focused by the sapphire lens on the part was calculated. Lagrange interpolation calculation established the relationship between the number of slopes and the focus position. The study provides compatible relationships for the physics and engineering of laser applications in energy practice.

**Keywords**
laser cutting, fiber laser, roughness, kerf

## 1. Introduction

Cutting steel with a fiber laser of metals can be performed with radiation emitted by a diode system that generates a power between 4600 and 4800 W. Gas jet cutting is performed by attacking the target with a convergent beam surrounded by gas (oxygen). The fiber laser has a continuous operation of pulsating the light wave, a focusing system and a system for moving the laser beam above the target. Irradiation of the material with a laser beam produces melting which, when discharged, creates parts. The laser wave is an electromagnetic wave with very intense electric and magnetic intensities that propagates in a single direction with a luminous intensity capable of producing physical and chemical transformations of the substance. The light defined by Newton, Maxwell, Planck, Einstein, De Broglie is made up of light particles called energy quanta, photons that interact with electrons and atomic nuclei. The collision between the photon and the electron can produce ionization of atoms, excitations and deexcitations of electrons that produce light or free electrons that produce a local electric current through movement. The intense electric current generated by the rapid movement of electrons produces through the Joule effect a local heat sufficient and necessary for local melting. It can be concluded that the electromagnetic field of the laser beam gives rise to and is transformed into the electromagnetic field of the metal portion. The cause-effect relationship is explained by the model of the electromagnetic field of laser light that almost instantly generates an induced electromagnetic field in the metal portion.

The two fields destroy an elementary portion of the metal resulting in the cut. In the future, research will be developed that will have as its subject the presence of fields originating from the laser and in the metal. In laser cutting, the light flux, the power density will participate in the emergence of a current density. The electric current destroys the metal network in a continuous mode, giving rise to a quantity of molten metal. The assist gas jet removes and cleans the molten metal.

There are recent researches with authors who support the research. Qi et al. [1] present the fact that the laser beam at the exit of the resonator has a Gaussian distribution impossible to use in practical applications and propose the modelling by the aperture method or the multiple aperture focusing method. Li et al. [2] improve the operation of laser weapons by using the dichroic mirror in the wavelength combination system. Adin [3] used fiber laser technology to investigate the effects of cutting parameters on Ra of API5LX60 steel. Optimal cutting parameters for a small Ra are laser power P = 2000 W, speed v = 2400 mm/min, pressure p = 4 bar. The steel is used in pipelines for oil and gas transmission. Tian et al. [4] developed laser additive manufacturing of Ti-6Al-4V alloy components by powder fusion in the aerospace, military and medical sectors. An input parameter optimization model was proposed to improve the upper and lower Ra of the start. Huang, Huang et al. [5] rely on a new technique in high-precision machining, called super-resolution. There are two modern methods in manufacturing based on diffraction limitation by shorter laser wavelengths or advanced focusing and overcoming the diffraction limit by manipulating the beam when interacting with materials.

Zhang et al. [6] used IN718 Alloy material in laser metal deposition (LMD) process. The result is a microstructure with decreasing hardness with increasing temperature.

Trifunović et al. [7] propose new methods for fiber laser cutting of mild steel using Fuzzy methodology. Three input parameters were run (focus position, cutting speed and oxygen pressure) and four output parameters were examined (Kerf- straight and curved profile, Ra, productivity), three Fuzzy criteria (TOPSIS fuzzy, WASPAS fuzzy and ARAS fuzzy) decided the ranking of the samples.

Madić et al. [8] increased the cutting accuracy of the samples in the case of 316L stainless steel by combining the cutting energy, auxiliary gas flow rate at four laser spot cutting radii. The laser system used to attack the targets was a carbon dioxide laser with a wavelength of 10.6 μm, which provided the cutting process. It was found from statistical mathematics that accuracy is ensured if cutting energy and assist gas flow are used at average values.

Kumar et al. [9] improve weld quality and strength of IS2026 carbon steel bars cut with a fiber laser. The S-z roughness (maximum height) is higher when using an oscillating beam from a fiber laser operating in continuous wave (CW) mode.

Babič et al. [10] fabricate EOS Maraging Steel MS1 parts using additive SLM technology. Ra is improved when fractal geometry and lattice theory are used for prediction. Hutten [11] approaches physics problems through experiment and mathematization, the evolution of particle and wave concepts. Landau and Kitaigorodski [12] deals with interesting topics, thermal expansion, specific heat, thermal conductivity, convection which always occur when materials are attacked by laser. Tarasov [13] states that the laser is a device in which the energy of the electromagnetic field appears in the laser beam.

## 2. Experimental Method

### 2.1. Design of Experiments

The experiment is a procedure used in physics and engineering [11]. The development and observation of the experience with the help of the intentionally provoked experiment is possible by using instruments and a set of monitored physical quantities that allow the results obtained to be interpreted correctly. Through experiments on cutting steel sheets with a laser, we have the opportunity to provoke new scientific, abstract ideas, useful for scientific research. Also, the theory and increasingly vast experiments in situations of laser attack on metal targets are expanding. On this occasion, the development of the laser intensity necessary for heating and melting, the number of features/wrinkles on the side of the piece considered square, the correspondence between the number of slopes and the focusing position of the laser spot will be followed. Of great importance in scientific research is the practical examination of the cut pieces in determining the number of peaks (measurement of the output parameter N).

The research team designed a factorial experimental design. It was proposed to study the parts resulting from the independent experiment 1, 14, 27. With the help of mathematization we proposed to expand the importance of the data through the Lagrange interpolation model. In cutting we used a state-of-the-art fiber laser from Bystronic. Using the ByVision interface we selected the input parameters (laser power, cutting speed and focus position) as well as the working parameters (spot diameter, gas type, gas pressure). The cutting mode was in continuous wave CW, the focus position was chosen by the laser system. The assistant gas was oxygen maintained under pressure. The material data were selected from the laser installation library.

### 2.2. Theoretical Model of Laser Attack of the Target

If a film of material is heated with a laser, we will obtain a more intense movement of atoms, they begin to repel each other and occupy a larger space [12]. To heat a film more, more energy is needed. The laser is an energy source that satisfies such a condition. According to Joule, the internal energy of the film depends on the temperature. To heat the film from the initial temperature T0 to the melting temperature Tm, the laser must transfer to the film thermal energy (heat) equal to the calorific capacity of the material multiplied by the temperature variation ΔT. Through the phenomenon of heating the metal target, the laser energy is lost completely (absorbed) or in part (reflected), where it is found that the internal energy ΔU of the film increases by the same amount of heat. Based on the theory of Hermann Helmholtz, it can be considered that the law of conservation of energy applies to the interaction of laser radiation with the substance as a fundamental law of natural and engineering sciences. The technique of laser melting and gas blowing of the molten metal quantity signifies the laser cutting process as a whole. Through this brief description we can develop the theoretical model of the heat equation or the laser intensity equation.

In the center of the laser spot is the spherical coordinate system which, depending on the radial distance r, we can calculate the value of the laser light intensity at a distance r from the center of the focal spot, as seen in fig. 1. The spherical coordinate system is a 3D three-dimensional coordinate system according to which we can determine the variation in different points in the field of the laser intensity. In the center of the focal spot the intensity is maximum, and in the other points located on the radial distance it decreases. The axes are the unit vectors, φ the azimuthal angle, and θ the polar angle. The Cartesian coordinates of the laser spot (x, y, z) depend on the radial coordinate, the azimuthal angle and the polar angle, (x, y, z) = f(r, φ, θ). The variation of a physical quantity (differential) is calculated depending on the spherical coordinates (r, φ, θ). In the plane the surface of revolution around Or is an ellipse or a circle.

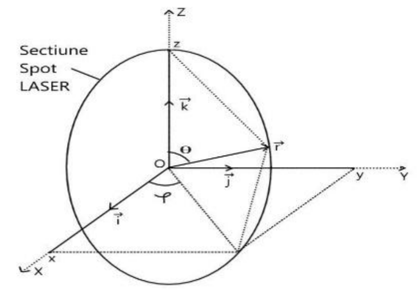


Fig. 1. Laser spot in the coordinate system [12]

A special steel used in thermotechnics and energy complexes was studied. This is an alloy of silicon, chromium, aluminum in combination with iron and carbon called SICROMAL in industrial practice. The sheet is 5 mm thick; the test piece is square 20×20 mm. The laser installation used to cut a full experimental plane is a FIBER laser with a power of 10 kW (Figure 2). The measurements were made on the side of the piece where the laser enters and exits the contour. An optical instrument, the magnifying glass, was used, where the number of slopes of the cut surface was measured. The length of the side of the studied piece is equal to 20 mm, Figure 4. It is also found that the number of grooves is increased when the laser power has critical values. In conditions of medium laser power, melting is more suitable due to the concentration of energy. The melt flow becomes constant under conditions where the input parameters are set to average values (Figure 3), the effect being the decrease in the number of grooves.

According to some authors [4, 7], the operating mechanism of the fiber laser is based on optical pumping performed by six laser diodes arranged in parallel, having as active medium a pn junction. An electrical signal, generated by a continuous low voltage source, excites electrons, populating the higher energy levels. Laser emission occurs by rapid depopulation of these levels, generating a coherent light beam. The light emitted by each diode is directed through a set of optical instruments (prisms, mirrors and filters) to an optical crusher. Here the laser waves interfere to produce an amplified beam. The resulting beam is guided in a fiber optic cable doped with Ytterbium, an essential material for the transmission of laser light. This configuration allows for high-power laser emission, up to 10 kW.

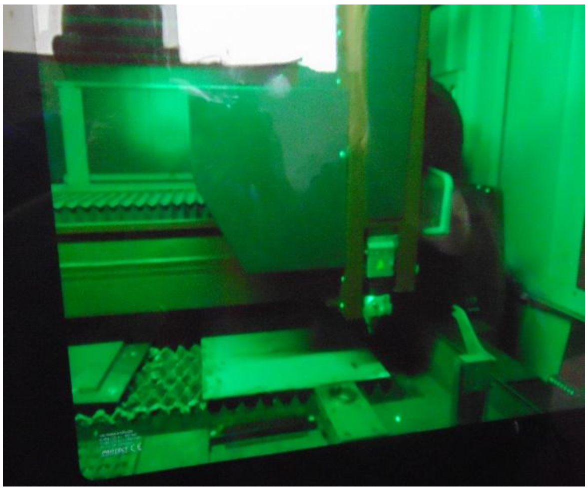

Fig. 2. Fiber laser and semi-finished products

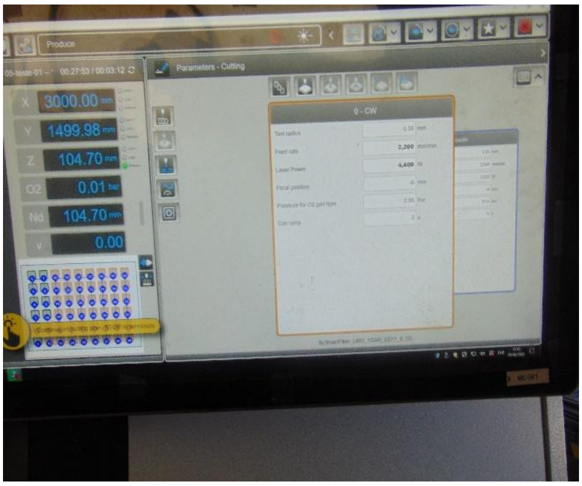


Fig. 3. Laser parameters interface

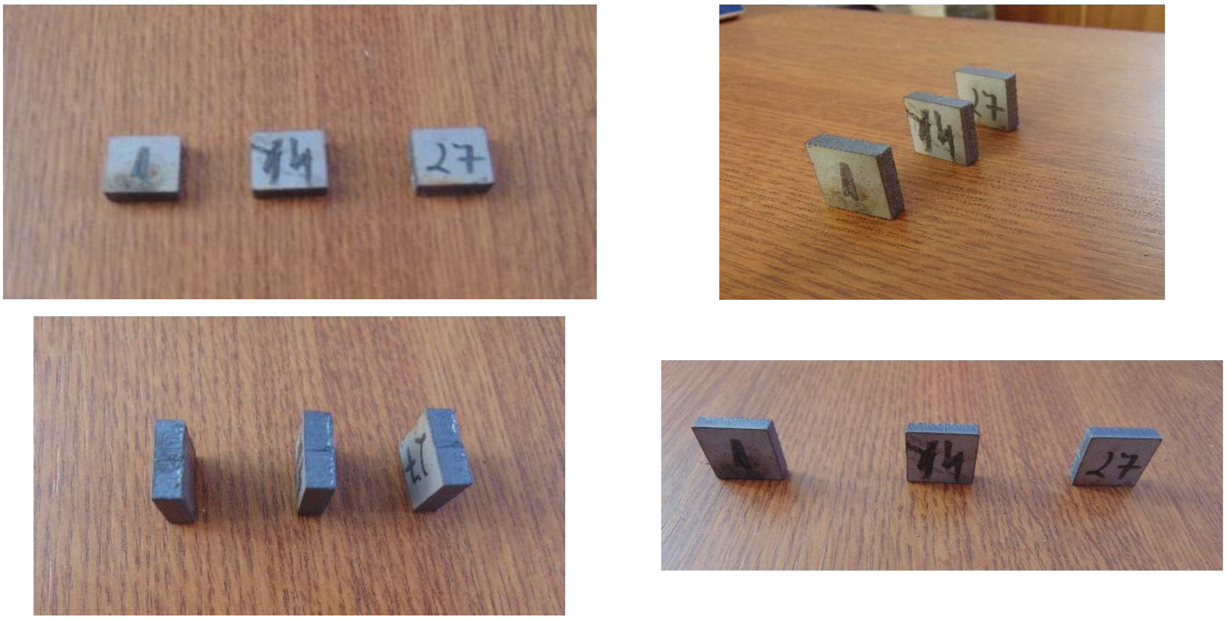

Fig. 4. Samples 1, 14, 27 processed with laser

The experimental data used in the laser processing of the material are presented in table no. 1.

Table 1. Input and experimental values

| Sample number | Laser power | Cutting speed | The focus position | Number of slopes |
|---|---|---|---|---|
| 1 | 4600 | 2100 | -7 | 31 |
| 14 | 4700 | 2200 | -6 | 25 |
| 27 | 4800 | 2300 | -5 | 29 |

## 4. Mathematical Relations

The intensity of a laser spot is an important physical quantity in laser material processing processes. Some books treat this quantity as the power density, i.e. the laser power per unit circular area of the laser spot. The cutting tool is based on the concentration of energy distributed by the lens. The energy flux crossing the circular section of the spot is another definition of the intensity of a laser. The laser beam has a diameter *D* before entering the lens which has main influences on the focusing position. The light enters the lens and travels an optical path equal to *e(n-1)*, where *e* is the thickness of the lens, and *n* the refractive index of the lens. The optical device is a biconvex lens that focuses the laser light into a spot of size $d$. At the entrance to the lens the laser beam has the incident intensity $I_0$. By refraction of the light in the lens a concentrated spot with giant energy is obtained. It has a focal spot in the center that has the amplified intensity $I$. We propose to calculate the intensity distribution in the laser spot.

It is found that by a reasoning of conservation of energy flux, in the case of fiber laser, D = 20 mm, d = 0.38 mm, the converging lens increases the intensity of the laser light. In the case of a laser spot we will take into account the spherical coordinates.

$$\begin{cases} x = rcos\varphi sin\theta \\ y = rsin\varphi sin\theta \\ z = rcos\theta \end{cases} \tag{1}$$

and the radial coordinate (distance) $r$:

$$r^2 = x^2 + y^2 + z^2 \tag{2}$$

The differential $dr$ signifies the increase which is given by $r = r(x, y, z)$:

$$dr = \frac{\partial r}{\partial x}dx + \frac{\partial r}{\partial y}dy + \frac{\partial r}{\partial z}dz \tag{3}$$

Here the position vector $\vec{r}$ can be written according to the relation:

$$\vec{r} = x \cdot \vec{\imath} + y \cdot \vec{\jmath} + z \cdot \vec{k} \tag{4}$$

The gradient is a differential operator given by the relation:

$$\nabla = \frac{\partial}{\partial x} \cdot \vec{\imath} + \frac{\partial}{\partial y} \cdot \vec{\jmath} + \frac{\partial}{\partial z} \cdot \vec{k} \tag{5}$$

The gradient of laser light intensity (scalar field) becomes a vector field:

$$\nabla \mathrm{I} = \frac{\partial I}{\partial x} \cdot \vec{\imath} + \frac{\partial I}{\partial y} \cdot \vec{\jmath} + \frac{\partial I}{\partial z} \cdot \vec{k} \tag{6}$$

Growth $\mathrm{d}\vec{r}$ is expressed by the relationship:

$$d\vec{r} = dx \cdot \vec{\imath} + dy \cdot \vec{\jmath} + dz \cdot \vec{k} \tag{7}$$

The laser intensity differential represents the scalar variation (increase) of the intensity field:

$$dI = \nabla I \cdot d\vec{r} = gradI \cdot d\vec{r} \tag{8}$$

Here the differential $I$ is the product of two vectors.

The Laplacian of the intensity field gives the differential equation of the laser intensity under conditions of spherical symmetry, spherical coordinates:

$$\Delta I = \nabla^2 I = \left(\frac{\partial I}{\partial x} \cdot \vec{\imath} + \frac{\partial I}{\partial y} \cdot \vec{\jmath} + \frac{\partial I}{\partial z} \cdot \vec{k}\right) \cdot \left(\frac{\partial I}{\partial x} \cdot \vec{\imath} + \frac{\partial I}{\partial y} \cdot \vec{\jmath} + \frac{\partial I}{\partial z} \cdot \vec{k}\right) = \frac{\partial^2 I}{\partial x^2} + \frac{\partial^2 I}{\partial y^2} + \frac{\partial^2 I}{\partial z^2} \tag{9}$$

The differential equation was developed by Drăgănescu for temperature, we propose the intensity:

$$\frac{\partial^2 I}{\partial r^2} + \frac{1}{r} \cdot \frac{\partial I}{\partial r} = 0 \tag{10}$$

We propose the substitution for the solution:

$$\frac{\partial I}{\partial r} = x \tag{11}$$

This results in a new differential equation taking into account the identity:

$$\begin{gathered} \frac{\partial I}{\partial r} = \frac{dI}{dr} \\ \frac{dx}{dr} + \frac{1}{r}x = 0 \\ \frac{dx}{x} = -\frac{1}{r}dr \end{gathered} \tag{12}$$

By integration we obtain:

$$\int \frac{dx}{x} = -\int \frac{dr}{r}; \quad lnx = -lnr$$
$$ln\frac{dI}{dr} = -lnr; \quad \frac{dI}{dr} = r^{-1}$$
$$\int_{I_0}^{I} dI = -\int_{D}^{d} \frac{dr}{r} \quad \Leftrightarrow \quad I - I_0 = -ln\frac{d}{D} \tag{13}$$
$$\Delta I = I - I_0 = ln\frac{D}{d}$$
$$\boldsymbol{I = I_0 + ln\frac{D}{d}} \tag{14}$$

The increase in laser intensity in the spot depends on the diameters of the beam before entering the lens and the focused one. The relation is a novelty in laser theory because it accurately approximates the increase in intensity in the laser spot. The variation in intensity $\Delta I = 4$, an important result when we place a sapphire lens in front of the laser beam. A new interpretation is that the role of the lens is to increase the laser light intensity approximately five times. The result is accessible to laser cutting of materials. The physical model of the laser spot is treated accordingly when we apply elements of field theory and operators to the spherical coordinate model, which is more accurate. The same is estimated for the focal spot.

It is found in the studied piece that the number of slopes n per unit length respects the physical relationship:

$$n = \frac{N}{L} \tag{15}$$

and the channel distance between 2 slopes (peaks) is the linear constant noted:

$$l = \frac{L}{N} \tag{16}$$

The fundamental relationship of the laser-attacked surface becomes:

$$n \times l = 1 \tag{17}$$

The Lagrange interpolation polynomial was applied to the data in Table 1. We determine by Lagrange interpolation the relationship between the number of slopes $N$ and an important input parameter of the cut, the focus position *f.* The input points are the three input levels of the focus. This input parameter was chosen because the laser radiation provides different values of the energy density. The input points are determined by the laser with the help of sensors, registered in the system:

The entry points are determined by the laser using sensors, registered in the system:

$$\begin{cases} f_{min} = -7\ mm \\ f_{ave} = -6\ mm \\ f_{max} = -5\ mm \end{cases} \tag{18}$$

The output variable, the answers are presented in the system:

$$\begin{cases} N_1 = 31 \\ N_2 = 25 \\ N_3 = 29 \end{cases} \tag{19}$$

The Lagrange polynomial establishes the function by which we can calculate the output variable - the number of slopes:

$$L(x) = \frac{(x - f_{ave}) \cdot (x - f_{max})}{(f_{min} - f_{ave}) \cdot (f_{min} - f_{max})} \times N_1 + \frac{(x - f_{min}) \cdot (x - f_{max})}{(f_{ave} - f_{min}) \cdot (f_{ave} - f_{max})} \times N_2 + \\ + \frac{(x - f_{min}) \cdot (x - f_{ave})}{(f_{max} - f_{min}) \cdot (f_{max} - f_{ave})} \times N_3 \tag{20}$$

The complete Lagrange polynomial:

$$(x) = 5 \cdot x^2 + 59 \cdot x + 199 \tag{21}$$

In the case of the laser spot focusing model, the equation gives the output variable under study $N$:

$$N(f) = 5 \cdot f^2 + 59 \cdot f + 199 \qquad (22)$$

By checking with $f$ = -6 mm we obtain $N$ = 25 by substituting in the relation (22).

## 5. Conclusions

Cr alloyed steel (11.9%), 5 mm thick sheet, is cut very well with a 10 kW fiber laser, the cut surface is classified between 2 and 5 μm, Ra.

DOE is a completely robust factorial design from which samples were selected for inspection with a magnifying glass on the laser-cut surface.

Drăgănescu's model for estimating temperature from the heat equation was studied for another important physical quantity, the laser spot intensity, using differential and integral calculus.

It is found that the lens increases the laser intensity five times at the ends of the laser spot, considering the diameter of the laser light entering the lens, for focusing or for researching the focal spot.

Sample 1 has the most slopes because the sheet was initially cold, preheating leads to better quality.

The defined cut indicators were the lattice constant and the number of striations per unit length.

The Lagrange quadratic interpolation polynomial defines exactly the functional relationship between the number of slopes N and the focusing position of the laser spot.

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