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Research on laser cutting of HARDOX steel parts

SUMMARY

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Content

Pg. sum. **Pg. tthes**

PREAMBE

The motivation of this doctoral thesis is given by a certain lack of scientific data which to support the production practice in the use of the CO_2 laser for the manufacture of industrial products from metallic materials such as HARDOX alloys.

The PhD thesis is a study that aims to bring some theoretical and practical contributions that could be useful to researchers, academics and industry specialists, regarding the operation and use of laser devices, as well as their applications in the processing and manufacturing of parts in industrial engineering.

The paper presents the general theoretical framework of the formation and propagation of laser light and its fields of application. Following an analysis of the scientific achievements in the field of laser use in the manufacture of industrial products, the main objective and the derived objectives of the doctoral thesis were defined. Following the doctoral research internship, in which theoretical research and experiments were carried out in the field of laser cutting, results were obtained regarding mainly models and mathematical relationships that describe the dependence of some determining factors for the properties and quality of products made by laser cutting on the parameters work regime. The research was oriented towards the study of the behaviour of some HARDOX steels during laser processing. The choice of the mentioned category of materials was motivated by the fact that in the literature there is some limitation of information regarding these steels, due to their wide use in the industry, and especially by the fact that HARDOX steels are very difficult to process using classic cutting technologies.

The theoretical component of the research aimed at explaining some aspects related to the phenomena that occur when the laser interacts with the processed material and identifying some directions for the experimental research. This was carried out based on experiments designed in the classical manner, but also according to full and fractional factorial designs.

The physical and mathematical modelling of the laser cutting process of steel allowed comparing the theoretical results with the practical ones and highlighting the existing correlations between the two levels. The processing of experimental data with advanced software allowed obtaining conclusive results with practical applicability.

The experimental research also targeted aspects related to environmental protection, namely, the specific energy consumption during laser processing. Experimental research has allowed the identification of the input/setting parameters of the laser cutting process that have the most significant influence on the machining results. Based on the findings, recommendations could be stated regarding the working regime for the processing of some steels from the HARDOX range.

The research results were validated through case studies.

We appreciate that the research results have materialized in a series of original contributions and useful conclusions both theoretically and practically for those involved in the use of laser cutting as a process for manufacturing industrial products.

It can be concluded, following the research carried out during the development of the doctoral thesis, that laser cutting proves to be a very suitable technological process for the processing of hard-to-machine materials.

CHAPTER 1 Introduction

1.3 Organization of the doctoral thesis

This doctoral thesis is organized in 3 parts structured in 7 chapters. The first part comprises the preamble, introduction, and a review of the current state of the scientific research on the use of lasers in part manufacturing.

Chapter 1 of the doctoral thesis presents in detail the technological process used in the manufacture of industrial products based on laser cutting. Cutting a part by means of a laser beam involves matching the characteristic properties of the laser radiation with the physical properties of the material to achieve the desired precision. The laser cutting process is introduced as a product processing technology based on the phase transformations that the material undergoes. Research done with laser devices has applications in laser machining operations (cutting, drilling, and welding).

Chapter 2 of the doctoral thesis presents the history of the appearance and development of the laser, the scientific revolution in the laser field from 1959 to nowadays. The production of the laser effect based on two basic phenomena is briefly presented: the inversion of the populations with atoms and the stimulated emission, so that following a process of optical pumping or excitation of the gaseous medium and multiplication of the number of photons, an amplified light results – laser light . The mathematical relationships describing the laser effect in the laser tube, the CO_2 laser, the current state of the research in the field of laser processing technologies, laser machining of alloys and metallic materials are presented.

Based on the conclusions stated at the end of Chapter 2, in Chapter 3 the main objective and secondary objectives of the doctoral thesis were formulated.

Chapter 3 presents the objectives of the PhD thesis and the research directions in the preparation and running of experiments that will bring the best information about how hardness, roughness Ra, width of cut - kerf are influenced by predictors. Research directions are focused on new specific objectives: selection of special steel materials, modern CO_2 laser equipment, full or fractional experimental plans, carrying out experiments to test the roughness, hardness and width of the cutting slot, under the conditions of industrial production.

The second part of the doctoral thesis contains the chapters related to theoretical and experimental research.

Chapter 4 – the theoretical research focused on some characteristic aspects of the CO_2 laser. The purpose of this study was to identify the intensity of the laser when interacting with metals, considering it the most important parameter dedicated to laser processing. Also, metal temperature is an important condition parameter with direct implications on the processing of metal surfaces. The superior mathematical calculation provides the theoretical approach of the phenomena accompanying the interaction of the laser beam with the metal target for practical applications.

Chapter 5 – *experimental research* presents, among other issues, the material and method used, the design of the experiments, the research infrastructure, the collection of experimental data and their processing. Each subchapter ends with conclusions. The experimental research was carried out at SC BYSTRONIC S.A. Brașov, using different types of laser equipment. At this unit, the experimental research of CO_2 laser cutting of HARDOX 400 sheets was carried out. The experimental data were obtained through measurements carried out at the Laboratory of the "Constantin Brâncusi" University in Tg-Jiu, the Oltenia Energy Complex-Measuring Laboratory of Rovinari Thermal Power Plant and industrial company MIRFO S.A. Data processing was performed with the Statistica 7.0 software package to determine how hardness, roughness, and kerf are influenced by predictors` variation.

Case studies and final conclusions are presented in the third section of the doctoral thesis.

Chapter 6 – presents the case studies carried out for the practical validation of the results of the experimental research. The mathematical relationships established in Chapter 5 are verified against the input parameters. The verification was done by establishing a target value for one of the output characteristics and selecting with by means of the identified mathematical relationships the values of the predictors that would theoretically lead to the target value being obtained. Finally, the practical results are compared with the mathematically estimated ones and the relative deviation between the two is determined.

Chapter 7 – *Conclusions*, summarizes the main achievements of the doctoral thesis, the general and specific conclusions based on the results of the research carried out and the relevance of the results. The most significant predictor is highlighted for each analysed output characteristic. Lastly, the synthesized personal contributions of the doctoral thesis are presented, the way of capitalizing and disseminating the research results, and the possible directions for the future development of scientific research are stated. The work also contains the list of figures, tables, and references.

CHAPTER 2 The current state of scientific research in the field of using lasers for steel cutting

2.3 Applications of lasers

2.3.1 Industrial applications

In industrial engineering, the most used laser is the CO_2 laser, because it has a system of mirrors and a lens, capable of reflecting, amplifying, and focusing the light so that the laser beam has sufficient power to melt the material [CHE14].

The main technological processes for processing materials (metals/steels, non-ferrous alloys, non-metallic materials) with the laser are as follows: cutting, drilling, welding, marking, engraving, in continuous or pulsed wave mode.

All these processes can be applied to metal processing subject to some restrictions regarding the physical properties of the materials and the thickness of the semi-finished product [BUZ15]. The latter is not a limiting factor for welding.

According to the average power, industrial lasers are classified as:
- 11 W – superficial engravings and cutting of thin metals;
- 21-41 W – engraving and cutting;
- 41-61 W – engraving and cutting thicker materials;
- 61-81 W – special operations;
- 81-121 W – deep cutting and engraving;
- 1-4 KW – power, for special applications, steel cutting;
- 5-6 KW – cutting ultra-hard steels [DON85], [SAV81], [DRĂ86].

2.4.2.8 Applications of lasers in industry

The most important parameters of a laser are power and wavelength [POP75]. An overview of the applications of lasers in welding, drilling, and cutting of materials are described in table 2.5.

Table 2.5 *Industrial applications of lasers [POP75]*

The laser device	The wavelength	Mode of operation	Industrial applications
Rubin:Cr^{+3}	6,69 μm	pulsed	cutting, welding, drilling
Neodim în sticlă	1,06 μm	pulsed	cutting, welding, drilling
Ar	0,48 μm	continuous	warm-ups
CO_2	10,6 μm	continuous	cutting
Neodim în YAG	1,06 μm	Q- switched	telemetry, industry
GaAs	0,90 μm	pulsed	communications
He-Ne	0,63 μm	continuous	alignment

In the works [DON85], [SAV81], [DRĂ86] the authors make contributions to the expansion of the application of the CO_2 and Nd-YAG laser in industrial engineering activities, as well as the applications in the production processes of laser cutting, drilling and welding in the manufacture of products industrial [PAR17].

Applications of lasers in industry rely on light energy carried by coherent electromagnetic waves. Lasers produce infrared, visible and ultraviolet radiation [PUȘ07].

The heat source of the laser beam is concentrated in a very small area on the material [POW09]. This result reduces the deformation of the parts. CO_2 laser and solid laser are installations for cutting sheet metal [WAR19]. Fiber laser ensures effectiveness when cutting thin plates. CO_2 lasers are used to cut sheet metal thicker than 5 mm, which requires high working power. The thesis uses the phrase the width of the cutting slot (cutting joint), which in English-language scientific works is called Kerf, a term also adopted in Romanian. From the point of view of terminology, there is an inconsistency.

There are a number of scientific papers and journal articles dealing with laser processing technology and its improvement by various methods, as briefly outlined below.

In the paper [POC16] the authors define cutting and melting efficiency. Research is being done on the type of material, thickness, wavelength and power of the laser. Fiber laser is found to have high cutting efficiency in thin sheet metal. Cutting efficiency decreases with increasing material thickness. These results are due to the change in the absorptivity of the work zone and the heat affected zone (HAZ).

In the paper [SEO19], the behaviour of the gas flow in the subsonic and supersonic nozzle was highlighted by analysis with the Nomarsk interferometer. The process of cutting stainless steel sheets with a thickness of 60 mm took place with the help of a laser with the power of 6 KW. Experiments were conducted to observe the effect of the geometrical configuration of the nozzles. Through the variation of the nozzle-piece distance, the removal capacity of the formed melt was determined. The results show that the supersonic nozzle has a higher melt removal capability.

In the research [HAJ19], a method for optimizing the laser cutting path to accumulate minimal heat is indicated. A genetic algorithm with neighborhood search is used. This technique is useful for surface hardening in the welding process where the working distance and heat build-up must be optimized to obtain quality parts.

In the paper [ZHA20] a group of researchers shows that laser cutting of thin sapphire sheets with a Bessel beam achieves zero taper and an order of magnitude higher roughness.

A team of researchers [DAR20] investigated the effect of nozzle characteristics (size, diameter) on the high-pressure gas jet to improve laser cutting. By Schlieren visualization it is observed that the exit jet from the supersonic nozzle has a constant flow rate, better dynamic properties and a gas stream with a longer length than the gas jet from the conical nozzle.

In the paper [ZHO21] the research team studied laser radiation polishing of S136D die steel using an L16/44 orthogonal experimental plane. Experiments indicated the variation trend of surface roughness as a function of laser energy density using a moving laser heat source.

Following the analysis of a large number of papers presented in scientific conferences or published in journals, there is a wide interest of researchers in examining the use of lasers for processing materials [POC18a]. Thus, a grouping of research topics can be identified in the literature in several categories: the study of the behaviour of the material under the action of the laser, the study of some technological processing procedures with by means of the laser (cutting, drilling, welding, engraving), the study of the influence of the input parameters of the process on the results obtained (roughness, hardness,and kerf). In recent years, there has been a particular interest in additive technologies applied to metallic materials in which the material powder is selectively melted or sintered using the laser (SLM, SLS). The hardening of the material with the laser is a special way of using the laser in the manufacture of industrial products.

2.5 Conclusions on the current state of research

From the analysis of the results of theoretical and experimental research published in the literature, the following conclusions can be drawn regarding the laser processing of materials:

1. laser processing of metal depends on the mechanical, optical, and thermal properties of each type of material. Thermal conductivity is a key property that depends on the conditions in which laser processing is carried out;
2. the input parameters of the laser processing process are decisive for the results obtained. Special attention is paid to how each of these parameters influences one aspect or another of the obtained result. Thus, the influence of the laser power, the cutting speed. and the pressure of the assistant gas on the roughness of the obtained surfaces, the hardness and the cutting joint (its width and the slope of the flanks) is mainly analysed.
3. depending on the processed material and the concrete working conditions, either the laser power or the cutting speed was identified as the most influential input parameter;
4. various models used for the design of experiments can be noted: with the variation of a single input parameter, or with the variation of several parameters simultaneously. In this case, the full and fractional factorial plans are highlighted;
5. neural networks, genetic algorithms and artificial intelligence are used as investigative techniques;
6. if the term Kerf is exclusively used in the English literature, in Romanian the cutting joint or the cutting width is used. Also, in the English language literature, "Kerf deviation" is used to refer to the inclination of the flanks of the cutting joint;
7. depending on the inclination of the flanks of the cut, both a convergent and a divergent inclination (V-shaped or A-shaped) can be distinguished in the cross-section of the cut;
8. the large majority of researchers study Kerf almost exclusively in terms of its width. There are scientific works that refer to the inclination of the cutting flanks - Kerf deviation. Kerf width is approached almost exclusively from the perspective of energy consumption, never as a technological aspect with implications on the dimensional and shape precision of the processed contour. The inclination of the flanks of the cut is approached only from the point of view of the magnitude of the inclination, not its direction (shape in cross-section);
9. as tools for analysis and interpretation of experimental data, the following software packages are mainly used: Statistica, Minitab and Graph;
10. no research has been explicitly identified that aims at the influence of the input parameters of the laser cutting process on the dimensional accuracy of the parts. The reason is that regardless of the influence that one input parameter or another would have on the dimensional accuracy, this influence can be compensated from the numerical control system of the laser spot along the theoretical contour of the part. Moreover, the most important parameter that influences the dimensional accuracy of the part is the diameter of the laser spot. In this context, the geometric precision can be directly controlled by the CNC equipment's ability to change the laser beam trajectory. However, it can be considered that the Kerf size is more relevant to the dimensional accuracy than the diameter of the laser spot [URS86];
11. only a small number of studies on hard-to-machina high-wear steels were identified;
12. it is noted that the materials of the HARDOX range have not been sufficiently studied (only four papers on this subject have been identified) [ALT19], [MIL20], [PRA13], [PAT11], although they are widely used in car construction, which is why it is an open research topic.

CHAPTER 3 The objectives of the doctoral thesis

Following the analysis of the current state of research, it is found that most researchers consider the roughness and hardness of the surfaces obtained, as well as the characteristics of the cutting joint (Kerf) to be relevant for the evaluation of the results of laser cutting of hard metals. Under these conditions, the research in this paper is focused on the study of the mentioned characteristics. Also, from the analysis of research carried out worldwide, it emerged that the most significant influence on the processing results is exerted by the adjustment parameters of the cutting process: the laser power, the cutting speed, and the pressure of the assistant gas. Consequently, these will be the working parameters targeted in this paper as well. Although the diversity of materials processed by the laser is very large, there is a paucity of information in the specialized literature regarding the behaviour of hard steels from the HARDOX range when processed by the laser. Also, most of the research presented in the scientific articles was carried out under laboratory conditions, without directly addressing aspects of the industrial use of the laser for the manufacture of metal parts. Starting from these considerations, on the one hand keeping the general line of current research, but also following aspects specific to the theme of the present work, on the other hand, the following main objective of the doctoral thesis is formulated:

"Establishing mathematical models that analytically describe the influence exerted by the main adjustment parameters of the laser cutting process on the quality of the surfaces, the compliance parameters and the technological parameters of the parts in the HARDOX range in the case of manufacturing the products under industrial production conditions"

To achieve this main objective, the following secondary objectives are formulated:

1. the analysis of some phenomena that occur during the laser cutting of hard steels and the interpretation of how they affect the processing results (roughness, hardness, Kerf);

2. identifying the influence of the gas pressure in the laser tube on the energy density of the laser beam;

3. determining the intensity of the laser light according to the intensity of the electric field of the radiation;

4. defining the mathematical relationships for calculating the energy required to cut the material;

5. determination of some mathematical relationships that reflect the influence of each considered input parameter (predictor) on the responses characterizing the processing results;

6. verification and validation of experimental research results through case studies;

7. formulating the final conclusions of the research with direct application in the manufacture by laser processing of industrial products.

CHAPTER 4 Theoretical research on the interaction between laser and metallic materials

4.2 Polytropic transformation of the assistant gas

The assistant gas passes through the cutting head surrounding the laser beam focused by the lens. It has the role of thermal maintenance of the laser beam. In the nozzle, the gas flows being bounded by the conical walls, the laser light is focused at a small distance from the nozzle. The nozzle heats up due to the laser and gas kinetics [KIM19]. The friction of the gas against the conical walls causes wear of the nozzle, which requires its periodic replacement.

The study can consider and model the assistant gas through the polytropic transformation of a gas mass under conditions of constant molar heat [PLĂ77]. The temperature of the nozzle increases from T_1 to T_2 because the laser light enters the nozzle with different diameters being surrounded by gas. At the entrance and exit of the nozzle the pressure and volume of the gas varies. As the cross-section of the nozzle varies along its axis, if a volume element of infinitesimally small height is considered at the entrance or exit of the conical area, a volume variation can be considered to occur. The entropy variation is calculated under these conditions (variable temperature and volume) and applying the 2nd principle of thermodynamics a new state function entropy S is introduced, whose variation is defined by the relationship (dU – internal energy variation, dL – variation of mechanical work, dQ – infinitesimal variation of heat). Replace dL with pdV according to the definition of the mechanical work done by the gas [PLĂ77].

The first law of thermodynamics written in terms of entropy, internal energy and mechanical work becomes:

$$TdS = \left(\frac{\partial U}{\partial V}\right)_T dV + \left(\frac{\partial U}{\partial T}\right)_V dT + pdV$$
$$TdS = \left(\frac{\partial U}{\partial T}\right)_V dT + \left[\left(\frac{\partial U}{\partial V}\right)_T + p\right] dV \tag{4.6}$$

By integration, the entropy variation of the gas is obtained:

$$\Delta S = S_2 - S_1 = \nu C_V \ln\frac{T_2}{T_1} + \nu R \ln\frac{V_2}{V_1} = \nu C_V \ln\frac{T_2}{T_1} - \nu R \ln\frac{V_1}{V_2} \tag{4.13}$$

Since for oxygen the polytropic index has the values, χ=1,2, C_V=5/2*R, C_p=7/2*R, [HRI84], [PLĂ77] one has 1.2*5/2*R-7/2*R, namely (3-3.5)*R<0. So,

$$\chi C_V - C_p \le 0 \tag{4.17}$$

it follows that the entropy of the gas S decreases, so the thermodynamic system of the real gas O_2 goes from a less ordered state to an ordered state when it passes through the nozzle. By ordering the molecules, the gas jet becomes laminar and is no longer turbulent, which allows it to maintain jet coherence over a greater distance from the nozzle exit. This has a positive effect on how the melt is removed from the cutting joint. Some researchers [ORA19], [DAR20], [KIM19] noted the changes induced in the gas jet by subsonic and supersonic nozzles, without having theoretically demonstrated these transformations through the entropy of the gas jet. One of the effects of passing the gas through the nozzle is the decrease in entropy.

4.3 Gas pressure in the laser tube

The laser gas in the laser tube is a mixture of gases made up of carbon dioxide, nitrogen, and helium molecules. In the laser tube, the addition of nitrogen has the role of exciting the CO_2 molecules in order to generate laser light, and the helium concentrates the CO_2 molecules towards the axis of the tube in order to increase the luminescence due to laser transitions [SAV81], [DON85].

Population inversion in the case of the CO_2 laser is achieved due to the resonant transfer of excitation between nitrogen and carbon dioxide. The spectral energy density of thermal radiation is given by Planck's formula [VLĂ83], [STE88], [LAN63], [POP00]:

$$I_\nu = \frac{8\pi h\nu^3}{c^3} \cdot \frac{1}{e^{\frac{h\nu}{kT}-1}} = \frac{A_{ji}}{B_{ji}} \cdot S \tag{4.18}$$

Here h is Planck's constant, [J*s] ν, frequency of radiation [s^{-1}], c speed of light [m/s]. A. Einstein developed the calculation by introducing the stimulated emission coefficient B_{ji} and the spontaneous emission coefficient A_{ji}. The ratio S between induced and spontaneous transitions with the energy spectral density is given by the mathematical relation [VLĂ83], [STE88], [PLĂ77], [POP00]:

$$S = \frac{1}{e^{\frac{h\nu}{kT}} - 1} = \frac{1}{\frac{N_i}{N_j} - 1} \tag{4.19}$$

Where kT-[J]is the energy of the CO_2 molecule and hν-the energy of the photon [J] that forms the light or can be seen as the energy of the quantum that is absorbed at the transition of the CO_2 molecule, N_i and N_j are the electron populations distributed to the participating levels to the laser transition. In lasers, the goal is to obtain a population inversion as high as possible $N_j - N_i > 0$. The ratio S derives from Einstein and Planck's research on radiation emission.

Starting from these two relationships, the energy of the CO_2 molecule is determined:

$$e^{\frac{h\nu}{kT}}-1=\frac{1}{S}$$
$$e^{\frac{h\nu}{kT}}=1+\frac{1}{S} \qquad (4.20)$$

An approximation method is used to develop the relation (4.20). The approximation calculation determines a possible, computable value of the exponent. The approximation theory is based on Taylor series development. (4.21) Polynomials in technique always approximate functions difficult to study [DRĂ86], [POP00].

$$e^{x}=1+x+\frac{1}{2!}x^{2}$$
$$e^{\frac{h\nu}{kT}}=1+\frac{h\nu}{kT}+\frac{1}{2}\cdot\left(\frac{h\nu}{kT}\right)^{2} \qquad (4.21)$$

Entering (4.21) in (4.20)

$$1+\frac{h\nu}{kT}+\frac{1}{2}\cdot\left(\frac{h\nu}{kT}\right)^{2}=1+\frac{1}{S} \qquad (4.22)$$

The ratio 1/kT is substituted by y, and a quadratic equation of variable y is obtained:

$$\frac{1}{2}\cdot(h\nu)^{2}\cdot y^{2}+(h\nu)\cdot y-\frac{1}{S}=0 \qquad (4.23)$$

The solutions of the equation are:

$$y_{1,2}=\frac{-1\pm\sqrt{1+\frac{2}{S}}}{h\nu} \qquad (4.24)$$

So, one can express the energy of the CO_2 molecule as a function of the ratio S and the photon energy:

$$kT=\frac{h\nu}{-1+\sqrt{1+\frac{2}{S}}} \qquad (4.25)$$

with the condition S>0. According to the fundamental formula of Kinetic-Molecular Theory (4.1), the laser gas pressure can be written [PLĂ77], [MAS03]:

$$p=nkT=n\cdot\frac{h\nu}{-1+\sqrt{1+\frac{2}{S}}}=\frac{N}{V}\cdot\frac{h\nu}{-1+\sqrt{1+\frac{2}{S}}}=\frac{N}{N'}\cdot\frac{N'h\nu}{V}\cdot\frac{1}{-1+\sqrt{1+\frac{2}{S}}} \qquad (4.26)$$

The pressure of the laser gas can be expressed as a function of the number N of CO_2 molecules, the number of photons in the laser radiation N', energy density of the laser beam w_E [J/m^3]

$$p=\frac{N}{N'}\cdot w_E\cdot\frac{1}{-1+\sqrt{1+\frac{2}{S}}} \qquad (4.27)$$

From relation (4.27) the energy density of the laser beam is calculated w_E :

$$w_E=p\cdot\frac{N'}{N}\cdot\left(-1+\sqrt{1+\frac{2}{S}}\right) \qquad (4.28)$$

The energy density of the laser beam in the tube increases with the increasing of laser gas pressure, it depends on the ratio between the number of photons and the number of CO_2 molecules because it ensures stability of the radiation amplification conditions in lasers by pumping with nitrogen molecules.

$$w_E = p \cdot \frac{N'}{N} \cdot \left(-1 + \sqrt{1 + \frac{2}{\left[\frac{N_i}{N_j} - 1 \right]^{-1}}} \right) \cong p \cdot \frac{N'}{N} \cdot \sqrt{2 \cdot \frac{N_i}{N_j}} \tag{4.31}$$

The energy density of the laser radiation depends on the populations N_j and N_i (the number of electrons) $N_j>N_i$, $E_j>E_i$, of energy levels for which there is population inversion, $N_j-N_i>>0$. This requires nitrogen molecules to be pumped into the medium in the laser tube. The laser system works at a regime in which to pump energy. The populations of atoms in the active medium influence the laser energy yield. Along with the increase in the difference in populations (N_j-N_i) a radiation field density is obtained in which the laser emission increases. An avalanche of photons is generated in a resonant cavity in the laser tube.

According to the relation (4.31), it follows that the energy density w_E of the laser light is proportional to the pressure p of the gas mixture in the laser tube.

4.4 Radiation-matter interaction

Some researchers [POP83], [DON85] found experimentally that the intensity (I) of the laser radiation in the material is proportional to the intensity of the electric field (E) propagated through that material. However, an analytical, theoretical demonstration of this dependence has not been identified.

Because the Poynting vector is directly related to the electric field intensity, the equation for the electric field distribution in the material results [LAN63]:

$$\Delta\vec{E} - \mu\sigma\frac{\partial\vec{E}}{\partial t} - \varepsilon\mu\frac{\partial^2\vec{E}}{\partial t^2} = 0 \tag{4.34}$$

Solving the equation of the laplacian of the electric field gives the solution of the exponential form of the electric field (4.35). The Laplacian solution obtained using the theory from physical-mathematical equations shows that the electric field intensity E is a harmonic function [LAN63], [TEO65]:

$$E(t) = E_0(t) \cdot e^{i\omega t} \tag{4.35}$$

In which E(t) is the variable electric field in the material, ω is the angular frequency and E_0 the electric field amplitude.

Relations (4.36) represent the material laws, which highlight that some electrical and magnetic properties of materials [KAV20] influence their behaviour in the electromagnetic field.

$$\begin{aligned} \vec{D} &= \varepsilon\vec{E} \\ \vec{B} &= \mu\vec{H} \\ \vec{j} &= \sigma\vec{E} \end{aligned} \tag{4.36}$$

Here, $\vec{E}$ – the electric field intensity of the laser wave, $\vec{D}$ – electrical induction in the environment, $\vec{H}$ – magnetic field strength, $\vec{B}$ - magnetic field induction, J – current density, μ - absolute magnetic permeability, ε – absolute electrical permittivity, σ – electrical conductivity. The local state of the electromagnetic field is described by these vectors.

All according [AGÎ56] the relationship is defined (4.37), of the electromagnetic wave in the material.

$$I = \frac{1}{T}\int_0^T E^2 dt \tag{4.37}$$

Substituting the solution of the Laplacian (4.35) into (4.37) and developing further (author's contribution) we obtain (4.38):

$$I = \frac{E_0^2}{T} \times \frac{T}{2} == \frac{E_0^2}{2} \qquad (4.38)'''$$

According to (4.38), the intensity of the electromagnetic wave (be it laser or thermal radiation) is proportional to the square of the amplitude of the electric field intensity. This proves analytically what was found experimentally by the cited authors.

Considering that steel has a much higher electrical permeability than other materials (Cu, Al, Ti and their alloys) and taking into account the relationships in (4.36) it can be concluded that the electrical induction in steel is much stronger than in the other media. The intensity of the laser radiation is increased when the electrical conductivity of the material is high, or the electrical resistivity as low as possible.

4.5 Energy consumed in the technological process of laser cutting

The efficiency with which a certain processing is carried out can be appreciated through various indicators. In general, efficiency is analysed through indicators resulting from reporting the results obtained to the resources consumed. In the case of laser metal cutting, the main resource consumed is energy, and the result is the parts obtained. The result expressed in this way is too vague, because it depends on (very) many factors – quantity, part size, material, geometric configuration, others. In this case, the definition and use of more synthetic indicators can be very useful [KOV87].

In the specialized literature, the problem of efficiency is rather treated through concrete processing situations, targeting certain materials and/or processes. Thus, in [SAH11] the optimization of the specific energy for drilling Kevlar plates was investigated and this quantity was evaluated as a function of the scanning speed, the laser power, and the diameter of the machined hole. The work [AHN16] presents a hybrid method of material processing using the preheating laser followed by classical cutting. In [GYO17] the authors understand by efficiency the ability of a laser equipment to cut a steel sheet up to 60 mm thick with the power of 7.5 KW. The paper [LEE18] introduces the laser cutting efficiency of electrodes for Li-Ion batteries depending on the cutting parameters.

To more eloquently compare the efficiency of laser cutting of metals, it is proposed to define some unitary indicators, based on the main parameters of the cutting regime and on geometric characteristics independent of the shape of the processed parts. In order to cover as large a range of cases as possible, three unitary indicators are defined **[GÎR19]**, as follows:

1. Energy consumed for cutting a unit length of the contour:

$$\begin{aligned} E_l &= \frac{P \times t}{L} \\ t &= \frac{L}{v} \\ E_l &= \frac{P}{v} \end{aligned} \qquad (4.39)$$

Here one noted: E_l – Linear specific energy [W*s/mm], [J/mm]; P – Laser power [W]; t – processing time [s]; L – the length of the side edge of the piece (contour) [mm]; v – cutting speed [mm/s].

2. Energy consumed for cutting a unit of side surface of the part:

$$
\begin{aligned}
&E_s = \frac{P \times t}{A} \\
&t = \frac{L}{v} \\
&A = L \times g = v \times t \times g \\
&E_s = \frac{P \times t}{v \times t \times g} = \frac{P}{v \times g} = \frac{P}{v} \times \frac{1}{g} = \frac{E_l}{g}
\end{aligned} \tag{4.40}
$$

in which E_S – Specific surface energy [J/mm^2]; A – the side surface of the part [mm^2];

g – sheet thickness [mm].

3. The energy consumed to melt a unit volume of material to detach the part from the blank. This indicator also depends on the dimensions of the Kerf. It should be judged based on experience gained in machining under varying conditions, or even first measurement of test pieces.

$$
\begin{aligned}
&E_V = \frac{P \times t}{V} \\
&t = \frac{L}{v} \\
&V = L \times g \times K\,\mathrm{er}\,f = L \times g \times \bar{K} \\
&E_V = \frac{P \times t}{L \times g \times \bar{K}} = \frac{E_l}{g \times \bar{K}} = \frac{E_l}{S_k} = \frac{E_s}{\bar{K}}
\end{aligned} \tag{4.41}
$$

in which E_V - Volume specific energy [J/mm^3]; V - The volume of molten material [mm^3]; S_k – Cross-sectional area of the cut [mm^2]; $\bar{K}$ - Average width of cut [mm].

Obviously, the first criterion lends itself to being applied in the case of parts with small thickness, where the length of the contour is more relevant than the thickness of the part. Moreover, the lateral area of the part depends on both the length of the contour and the thickness, but in much different proportions. So the second criterion is better suited to relatively thick parts. The third criterion is more suitable for machining that results in a large Kerf, which implies a large volume of material that should be melted. It is clear that these indicators must be used with discernment, so that they fit as well as possible to the concrete case of processing. By comparing various processes by means of the proposed indicators it is possible to appreciate to what extent a certain process is efficient. In addition, considering that energy consumption produces a negative impact on the environment, it is also possible to appreciate to what extent a certain process is *Eco-friendly*. **[GÎR19a]**

4.7 Conclusions

Based on the theoretical research on the cutting of HARDOX steels by the laser, the following conclusions can be drawn:

1. the energy density of the radiation in the laser emission mode increases with the gas pressure in the laser tube;
2. the energy density of the radiation is directly proportional to the number of photons and inversely proportional to the number of CO_2 molecules. However, it follows from the mathematical model that this enhancement is attenuated by the ratio between the electron populations N_i of the lower laser level and N_j of the upper level from which the stimulated emission occurs;
3. when the laser beam interacts with the metallic material, a series of physical factors contribute to the production of an electric current through the material. These are the stimulation of electrons in the material by the laser and the variable electromagnetic field of the laser. The electric current thus produced is transformed by the Joule effect into heat. This additionally contributes to the melting of the material;
4. metallic materials with low relative electrical permittivity such as Cu, Al require a bigger amount of energy to be cut than those with high electrical permittivity (for example steels);

5. in the metallic materials the electric field produced by the laser radiation also induces a magnetic field. This is the more intense the higher the relative magnetic permeability of the material is. From the considerations that have already been mentioned above, it can be concluded that materials with high magnetic permeability require a smaller amount of laser energy to be cut (steels);
6. the influence of the part thickness (g) on the specific energy Es, shows that this indicator becomes more useful when comparing, from the point of view of cutting efficiency, pieces made of different materials and having different thicknesses;
7. it is important to correctly select the indicator used to assess a particular case (set of sample pieces), depending on the variable input data, which can be controlled. It should be noted that in some cases some inputs might be fixed and cannot be changed (eg material or part thickness);
8. the calculation relationships presented, confirmed by experimental data, indicate that, in general, good efficiency is obtained when working with low power and high cutting speed. However, this general rule cannot be applied in all cases, because there are certain technological limitations: some materials require a relatively high power to be cut, and the cutting speed is limited by the properties of the processed material and its thicknes **[GÎR22]**;
9. unlike the approaches of other authors, [SAH11], [AHN16], [GYO17], [LEE18], which treat particular cases punctually, the proposed method for assessing the energy efficiency in laser cutting allows a coherent treatment, applicable regardless of the conditions concrete work and material properties, provided the correct choice of the specific index used;
10. the luminous intensity of the laser is directly proportional to the square of the electric field intensity of the electromagnetic radiation. This is proven analytically by the author.

CHAPTER 5 Experimental research on roughness, hardness, kerf, and surface inclination of parts manufactured by laser cutting

5.1 Material and method

The main research activities are detailed below:
1. selection of materials in order to carry out experimental research;
2. design of experiments;
3. carrying out the planned cutting experiments;
4. performing measurements on steel parts and semi-finished products;
5. processing data obtained from measurements;
6. identifying important results related to roughness Ra, hardness Ha and cutting width Kerf.
7. interpretation of the results obtained through the linear and quadratic predictive model, as well as with that of the mathematical regression model, the differences and concordance between the obtained models;
8. statistical analysis, graphic analysis, tabular grouping and establishing influence parameters;
9. identification of the recommended combination for influencing factors in order to control the roughness Ra, hardness and Kerf responses;
10. formulating conclusions regarding the influence of the input parameters on the roughness, hardness and width of the cutting slot;
11. formulation of general conclusions on the results of experimental research.

Laser cutting is a manufacturing method that preserves the internal microstructure of manufactured parts [LEP17]. In the processes of processing parts by the laser, the energy of the laser radiation that is absorbed by the metal and converted into heat, which produces phase transformations of the local penetration zone, with changes in the metallographic structure, will be taken into account [THO14]. Through spectral analysis measurements, it can be determined whether there are changes in the chemical composition of the processed area.

5.2 Design of experiments

As part of the research carried out on laser cutting [MAD20], the experimental plans were developed using various methods: **full factorial** for the study of the behaviour of the HARDOX400 material with a thickness of g=8 mm, **fractional factorial** for the study of the HARDOX400 material with a thickness of g=10 mm and HARDOX450 with a thickness of g= 12 mm.

The full factorial design contains a number of experiments determined by considering that each level of one factor interacts with each level of the other factors in the experiment. The number of combinations is equal to 2^k, 3^k, where 2 and 3 respectively represent the input levels, and k – the number of laser input parameters or influencing factors. The full factorial design used in the pruning experiments has 27 instances. Simple, three input parameters were used, each with three levels. At each trial, the input parameters change. The Box-Wilson design describes the full factorial design running with all input parameters at each level. The full factorial design provides results closer to reality.

Fractional factorial design is a reduced method of design of experiments. This method consisting of a small number of trials was introduced. Thus, he reduced the 3^3 full factorial design with 27 trials to a balanced fractional factorial design 3^{3-1}=9 trials. Reduced design develops a matrix with the level of factors distributed equally in weight to the central point. To save material, time, energy, a fractional factorial plan is chosen, which provides conclusive, truthful results, but less faithful than the full factorial plan.

5.4 Selection of the appropriate experimental plan for the research

Knowing how the predictors influence the hardness, their values can be chosen that lead to lower or higher hardness values, according to the specifications on the part drawing, or the needs regarding the exploitation of the parts. Good response results are obtained with the fractional plan, but it depends on what is being pursued and what resources are available. In the case of the hardness analysis experiment, the cutting parameters were chosen to run over time at three input levels according to table 5.10:

Tab. 5.10 *Input parameters in the case of the HARDOX450 semi-finished product*

Experiment Ha	**LEVEL**		
Parameters	**Minimum**	**Medium**	**Maximum**
Laser power [W]	3700	3800	3900
Cutting speed [mm/min**]**	1250	1450	1650
Gas pressure [bar**]**	0,55	0,65	0,75

Table 5.11 *Input parameters in the case of the HARDOX400 semi-finished product, thickness 10 mm*

Experiment Ra	**LEVEL**		
Parameters	**Minimum**	**Medium**	**Maximum**
Laser power [W]	4100	4200	4300
Cutting speed [mm/min**]**	1200	1400	1600
Gas pressure [bar**]**	0,35	0,45	0,55

The selection of the central parameters was obtained by tests on test parts. The levels of the input parameters were chosen based on the practical experience accumulated over time, the factory technical specifications, as well as the results of a selection experiment carried out in advance, in the process of checking the machine settings, maintenance. The experiment has five replications, the number of pieces increased to a total of 45 experimental pieces that will be subjected to measurements to investigate the results obtained during laser cutting.

Table 5.12 *Input parameters in the case of the HARDOX400 semi-finished product, thickness 8 mm*

Experiment full Kerf	**LEVEL**		
Parameters	**Minimum**	**Medium**	**Maximum**
Laser power [W]	4900	5000	5100
Cutting speed [mm/min**]**	1700	1800	1900
Gas pressure [bar]	0,45	0,50	0,55

5.6 Research infrastructure

The research infrastructure used to develop scientific research consisted of hardware and software resources. ByAutonom 3015, figure 5.22, BY Speed 3015, figure 5.23 and ByAutonome 4020, figure 5.24 machines were used as processing equipment.

All the three machines have similar technical characteristics, are manufactured by the same manufacturer, and were selected based on the availability of the company that provided technical support for the execution of trial processing and those planned for the purpose of scientific research.

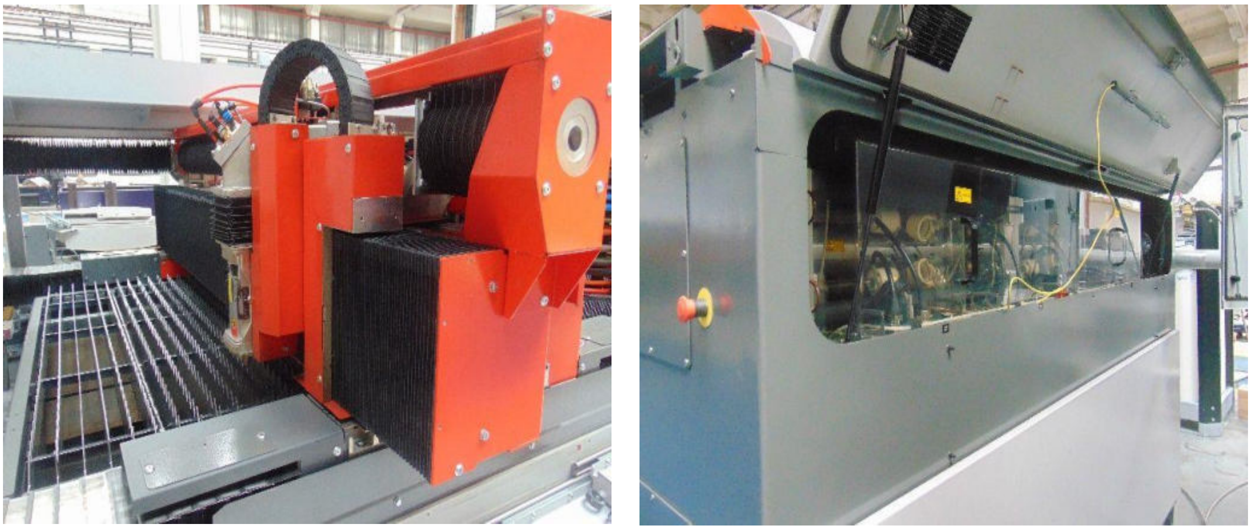


Fig. 5.22 *ByAutonom 3015 laser installation (a) machine, (b) Laser tube for light amplification*

Fig. 5.23 *Laser installation 3015*

Fig. 5.24 *Laser installation ByAutonome 4020*

To evaluate the results of the laser cutting processing, measurements of the values of the observed characteristics were carried out **[GÎR19b]**. The equipment used to perform the measurements consisted of the following:

Digital caliper: manufacturer VOREL BYTOYA 15240. It is a measuring instrument with the aperture of 0-150 mm, with measurement accuracy ±0,03 mm. It has two systems for measuring the size in mm and in inches. The measurement result is displayed on an LCD screen. At each measurement operation, the caliper is calibrated to 0 mm. The caliper vernier is graduated from 0 to 150 mm. With the help of the stainless steel arms, the position to be measured is fixed, for example the diameter of a hole or the cutting joint between the part and the plate.

Electronic Digital Micrometer is a tool that displays measured data in mm or inches. It can measure dimensions between 0-25 mm with an accuracy of 0.001 mm. It is equipped with LCD screen, calibration button. It can be connected to a computer with a data cable. It can search the maximum, minimum value and store it.

Hardness testing device KrautKramer MIC 2V 050 33899 was used to determine the HRC hardness on the laser cut surface, near the cut edge or in the center of the part. The tool is used to measure hardness on HARDOX steel parts. Hardness is the property of a metal to resist the destruction of the surface layer. The durometer probe acts on a very small surface by exerting a local pressure. This imprints the material of the workpiece. In the head of the durometer there is a steel ball that hits the surface of the part at a certain speed, exerting a force for testing. At each measurement, the durometer is calibrated with a standard probe. The value of a recorded measurement was calculated as the arithmetic mean of 3 successive measurements indicated by the digital screen. The parts were tested statically to evaluate the mechanical properties of the film layer subjected to probe traction and compression.

Roughness Mytutoyo – SJ 201 Using the Mitutoyo SJ 301 roughness meter, the roughness on the cutting surface of the HARDOX parts was measured in the UCB laboratory. The measured roughness: Ra – the average deviation of the roughness, Rz – the average depth of 10 points of the roughness and the roughness Rq. Measurements were made on a laser thermally cut rectilinear contour using a diamond tip probe on one of the cut faces of the part. The instrument has a printer for printing data. Measuring speed 0.25-0.5mm/s. Y-axis measuring range up to 150 µm **[MIL20]**.

Microscope OLYMPUS- MODEL MICROSCOPE TIP BX51. The microscope is equipped with a camera and integrated software for investigations in the biological field, petrography, metallography, manufacturer Olympus. The microscope is equipped with two eyepieces. The objectives that can be used are of the UPLFLN-P type where one can select Objective 4 x NA 0.13 with working distance 17 mm, 10 mm, 2.1 mm. The magnification of the portion studied by the microscope is x200. The microscope is used to determine the metallographic structure of the treated part. Ferrite, pearlite, cementite can be observed.

Microscope digital CELESTRON: The portable tool is used for the inspection of laser-cut HARDOX surfaces, holes made in stationary piercing mode. It is equipped with a x30 magnification system - microscopic lenses, LCD screen, eyepiece, LED with adjustable intensity, with connection to the computer.

Spectrometer XRF OLYMPUS Elements: OLYMPUS is a portable device that emits X-rays using a tube. The high-energy X-rays interact with the sample, which crystallizes (unnoticeably) and emits a secondary X-ray flux to the analyzer. The emission spectrum of the sample is displayed on the device screen. Based on the energy of the electrons, the presence of each element in the chemical composition of the material can be identified.

Spectrometer X-MET 3000TX+: Energy dispersive X-ray spectroscopy is a technique used to identify elements in a part. It is based on the interaction of X-rays with the material, excitation, production of characteristic X-rays and emission spectral analysis using an analyser for chemical characterization of the sample. The examined layer is of the order of tens of microns.

PHASEC 3D is a detector for observing the defects of the surfaces affected by the laser with the help of a probe. By moving the probe on the cut surface, a green or red mark can be seen on a screen, which confirms the absence/appearance of cracks and corrosion in the part. The detector uses low frequency eddy currents which by surface inspection can identify a possible defect.

LERA UNIOR 701 produced according to the DIN 2275 standard, manufactured by UNIOR TOOLS. To measure the slot on the right profile, the Lera tool was used - caliper - brand UNIOR 701. Size range from 0.05 mm to 1.00 mm, calibrated tool for determining internal dimensions (bearing clearances, bearing balls, slots etc.) of high precision. To determine the laser cutting joint, position the stainless-steel blade inside the slot of the rectilinear profile and check the nearest edge by feel, the pass-no-pass principle. The degree of precision of the measurement is 0.001mm. The Lera has many steel blades to measure the cut through the material, being a tool that ensures precision and quality certified according to standards.

5.7 Conducting the experimental research

After selecting the materials for the scientific research and the experimental plans, we moved on to the actual processing of the test parts. For this purpose, the following steps were taken, regardless of the material processed and the equipment used:

1. preparation of the semi-finished product for processing: its examination, checking the plate thickness, cleaning of oxides or other foreign substances;
2. installation the raw material on the machine table. Clamps and/or magnetic fixing system were used for this purpose;
3. entering the data according to the sketch with the layout of the parts to be cut;
4. setting the null (part reference);
5. checking the cooling system;
6. performing trial runs to establish the centre point for each of the various working parameters: laser power, speed-rate and assistant gas pressure [PAT21]. Initially, their values were programmed according to the production experience and recommendations made by the machine software for materials in the category of hard steels. Starting from the values thus chosen, they were modified (increase and decrease) to observe visually, roughly, the effect. Measurements of roughness and hardness were made on the parts thus made. The values of the input parameters for which the best results were found were adopted as central values. Increasing/decreasing the input values was continued, until the results became unsatisfactory, to determine the extremes (minimum and maximum level respectively) for the input parameter values.
7. performing processing according to the previously selected experimental plan;
8. measurement of the values of the studied output sizes, the roughness and hardness on the machined flanks and the width of the cut (cutting joint, kerf);
9. experimental data processing;
10. interpretation of the results;
11. formulation of conclusions.

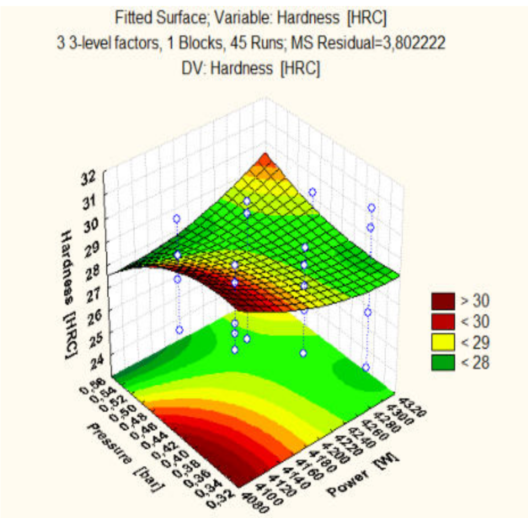
5.8 Experimental data processing

The parts processed for the experimental research were evaluated from the point of view of three output parameters (results): hardness and roughness on the surfaces obtained by laser cutting and the width of the cutting joint - kerf as it is known in literature. In addition to these measurements, observations were also done on the microstructure of the material of the parts in the area processed by the laser, the microhardness in the areas adjacent to the processed surfaces. For all processed parts, regardless of the material, the thickness of the semi-finished product, or the equipment on which the processing was done, the same measuring device was used, according to the *Research Infrastructure* chapter. The obtained results are presented separately for the two materials studied.
By defectoscopic analysis, no cracks were detected on the laser cut surfaces. The chemical composition of the processed surface layer was also determined to identify any changes induced by the laser processing.

5.8.1 HARDOX400 steel with a thickness of 10 mm

5.8.1.1 Influence of cutting parameters on surface hardness

Variation of hardness as a function of laser power and assistant gas pressure



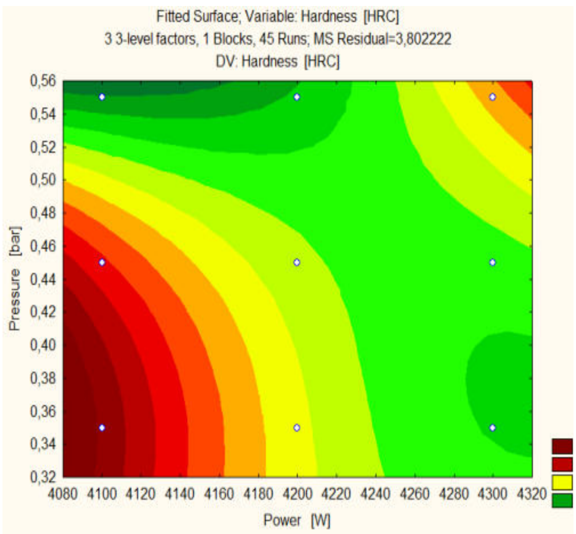
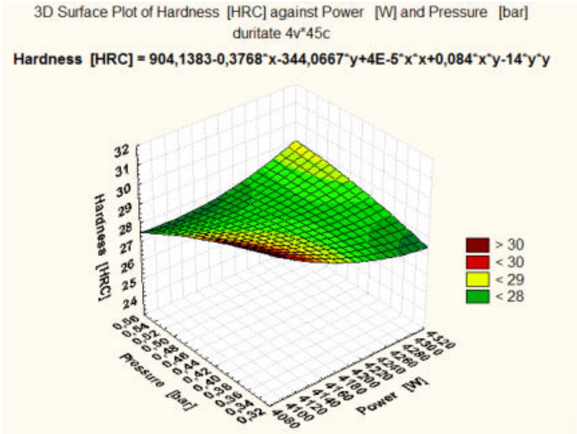


Fig. 5.49 *The predicted quadratic model Ha(P,p)*

Fig. 5.50 *The predicted contour plot Ha(P,p)*



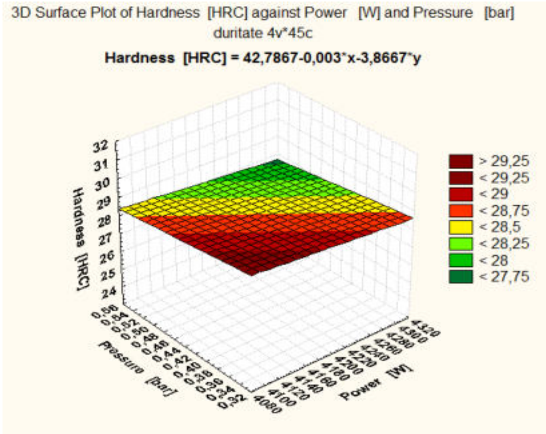
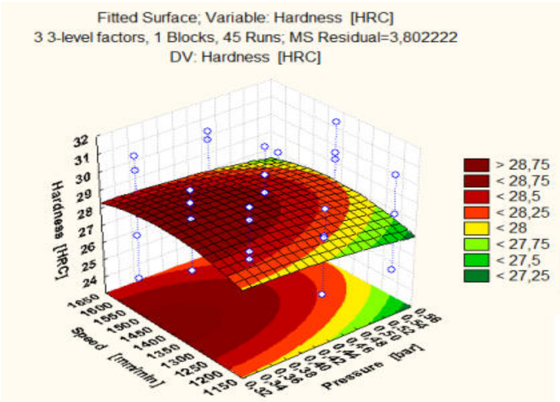


Fig. 5.51 *Quadratic regression model Ha(P,p)*

Fig. 5.52 *The linear regression model Ha(P,p)*

Variation of hardness against assistant gas pressure and cutting speed



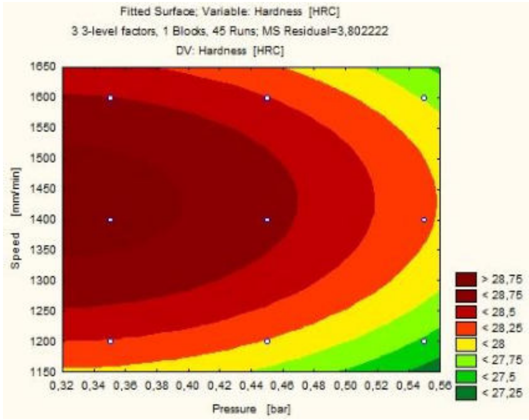
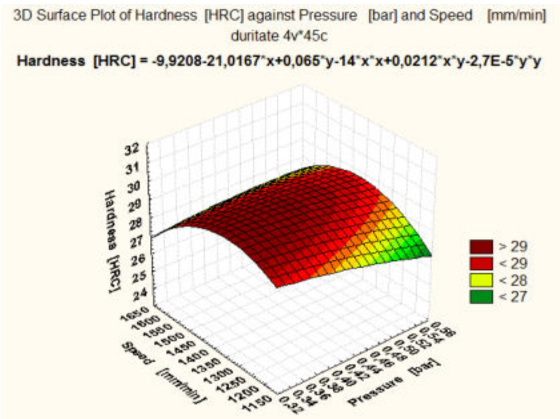


Fig. 5.53 *The anticipated quadratic model Ha(p,v)*

Fig. 5.54 *The predicted contour plot Ha(p,v)*



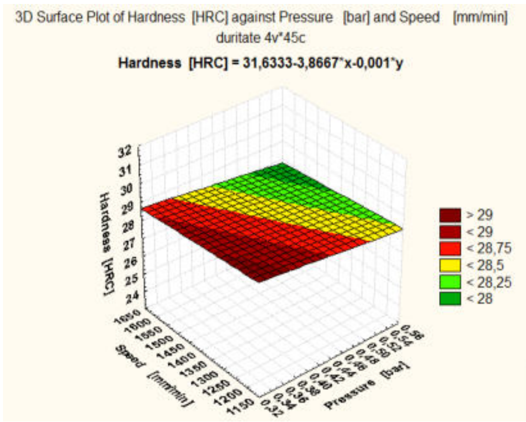


Fig. 5.55 *Quadratic regression model Ha(p,v)*

Fig. 5.56 *The linear regression model Ha(p,v)*

Variation of hardness against laser power and cutting speed

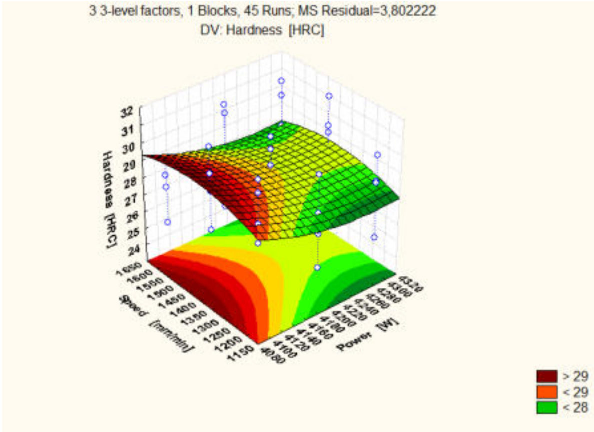


Fig. 5.57 *The predicted quadratic model Ha(P,v)*

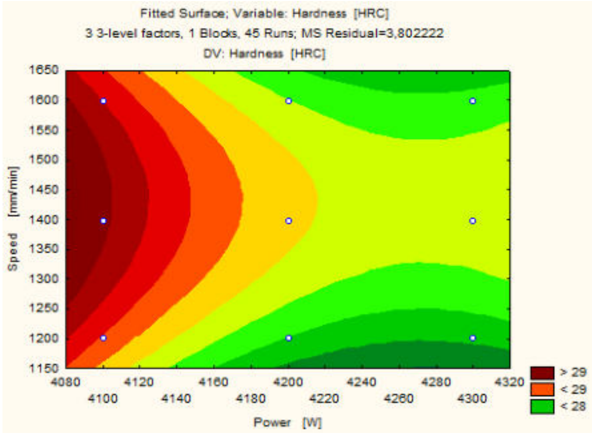


Fig. 5.58 *The predicted contour plot Ha(P,v)*

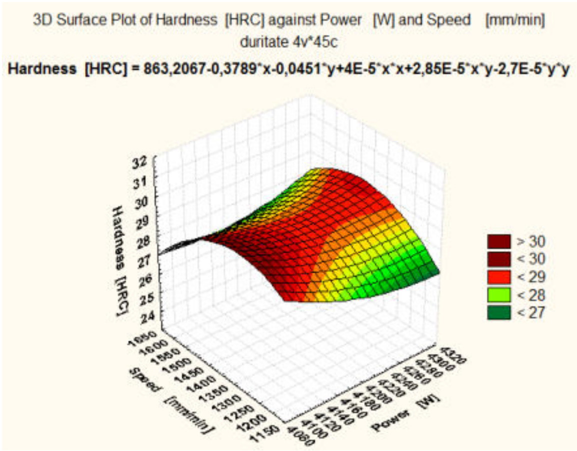


Fig. 5.59 *Quadratic regression model Ha(P,v)*

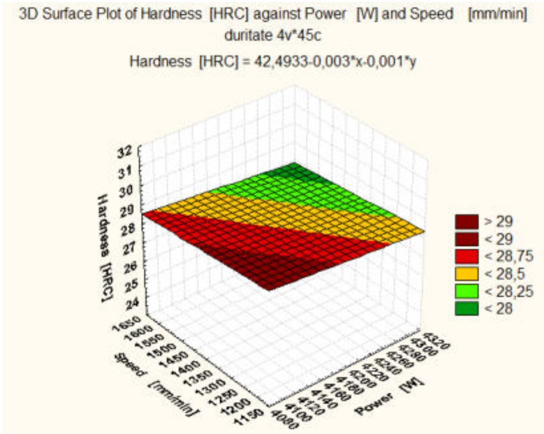


Fig. 5.60 *The linear regression model Ha(P,v)*

5.8.1.2 The influence of cutting parameters on surface roughness [COR21]

The linear and quadratic mathematical model of pressure-speed roughness Ra:

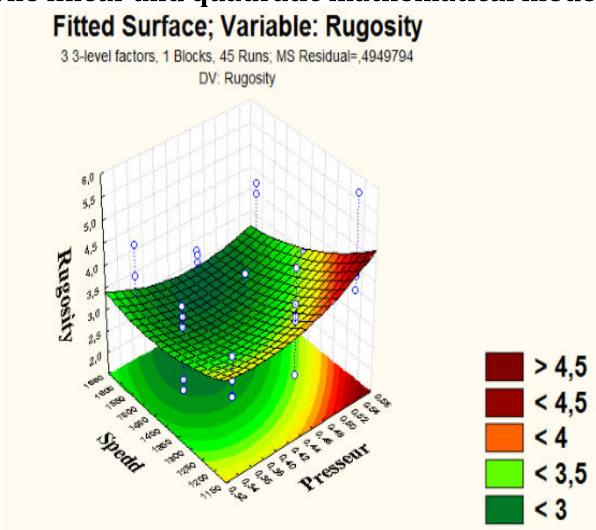


Fig. 5.64 *Quadratic prediction model*

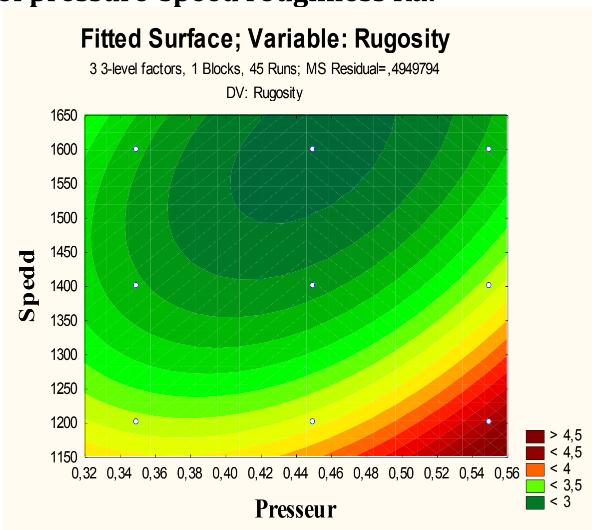


Fig. 5.65 *Prediction contour plot*

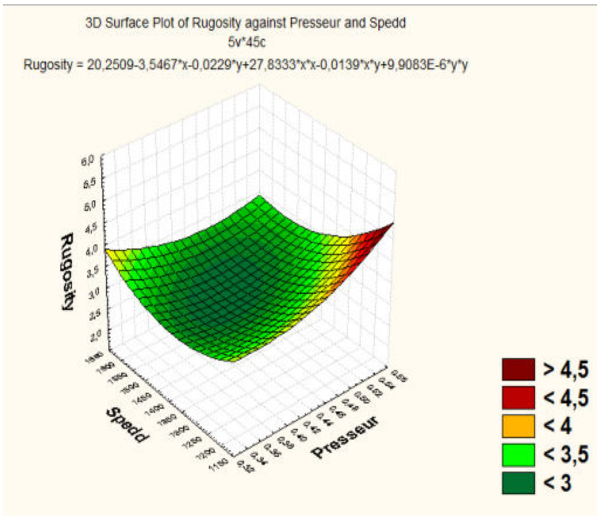


Fig. 5.66 *Quadratic regression model*

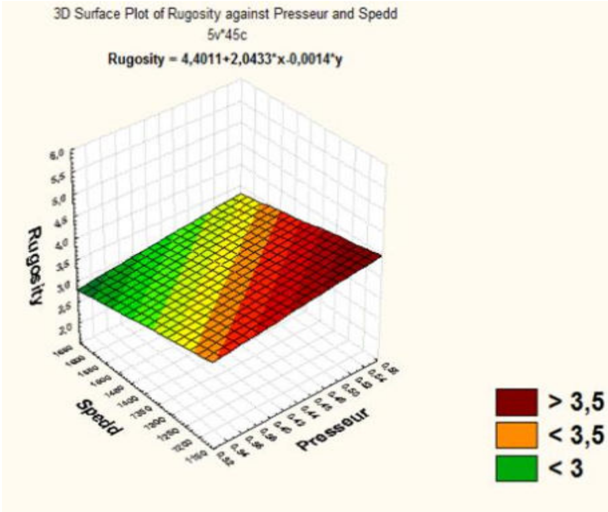


Fig. 5.67 *The linear regression model*

The linear and quadratic mathematical model of cutting speed-laser power: [GÎR21b]

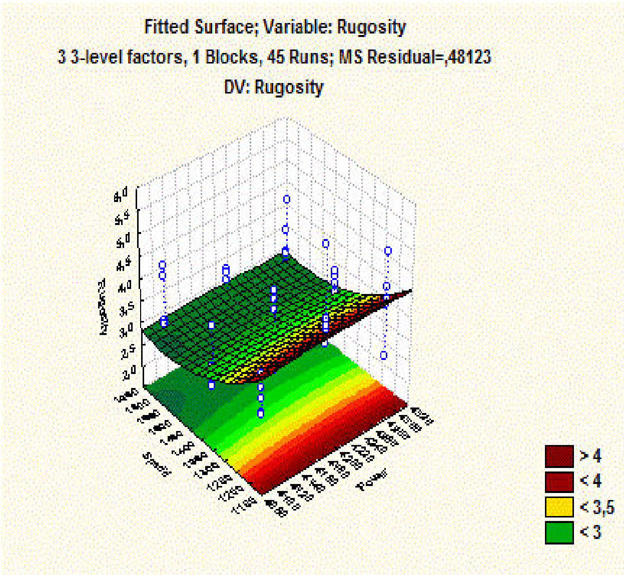


Fig. 5.68 *RSM plot for the prediction (Q) Ra*

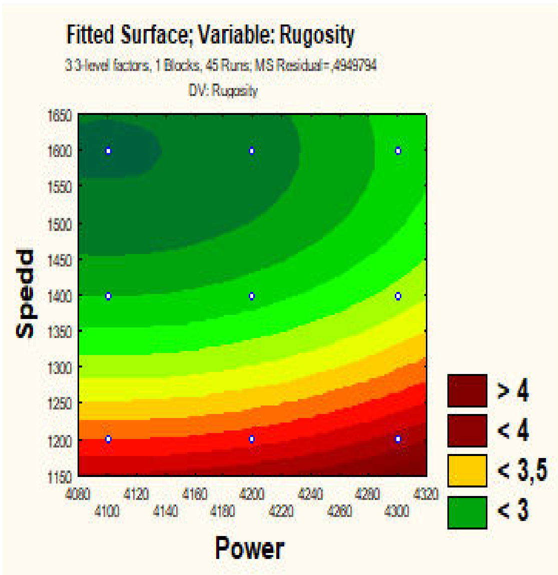


Fig. 5.69 *Contour plot for the prediction Ra*

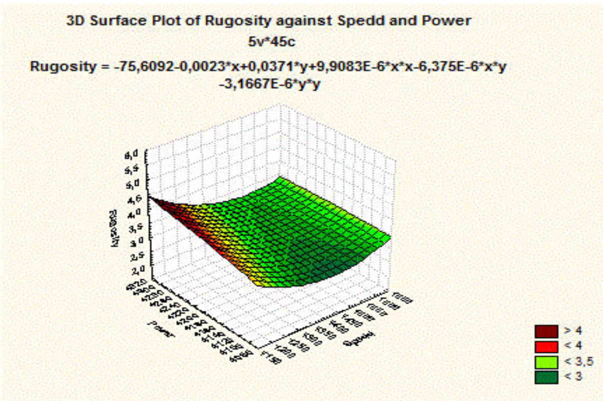


Fig. 5.70 *RSM plot for the regression (Q) Ra*

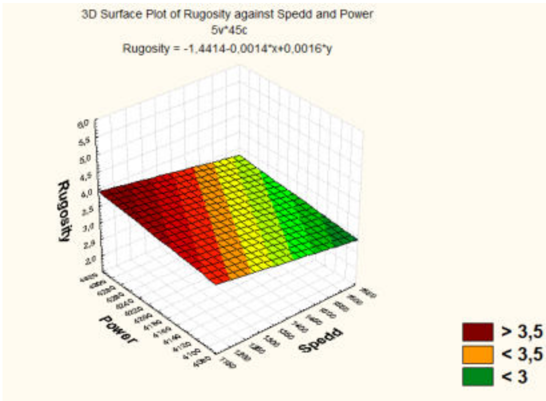


Fig. 5.71 *RSM plot for the regression (L) Ra*

The linear and quadratic mathematical model of the roughness Ra power-pressure:

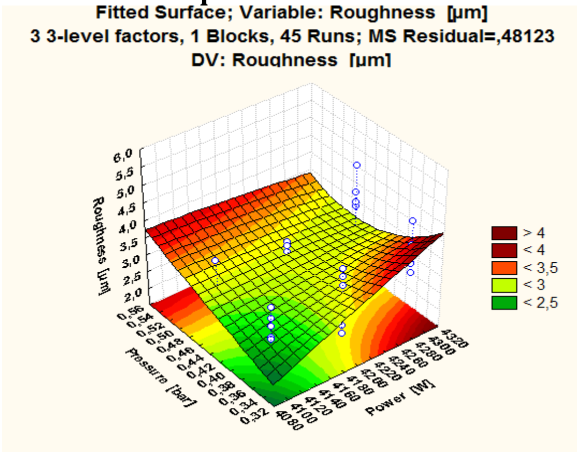


Fig. 5.72 *Predictive quadratic graph Ra(P,p)*

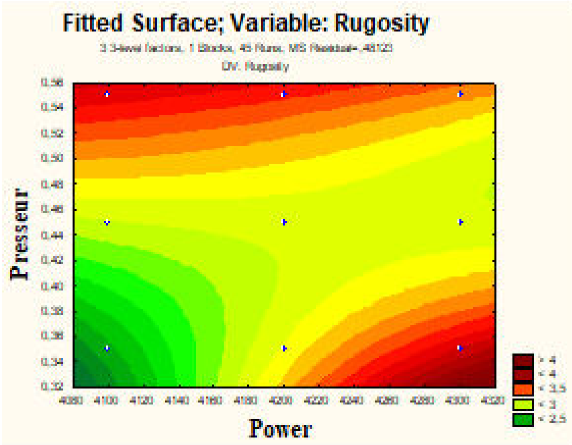


Fig. 5.73 *Predictive contour plot Ra(P. p)*

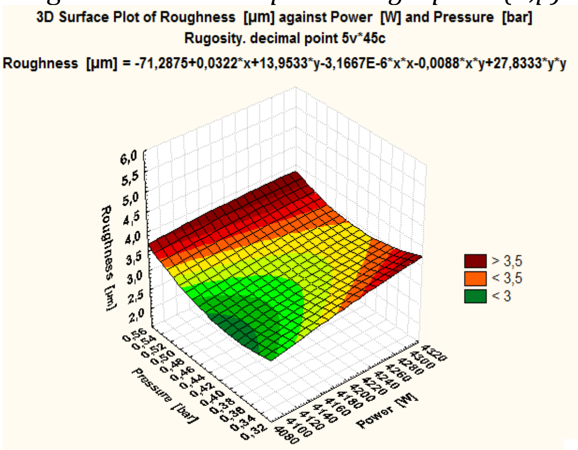


Fig. 5.74 *The regression graph Ra (P,p)-Q*

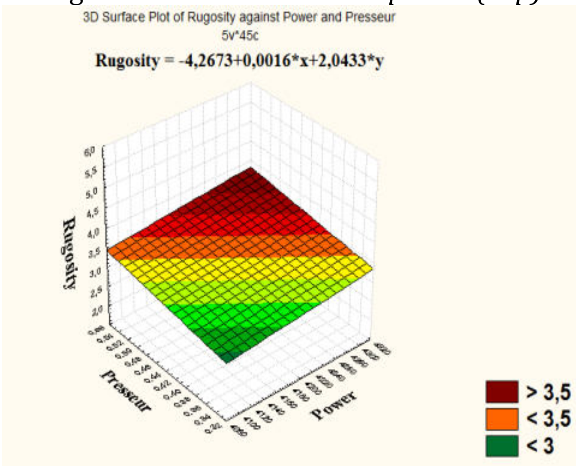


Fig. 5.75 *The regression graph Ra (P,p)-L*

5.8.1.3 Influence of cutting parameters on cutting width

The influence of the torque of power pressure parameters on the width of the cutting joint

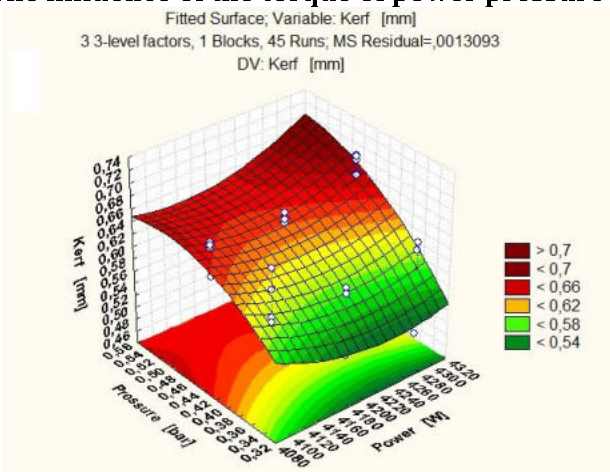


Fig. 5.79 *Quadratic prediction model Kerf (P,p)*

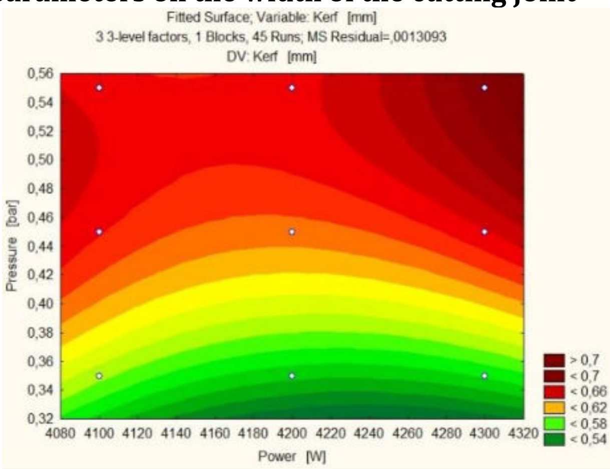


Fig. 5.80 *Prediction graph putere-presiune*

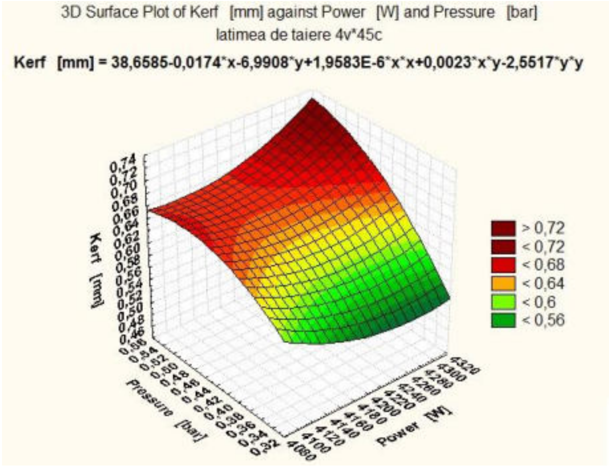


Fig. 5.81 *Quadratic regression plot Kerf(,-p)*

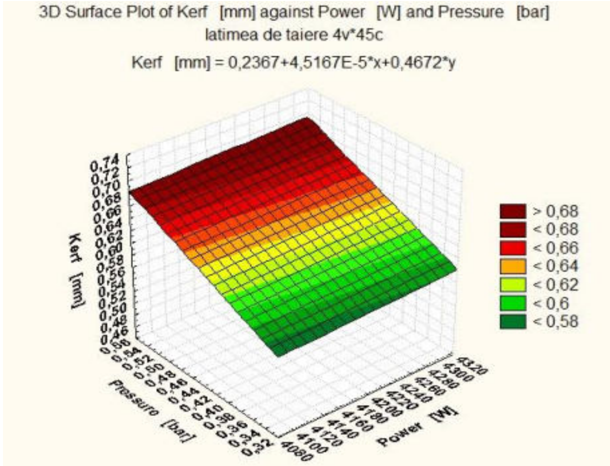


Fig. 5.82 *Power-pressure linear regression graph*

The influence of the pressure-speed on Kerf

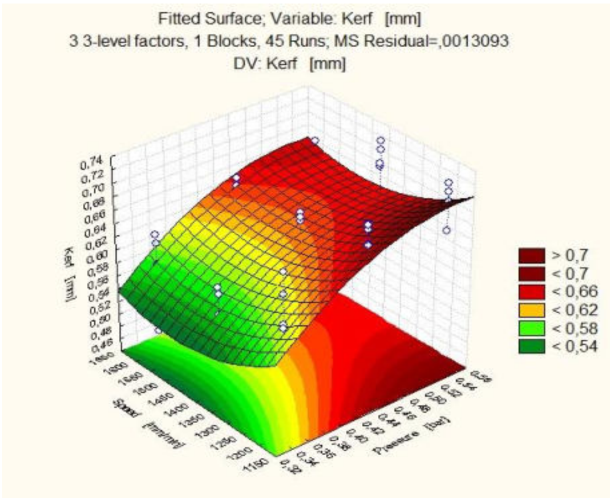


Fig. 5.83 *Quadratic prediction model Kerf (p,v)*

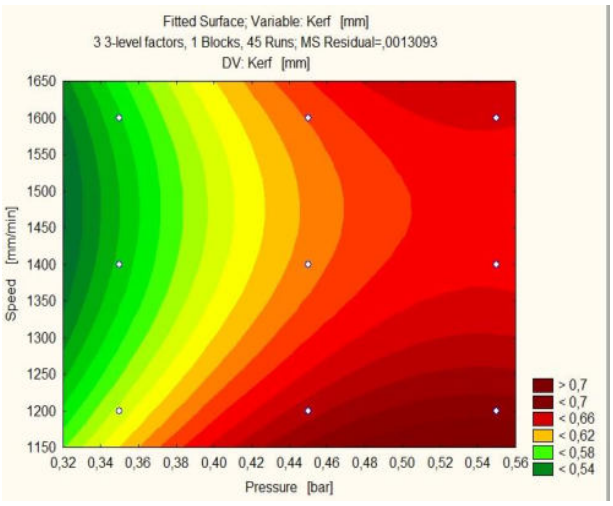


Fig. 5.84 *Prediction graph Kerf(p,v)*

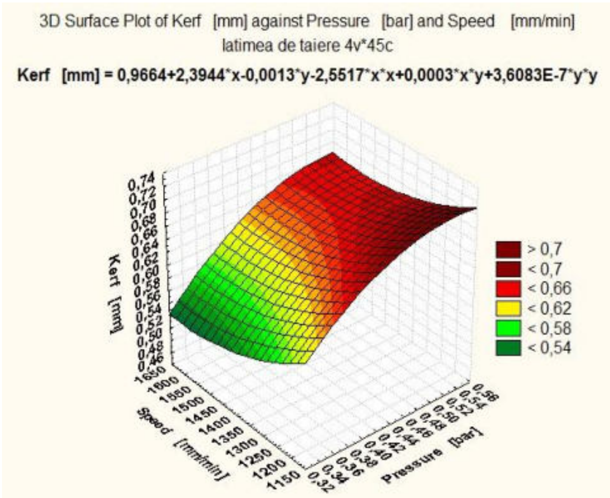


Fig. 5.85 *Quadratic regression plot Kerf(p,v)*

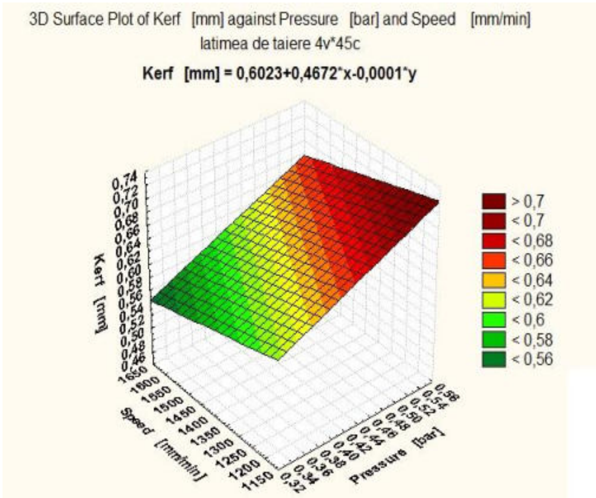


Fig. 5.86 *Linear regression graph Kerf(p,v)*

The influence of the power - speed on the Kerf

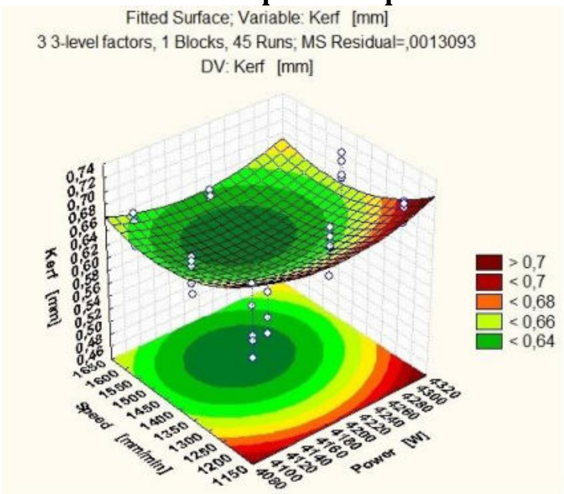


Fig. 5.87 *Quadratic prediction model Kerf(P,v)*

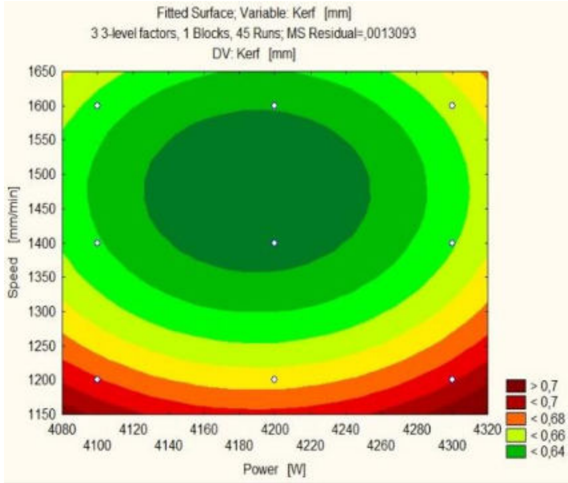


Fig. 5.88 *Prediction graph Kerf(P,v)*

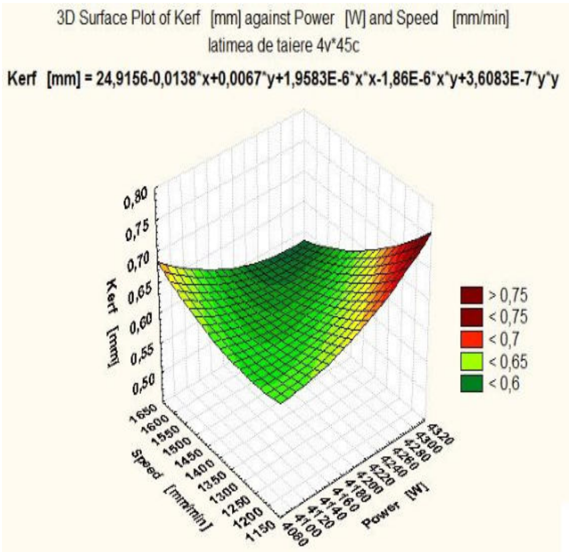


Fig. 5.89 *Quadratic regression plot (P-v)*

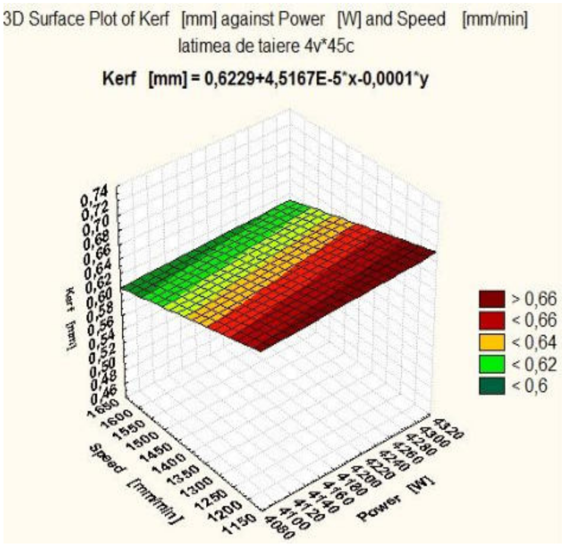


Fig. 5.90 *Linear regression graph Kerf(P,v)*

Based on the experimental data, the following mathematical relations were determined that describe the dependence of the hardness, roughness, and Kerf on the parameters of the cutting regime:

$$Ha = 42{,}7867 - 0{,}003 * P - 3{,}8667 * p \quad (5.5)$$

$$Ha = 904{,}1383 - 0{,}3768 * P - 344{,}0667 * p + 4 * 10^{-}5 * P^2 + 0.084 * P * p - 14 * p\text{^}2 \quad (5.6)$$

$$Ha = 31{,}6333 - 3{,}867p - 0{,}001v \quad (5.7)$$

$$Ha = -9{,}9208 - 21{,}0167p + 0{,}065v - 14p^2 + 0{,}0212pv - 0{,}000027v^2 \quad (5.8)$$

$$Ha = 42{,}4933 - 0{,}003 * P - 0{,}001 * v \quad (5.9)$$

$$Ha = 863{,}2067 - 0{,}3789P - 0{,}0451v + 0{,}00004P^2 + 0{,}0000285P * v - 0{,}000027v^2 \quad (5.10)$$

$$Ra = 4{,}4011 + 2{,}0433\,p - 0{,}0014v \quad (5.11)$$

$$Ra = 20{,}2509 - 3{,}547p - 0{,}0229v + 27{,}8333p^2 - 0{,}0139vp + 0{,}0000099v^2 \quad (5.12)$$

$$Ra = -1{,}4414 - 0{,}0014\,v + 0{,}0016P \quad (5.13)$$

$$Ra = -75{,}6092 - 0{,}0023\,v + 0{,}0371P + 0{,}0000099v^2 - 0{,}00000637vP - 0{,}00000316P^2 \quad (5.14)$$

$$Ra = -4{,}2673 + 0{,}0016\,P + 2{,}0433p \quad (5.15)$$

$$Ra = -71{,}2875 + 0{,}0322P + 13{,}9533p - 0{,}0000031667P^2 - 0{,}0088p * P + 27{,}8333p^2 \quad (5.16)$$

$$Kerf = 0{,}2367 + 0{,}00004516P + 0{,}4672p \quad (5.17)$$

$$Kerf = 38{,}6585 - 0{,}0174P - 6{,}9908p + 0{,}0000019583P^2 + 0{,}0023Pp - 2{,}5517p^2 \quad (5.18)$$

$$Kerf = 0{,}6023 + 0{,}4672p - 0{,}0001v \quad (5.19)$$

$$Kerf = 0{,}9664 + 2{,}3944p - 0{,}0013v - 2{,}5517p^2 + 0{,}0003pv - 0{,}00000036083v^2 \quad (5.20)$$

$$Kerf = 0{,}6229 + 0{,}00004516P - 0{,}0001v \quad (5.21)$$

$$Kerf = 024{,}9156 - 0{,}0138P + 0{,}0067v + 0{,}0000019583P^2 - 0{,}00000186Pv + 0{,}00000036083v^2 \quad (5.22)$$

Following what is presented in this subchapter, a series of conclusions are drawn. They can be useful for research and production practice:

1. from the analysis of the prediction model and the mathematical model, it is found that the cutting gas pressure is the most influential factor;
2. for industrial practice, the minimum pressure 0.35 bar will be chosen with the maximum speed 1600 mm/min at a moderate power of 4200 W;
3. using the determined mathematical relations, it is possible to estimate the Kerf value for a certain combination of values of two input parameters, while the third one is considered at the average value;
4. the value of the kerf has a special meaning in laser cutting because this value is directly involved in the programming of the tool trajectory. Half of the kerf width is used as tool radius compensation. It's worth noting that this should be the tool radius offset, not the laser beam radius:
5. when the dimensional accuracy of the part and that of the shape of the contour are the main criteria, special attention must be paid to the width of the cutting joint, and therefore to the factors that influence it;
6. assistan gas pressure and laser power-pressure combination have a significant influence on the cutting width.

5.8.2 HARDOX400 steel with a thickness of 8 mm

5.8.2.1 Influence of cutting parameters on hardness

The influence of the couple of power - pressure parameters on the hardness

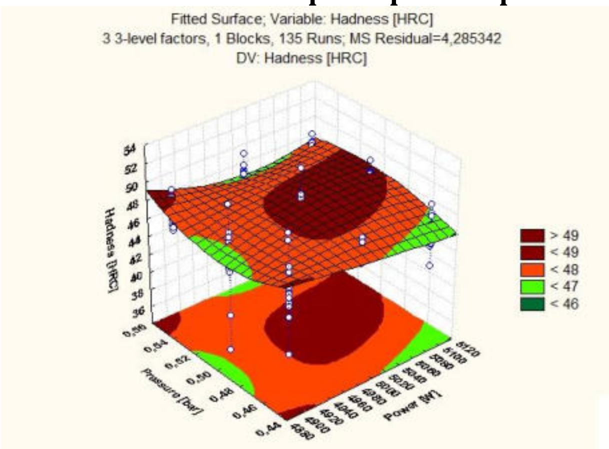


Fig. 5.106 *Quadratic prediction model Ha(P,p)*

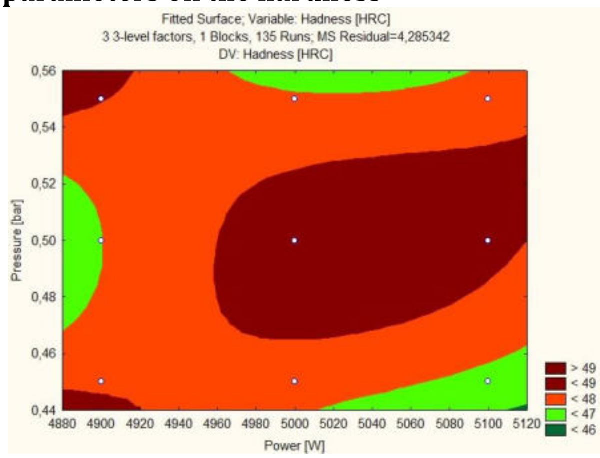


Fig. 5.107 *The contour plot of the prediction Ha(P,p)*

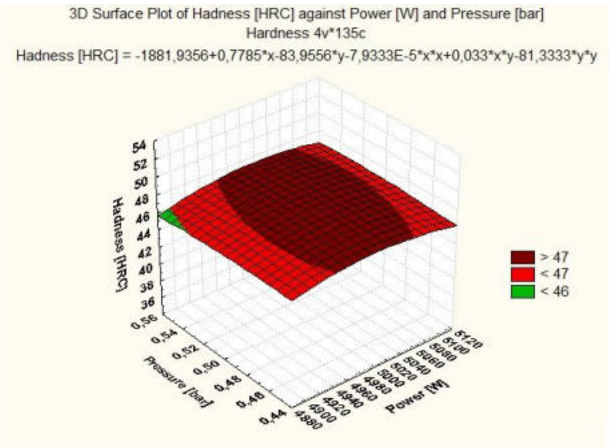


Fig. 5.108 *Quadratic regression plot Ha (P,p)*

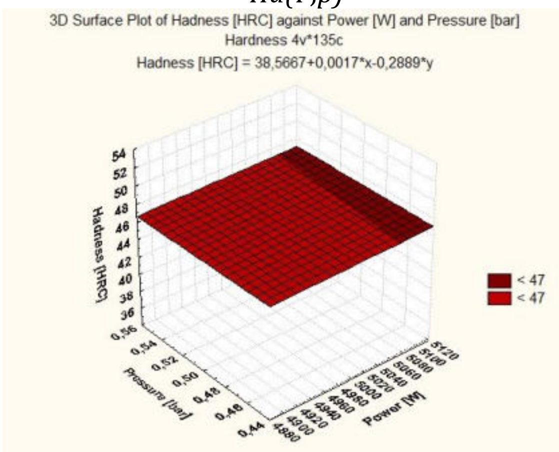


Fig. 5.109 *Linear regression graph Ha (P-p)*

The influence of the speed-pressure parameter couple on the hardness

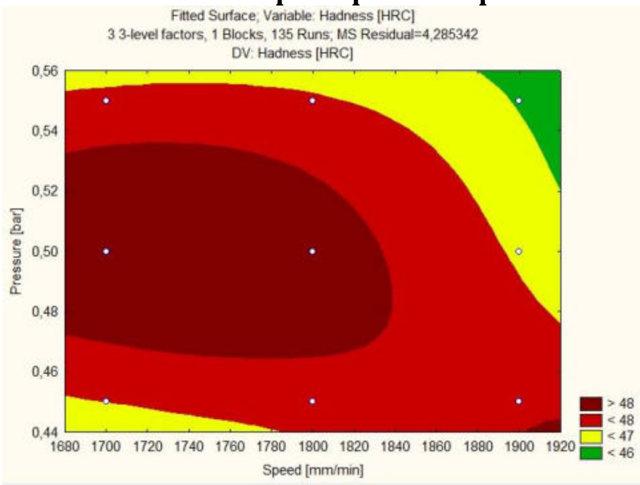


Fig. 5.110 *Prediction contour plot Ha(v,p)*

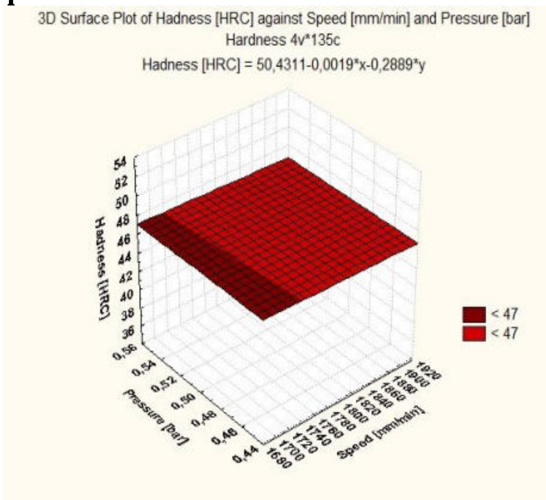


Fig. 5.111 *Regression graph Ha(v,p)*

The influence of the power-speed parameter torque on the hardness

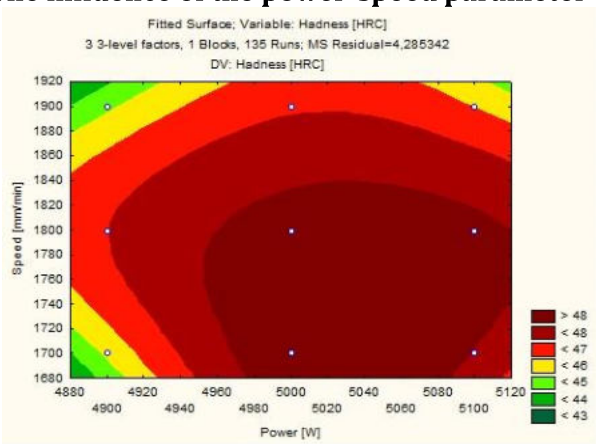


Fig. 5.112 Prediction graph Ha(P,v)

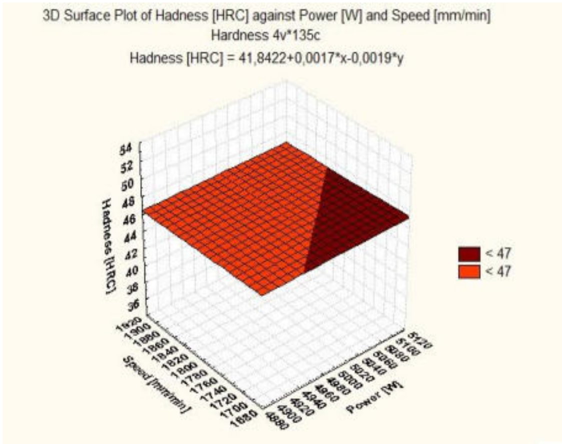


Fig. 5.113 Regression graph Ha(P,v)

5.8.2.2 The influence of cutting parameters on surface roughness [SHU18]

The predictive and mathematical model of roughness Ra power - speed:

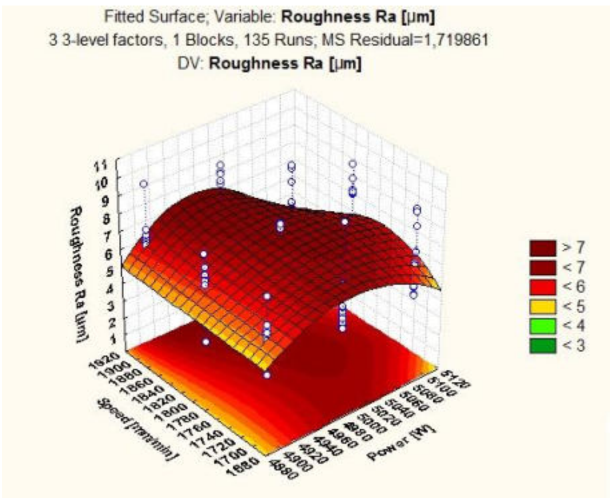


Fig. 5.116 *The predictive chart Ra(P,v)*

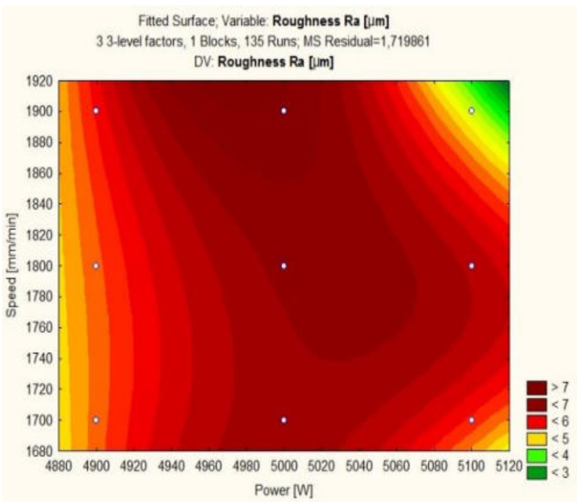


Fig. 5.117 *Predictive contour plot Ra(P,v)*

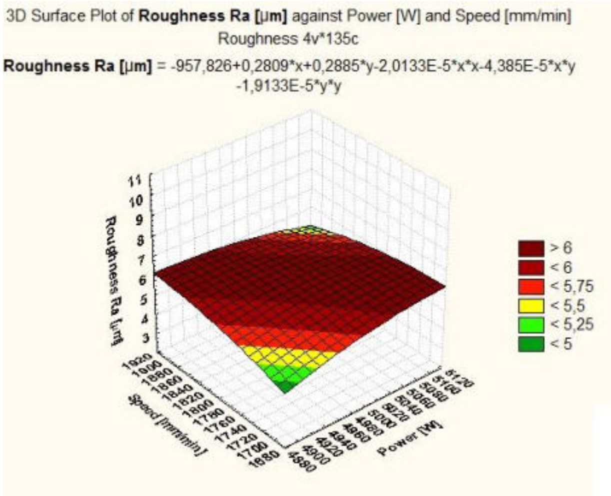


Fig. 5.118 *Quadratic regression plot Ra(P,v)*

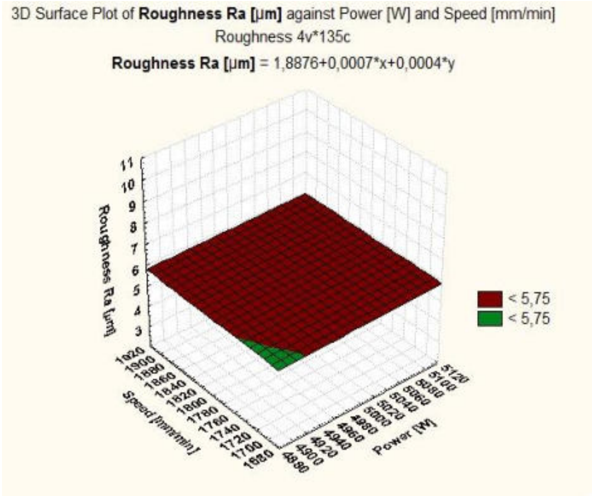


Fig. 5.119 *Linear regression graph Ra(P,v)*

The predictive and mathematical model (linear and quadratic) of roughness Ra power-pressure:

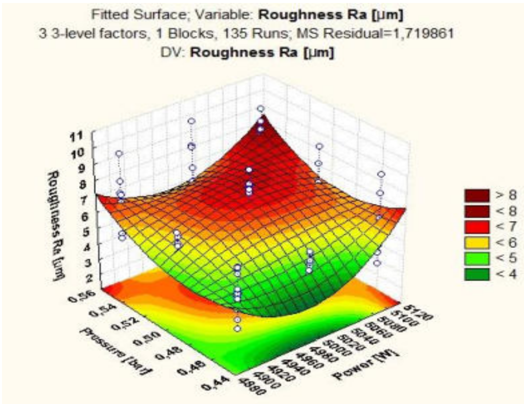


Fig. 5.120 *Predictive quadratic graph Ra(P,p)*

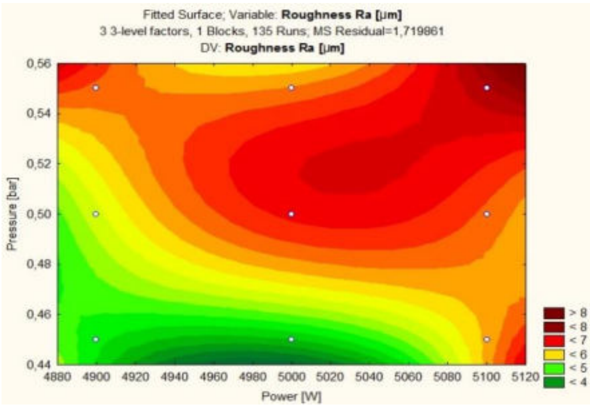


Fig. 5.121 *The predictive chart Ra(P,p)*

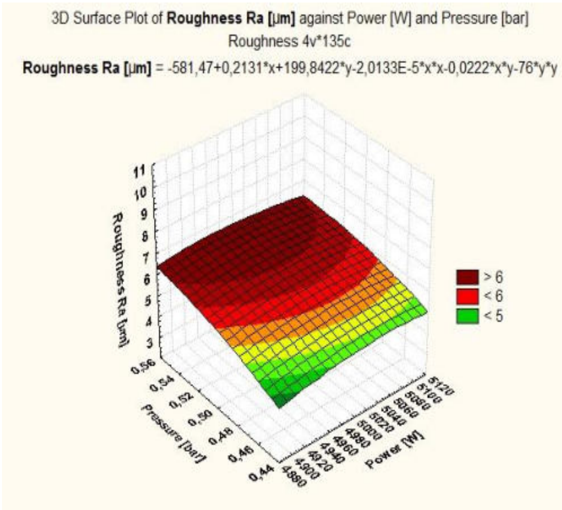


Fig. 5.122 *Quadratic regression plot Ra(P,p)*

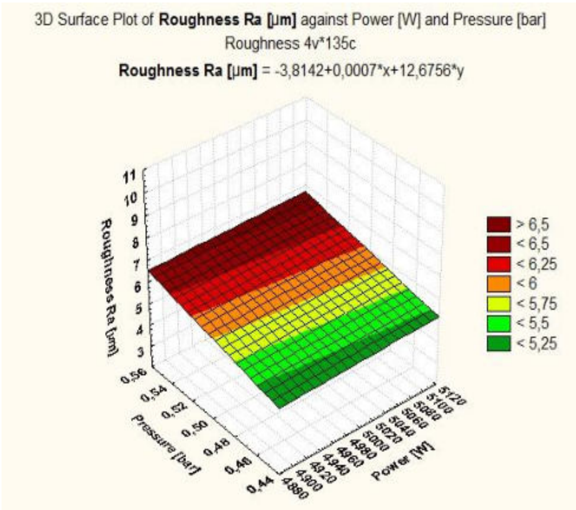


Fig. 5.123 *Linear regression graph Ra(P,p)*

The predictive and mathematical model of roughness Ra speed - pressure:

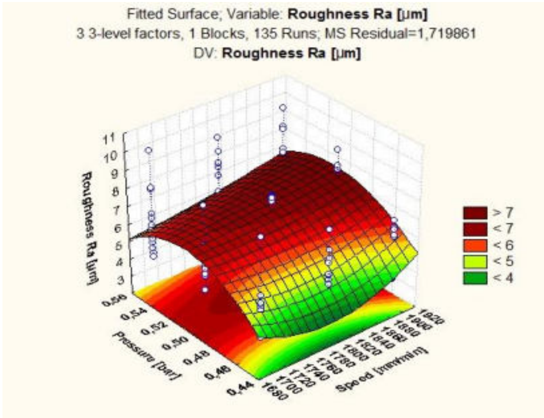


Fig. 5.124 *Predictive quadratic graph Ra(v,p)*

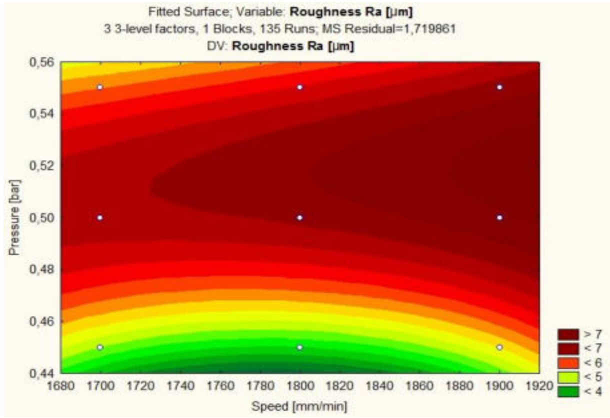


Fig. 5.125 *The predictive chart Ra(v,p)*

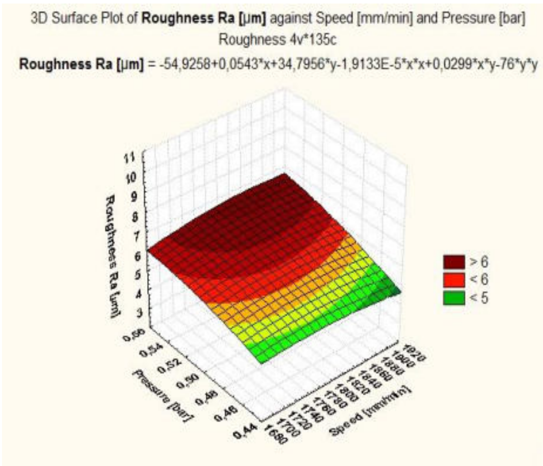


Fig. 5.126 *Quadratic regression plot Ra(v,p)*

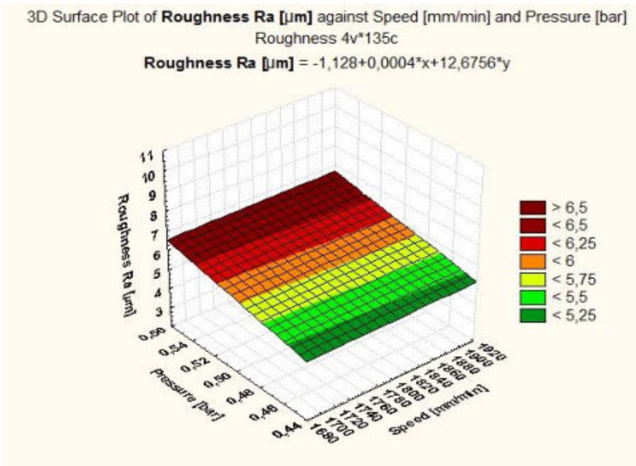


Fig. 5.127(a) *Linear regression graph Ra(v,p)*

5.8.2.3 Influence of cutting parameters on cutting width

The influence of the coupple of power-pressure parameters on the width of the cutting joint

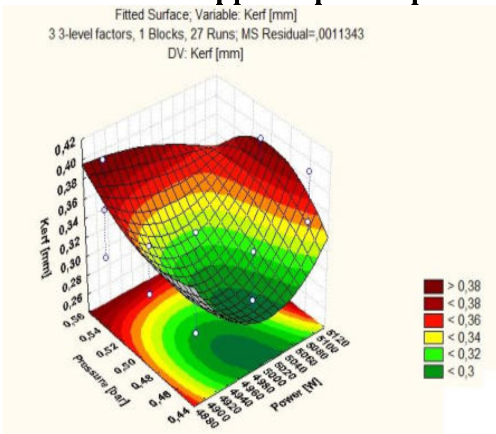


Fig. 5.132 *Quadratic prediction model Kerf(P,p)*

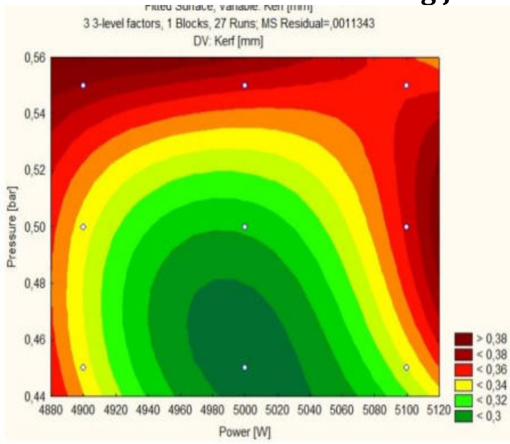


Fig. 5.133 *Prediction graph Kerf(P,p)*

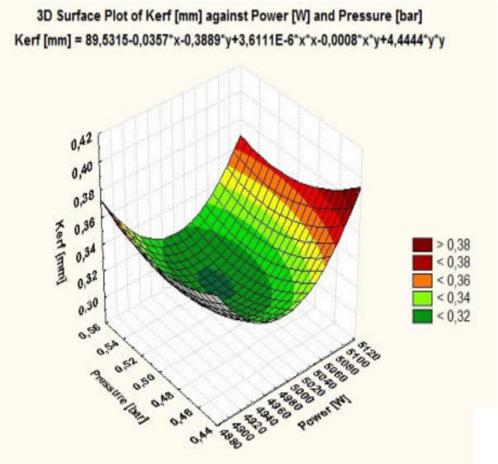


Fig. 5.134 *Quadratic graph Kerf(P,p)*

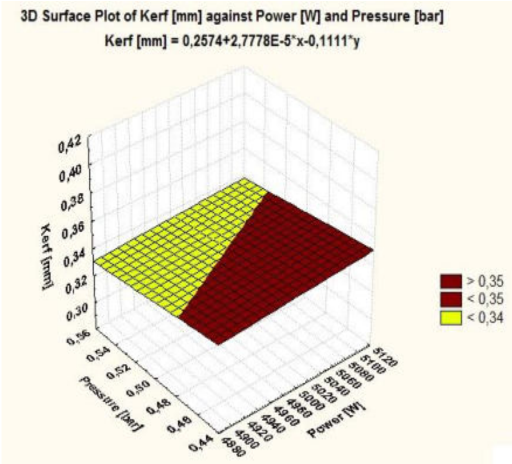


Fig. 5.135 *Line graph Kerf(P,p)*

The influence of the pressure-speed parameter couple on the width of the cutting joint

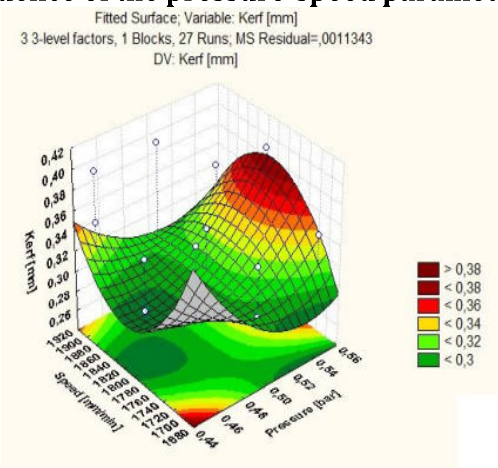


Fig. 5.136 *Quadratic prediction model Kerf(p,v)*

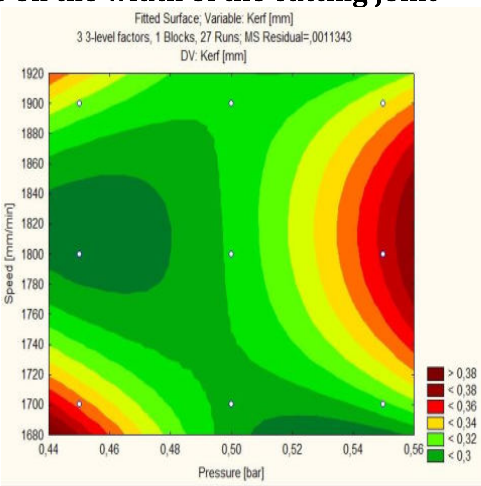


Fig. 5.137 *Predictive chart Kerf(p,v)*

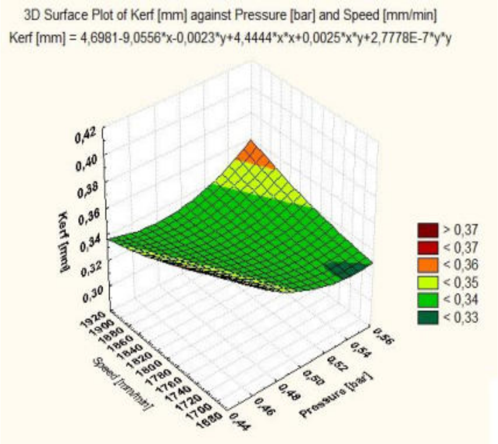


Fig. 5.138 *Quadratic regression plot Kerf(p,v)*

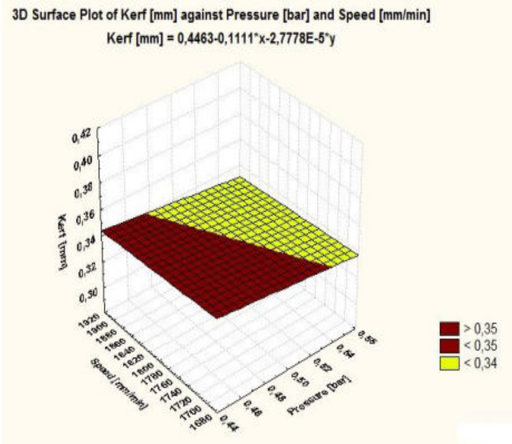


Fig. 5.139 *Linear regression graph Kerf(p,v)*

The influence of the power-speed parameter torque on the width of the cutting Kerf [GÎR21a]

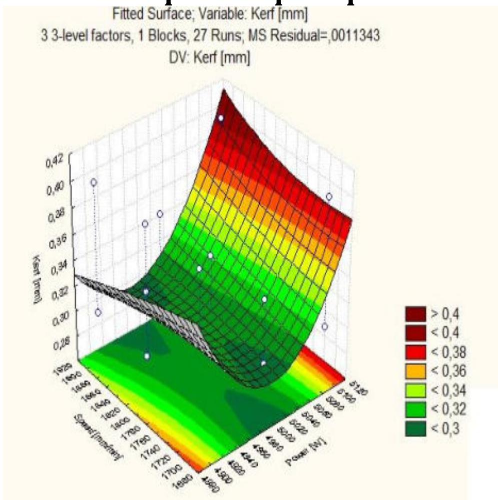


Fig. 5.140 Quadratic prediction model Kerf(P,v)

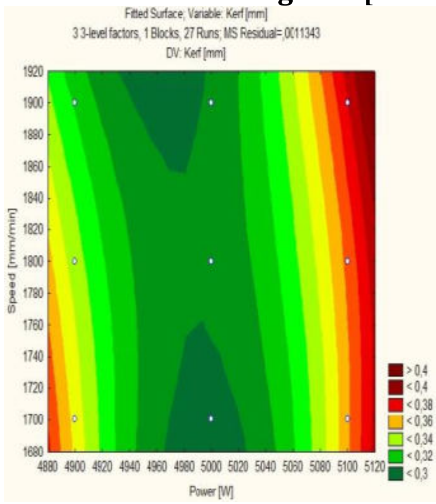


Fig. 5.141 The prediction model Kerf(P,v)

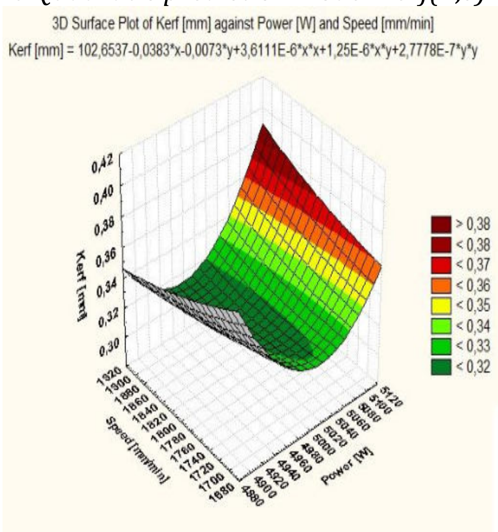


Fig. 5.142 *Quadratic regression plot Kerf(P,v)*

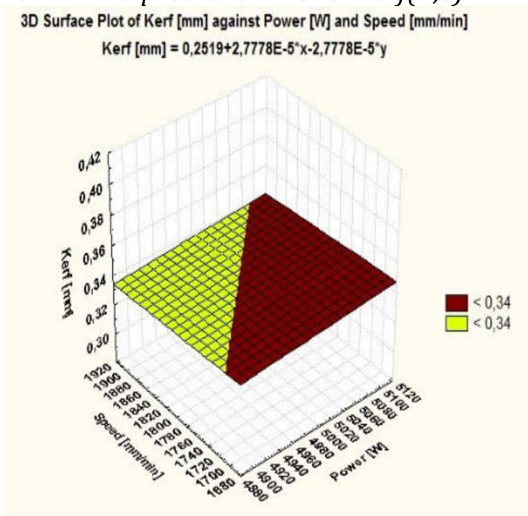


Fig. 5.143 *Linear regression graph Kerf(P,v)*

Following the processing of the experimental data with specific means, the next mathematical relations resulted that describe the dependence of the results of laser cutting on the parameters of the cutting regime:

$$Ha = 38{,}5667 + 0{,}0017P - 0{,}2889p \quad (5.23)$$

$$Ha = -1881{,}9536 + 0{,}7785P - 83{,}9556p - 0{,}000079333P^2 + 0{,}033Pp - 81{,}3333p^2 \quad (5.24)$$

$$Ha = 50{,}4311 - 0{,}0019v + 0{,}2889p \quad (5.25)$$

$$Ha = 41{,}8422 + 0{,}0017P - 0{,}0019v \quad (5.26)$$

$$Ha = 46{,}731 + 1{,}206Pp - 1{,}286vp + 1{,}041Pp^2 \quad (5.27)$$

$$Ra = 1{,}8876 + 0{,}0007\,P + 0{,}0004v \quad (5.28)$$

$$Ra = -957{,}826 + 0{,}2809P + 0{,}2885v - 0{,}00002P^2 - 0{,}00004385Pv - 0{,}0000191v^2 \quad (5.29)$$

$$Ra = -3{,}8142 + 0{,}0007P + 12{,}6756p \quad (5.30)$$

$$Ra = -581{,}47 + 0{,}2131P + 199{,}8422p - 0{,}000020133P^2 - 0{,}0222Pp - 76p^2 \quad (5.31)$$

$$Ra = -1{,}128 + 0{,}0004v + 12{,}6756p \quad (5.32)$$

$$Ra = -54{,}9258 + 0{,}0543v + 34{,}7956p - 0{,}0000191v^2 + 0{,}0299vp - 76p^2 \quad (5.33)$$

$$Kerf = 0{,}2574 + 0{,}000027778P - 0{,}1111p \quad (5.34)$$

$$Kerf = 89{,}5315 - 0{,}0357P - 0{,}3889p + 0{,}0000036111P^2 - 0{,}0008Pp + 4{,}4444p^2 \quad (5.35)$$

$$Kerf = 0{,}4463 - 0{,}1111p - 0{,}000027778v \quad (5.36)$$

$$Kerf = 4{,}6981 - 9{,}0556p - 0{,}0023v + 4{,}4444p^2 + 0{,}0025pv + 0{,}0000027778v^2 \quad (5.37)$$

$$Kerf = 0{,}2519 + 0{,}000027778v - 0{,}000027778P \quad (5.38)$$

$$Kerf = 102{,}6537 - 0{,}0383v - 0{,}0073P + 0{,}0000036111v^2 + 0{,}00000125vP + 0{,}00000027778P^2 \quad (5.39)$$

Following what is presented in this subchapter, a series of conclusions are drawn, which can be useful for research and production practice:

1. from the experimental data it follows that the combination of the maximum power and speed parameters and average pressure results in the lowest roughness;
2. statistical analysis models show that gas pressure is the most significant parameter. The RSM graphs indicate the more pronounced influence of the gas pressure, in the power-pressure and speed-pressure analysis, on the surface roughness Ra;
3. the second influencing factor is the laser power, and the speed has the least influence;
4. the values of the input parameters used to obtain parts with minimum roughness are: gas pressure 0.45 bar, cutting speed 1900 mm/min, laser power 5000 W;
5. the surfaces obtained by laser cutting have an improved Ra roughness when the gas flow has a low flow rate, the laser power is moderate;
6. the combination of power-speed and power-pressure have a strong influence on Ra.

5.8.2.4 The influence of the parameters of the cutting regime on the inclination of the machined surface

Observing the cutting slot between the part and the semi-finished [MAD22] product in a section perpendicular to the contour of the part, one can see that due to the inclination of the flanks it has a general shape with the appearance of the letter A or V, as in the figure 5.144 şi 5.145:

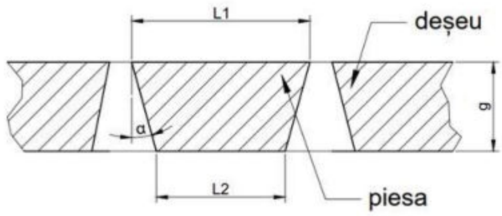


Fig. 5.144 *Cutting slot with inclined flanks. (a) shape A*

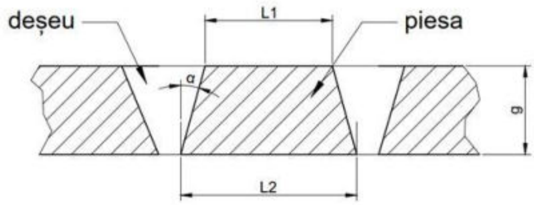


Fig. 5.145 *Cutting slot with inclined flanks. (b) shape V*

Figure 5.146 shows the analysis of the Linear Model on the impact of the input factors on the studied response:

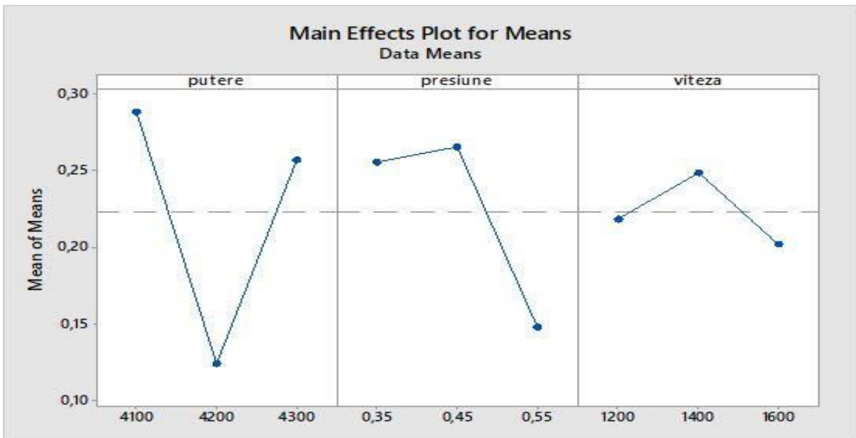


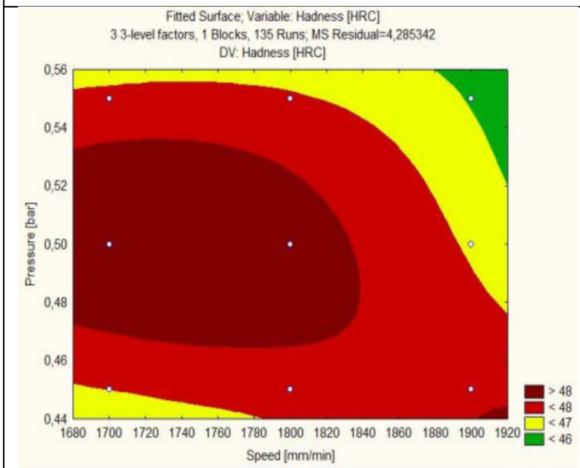
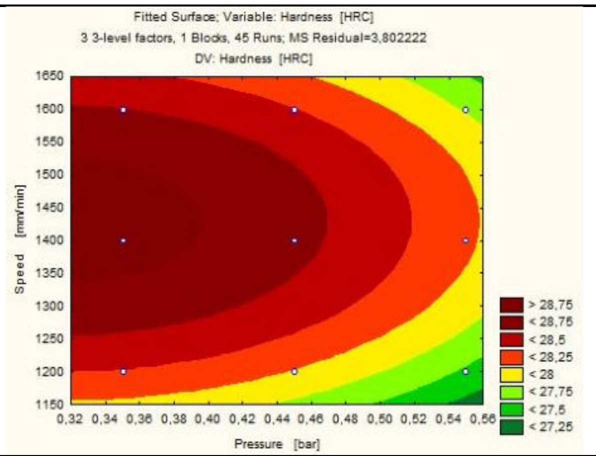
Fig. 5.146 *Plot of the influence of the input parameters on the slope of the parts flanks*

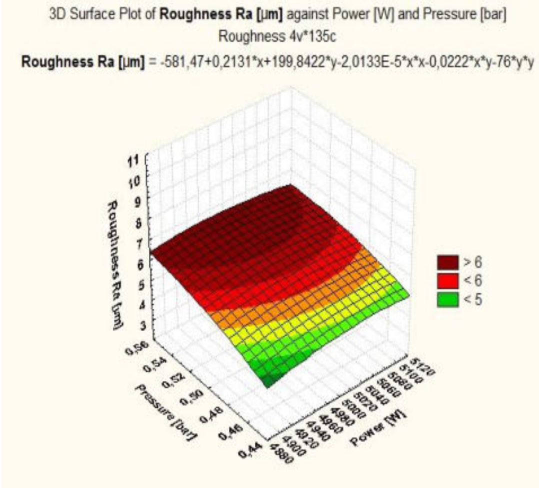
From the graph of the effects of the cutting parameters (fig. 5.146), the following can be preliminarily noted:

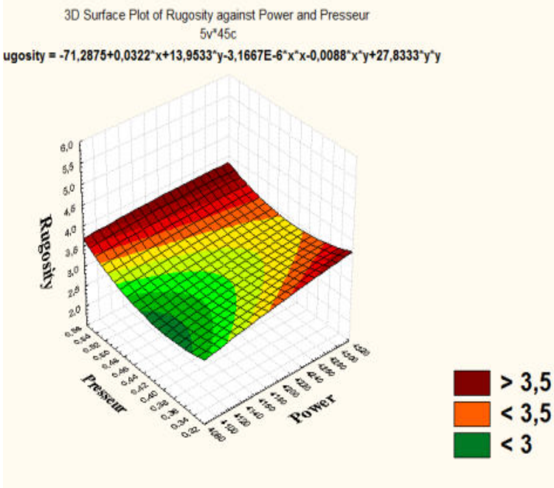
1. the slope of the flanks is minimum at the average power value and maximum at the smallest of this input parameter;
2. the average values of the cutting speed and the assist gas pressure give maximum values of the slope of the flanks.

5.9 Conclusions

Based on what was presented in the previous subsections, a series of conclusions are formulated that highlight the common aspects, but also the particularities of laser cutting processing of HARDOX400 steel sheets with a thickness of 8 mm and 10 mm, respectively.

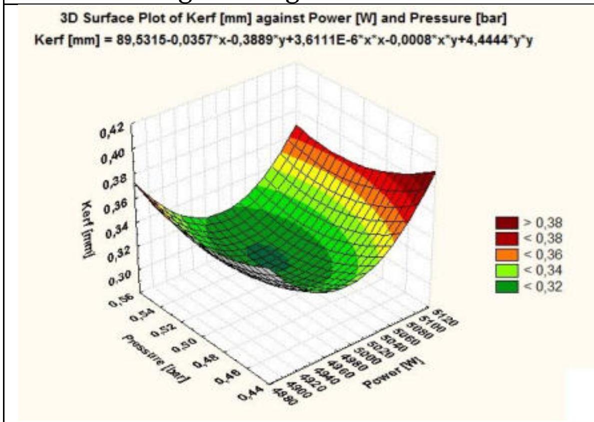
<table>
<tr><th>HARDOX400, g=8 mm</th><th>HARDOX400, g=10 mm</th></tr>
<tr><td colspan="2">1. The holes produced by laser beam piercing have a larger diameter than the width of the cutting slot obtained on and along the approach path of the contour. The explanation is that at the entry point the laser spot is stationary until the penetration is achieved, and then moves at the programmed speed. During dwell a large amount of heat builds up in the material causing the excess material to melt. This is also the reason why the perforation is always done outside the contour of the part. In addition, at the point of perforation the laser operates in pulse mode, and in the cutting phase in continuous mode.</td></tr>
<tr><td>2. In the superficial layer along the cut contour the concentration of iron decreases, while that of manganese, chromium, and molybdenum increases.
The chemical composition changes very little, without influencing the physical properties of the surface layer. They are affected by changes in structure, grain size, etc.</td><td>2. The chemical composition in the surface layer was changed: the concentration of molybdenum and iron increased, while that of chromium decreased. Mn partially decreases on the cut surface.</td></tr>
<tr><td colspan="2">3. The different behaviour of the two semi-finished products can be attributed to the different regimes with which they were cut. The variation in the concentration of the alloying elements in the superficial layer is detectable by means of scientific investigation, but still small enough to be considered significant (the observed variation in the concentration of the alloying elements is of the order of tenths and hundredths of a percent, therefore it is estimated that the alteration the chemical composition of the material in the surface layer is not decisive for changing the physical properties, especially the hardness).</td></tr>
<tr><td colspan="2">4. The increase in hardness with the reduction of cutting speed and assistant gas pressure can be attributed to the more intensive accumulation of heat in the heat-affected zone of the part. This phenomenon favors the more pronounced formation of hard constituents.</td></tr>
<tr><td colspan="2">5. Predictive graph (v-p) determines maximum hardness under medium pressure and velocity conditions</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td colspan="2">6. The hardness of the cut surface increases above 45 HRC after laser cutting, compared to about 40 HRC in the raw (unprocessed) material.</td></tr>
<tr><td colspan="2">7. At both material thicknesses the roughness Ra shows maximum values at high values of the assistant gas pressure, regardless of the laser power (this has small influence)</td></tr>
</table>

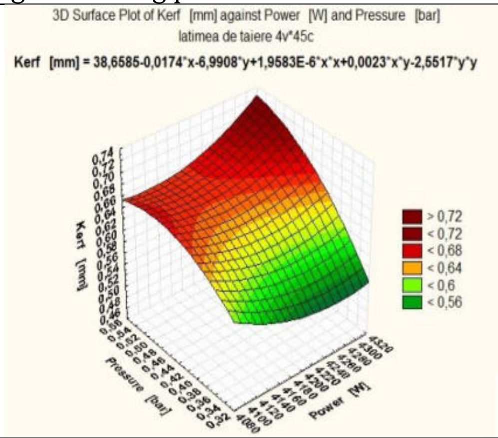




A good similarity of the behaviour of the steel HARDOX400, g=8 mm with HARDOX400, g=10 mm is found in terms of the maximum roughness obtained under the conditions of using the maximum pressure of the assistant gas at any level of the laser power. It is observed that Ra decreases as the power and pressure approach their minimum value.

8. The width of the cutting slot is influenced by the power-pressure (P-p) input parameter couple similar for the two blank thicknesses. However, a shift of the minimum Kerf zone towards average values of the laser power at g=8 mm is observed. meanwhile at g=10 mm the minimum Kerf occurs at values close to the maximum of the laser power.
Both blanks show an increase in the width of the cutting slit when using a higher laser power, due to the melting of a larger amount of material along the cutting path.





9. The average cutting width is 0,348 mm.	The average cutting width is 0,619 mm.

10. The average kerf is wider in the thicker blank because it requires a bigger amount of energy to pierce and cut.

The following four general conclusions can be drawn:

1. **Regarding the extent to which the three output parameters are affected by the variation of the input data of the cutting regime, it is found that the most sensitive output parameter is the roughness, and the least sensitive is the hardness of the surface layer of the machined surface.**
2. **Each of the input parameters (predictors) acts with different intensities on the responses. Thus, for the roughness, the most influential factor is the cutting speed at the semi-finished product with g=10 mm and the gas pressure of the assistant at g=8 mm.**
3. **For hardness the most influential factor is the laser power on the blank with g=10 mm and the term (p X v) that quantifies the interaction between pressure and speed at g=8 mm**
4. **For the cutting width-Kerf the most influential factor is the gas pressure assisting the semi-finished product with g=10 mm. In the semi-finished product with g=8 mm, no obvious predominant influence of any predictor was identified. [HOH20]**

CHAPTER 6 Practical validation of determined mathematical models

In order to verify and validate the results obtained in the experimental research stage, several case studies were carried out. Parts were machined aiming to a certain target value for roughness or hardness. The parameters of the cutting regime were selected according to the values resulting from the use of mathematical relationships determined based on of experimental research. Depending on the deviation of the physically realized value from the estimated one, conclusions could be drawn on the correctness of the mathematical relationships determined through the scientific processing of the experimental data. A few such case studies and their results are presented below.

It should be noted that in certain situations the relative error found may seem large from a scientific point of view. However, it must be mentioned that for the analysed mathematical relations the applicability in practice is sought, and that in this field the results are also affected by the influence of (many) other factors – the purity of the assistant gas and its nature, the position of the focus point, the diameter of the laser spot, the diameter of the nozzle, and they were not all listed. Even in the case of apparently large relative errors, they were considered acceptable if the results were not significantly affected, for example, the roughness class was the same for the estimated and the physically realized value.

6.1 Validation of the relationship for the determination of Ra

The relationship considered is the one that determines roughness as a function of cutting speed and assistant gas pressure (6.1)

$$Ra = 20{,}2509 - 3{,}547p - 0{,}0229v + 27{,}8333p^2 - 0{,}0139vp + 0{,}0000099v^2 \qquad (6.1)$$

The input data of the cutting process for the test machining is shown in the table 6.1:

Tab. 6.1 *Parametrii de tăiere utilizați în experimentele de verificare Ra*

Input parameters	Medium	Unit of measure
Laser power	4200	W
Assistant gas pressure	0,45	bar
Cutting speed	1300	mm/min

The roughness of the parts processed with the regime mentioned above was measured under the same conditions as in the case of experimental research. The recording values of the experimental data are presented in the table 6.2.

Tab. 6.2 *Experimental data of roughness Ra on part 2*

No. piece	Roughness Ra	Unit of measure
1	2,98	µm
2	3,88	µm
3	4,25	µm
4	3,00	µm
Ra medium	**3.52**	**µm**

It is found that the deviation of the practically obtained Ra value (3.52 µm) has a deviation of 0.40 µm compared to the theoretically estimated one (3.12 µm) with the relation (6.1), which indicates a good correlation between them. The conclusion is that the relation (6.1) is verified in practice, so it is reliable. The two values fall into the same roughness class – 3.2 µm.

Another option to check the mathematical relationship is the following: it is required to obtain parts with a certain roughness (Ra=3.20 µm) under the conditions of using an imposed cutting speed of 1300 mm/min. With relation 6.1, the assistant gas pressure that should be adjusted to meet the target Ra=3.20 µm can be determined.

According to this relationship, substituting the desired values for Ra and v gives:

$$27{,}8333p^2 - 21{,}61p + 4 = 0 \qquad (6.2)$$

with one of the roots p=0.47 bar.

Processing the test pieces under these conditions (v=1300 mm/min and p=0.47 bar) and measuring the roughness, a global average value of 3.19 µm is found. The practically obtained roughness value has a deviation of 0.33% from the one set as an objective. In this case, also the conclusion is that the relation (6.1) is verified in practice, so it is reliable.

6.2 Validation of the relationship for the determination of hardness

For the validation of the relationship (6.3) apply a course similar to the one presented in the previous subchapter, with strict adaptations.

$$Ha = 31{,}6333 - 3{,}8667p - 0{,}001v \qquad (6.3)$$

Tab. 6.3 *Experimental data of hardness Ha on part 1*

No. piece	The hardness	Unit of measure
1	30	HRC
2	30	HRC
3	27	HRC
4	30	HRC
Ha medium	**29,25**	**HRC**

It is found that the practically obtained hardness value (29.25 HRC) has a deviation of (0.66 HRC) over 2% compared to the theoretically estimated one (28.59 HRC) with relation (6.3), which indicates a good correlation between they. The conclusion is that the relation (6.3) is verified in practice, so it is reliable.

Another method to check the quadratic regression relationship is as follows: it is required to obtain parts with a certain hardness (Ha=29 HRC) under the conditions of using an imposed cutting speed of 1300 mm/min. With relation 6.4 one can determine the assistant gas pressure that should be adjusted to meet the objective of Ha=29 HRC.

$$Ha = -9{,}9208 - 21{,}0167p + 0{,}065v - 14p^2 + 0{,}0212pv - 0{,}000027v^2 \qquad (6.4)$$

According to this relationship, substituting the desired values for Ha and v gives p=0.46 bar. Since the pressure adjustment on the laser cutting machine can be done in steps of 0.05 bar, the pressure of 0.46 bar cannot be adjusted. A pressure of 0.45 bar was used for processing the test pieces. In order to have the same terms of comparison, the hardness Ha corresponding to the input parameters v=1300 mm/min and p=0.45 bar is determined with relation 6.4. This results in a value of 29.05 HRC. This hardness value has a deviation of less than 0.20 HRC from the value obtained in practice, which indicates an error of less than 1% between the value obtained from theory and the practical value. And in this case the conclusion is that the relation (6.4) is verified in practice, so it is reliable. This fact also confirms the fact that the quadratic function is more accurate than the linear one where the error is over 2%.

6.6 Conclusions

Based on the findings in this chapter, the following conclusions can be drawn:

1. all linear and quadratic mathematical relationships have been validated and can be used in production practice and research by directly replacing the values of the input parameters used;
2. the calculated roughness and hardness values have a small deviation compared to the average values obtained experimentally;

CHAPTER 7 Final conclusions

7.1 General conclusions

Following the research carried out, the next general conclusions emerge:

1. the cutting speed factor is the most influential on the surface roughness Ra at g=10 mm;
2. the assistant gas pressure factor is the most influential on the surface roughness Ra at g=8 mm;

3. the laser power factor is the most influential on the hardness of the thermally affected layer at g=10 mm;
4. the factors cutting speed and pressure of the assistant gas interact linearly, being the most influential on the hardness at g=8 mm.
5. the assistant gas pressure factor is the most influential on the width of the cutting slot at g=10 mm;
6. both at g=10 mm and at g=8 mm the average hardness under the surface layer decreases, respectively the average hardness of the surface layer increases following laser processing;
7. at g=10 mm the average value of Kerf is 0.619 mm, and at g=8 mm Kerf has an average value of 0.348 mm;
8. some of the mathematical relations describing the roughness Ra at g=10 mm were determined by two methods (regression and Lagrange interpolation), leading to similar results that confirm each other;

7.2 Personal contributions to the doctoral thesis

This doctoral thesis presents a series of personal contributions summarized in the following:

1. classification of the scientific achievements in the field of the doctoral thesis presented in literature according to various criteria:

a) sources – scientific articles, monographs/manuals/books, doctoral theses;
b) materials processed with the laser: metallic materials – non-ferrous steels/cast irons/alloys, non-metallic materials;
c) fields of laser use: industry/medicine/communications/military etc.;
d) laser processing procedures: cutting/drilling/welding, etc.;

2. determining the influence of some of the magnetoelectric and thermal properties of the processed material on the energy consumption when cutting metals with the laser;
3. the study regarding the possibilities of controlling the pressure of the assistant gas through the construction of the nozzle;
4. identification of the additional input of heat obtained as a result of the Joule effect transformation of the electric current induced in the part by the variation of the electromagnetic field of the laser beam;
5. the combined use of some theories of Prof. I. Agîrbiceanu [AGÎ56] and of the researcher L. D. Landau [LAN63] to demonstrate analytically the experimental findings regarding the influence of the electromagnetic properties of the material on the characteristics of the electromagnetic radiation;
6. the definition of three energy efficiency indicators for laser cutting, indicators that can be applied uniformly in different technological contexts;
7. the study of the width of the cutting slot as a factor of technological importance in the aspect of using its value in determining the radius correction of the tool when programming the contour to be processed. Indirectly, the correct estimation of the value of this size can contribute to ensuring the dimensional accuracy of the part;
8. conducting experimental research on a material (HARDOX) frequently used in the manufacture of products, but for which recommendations regarding the choice of parameters of the cutting regime have not been identified in the specialized literature;
9. determination based on experimental research of some mathematical relationships that describe the dependence of responses on predictors as follows:
   -hardness = f(power, pressure), hardness = f(power, speed), hardness = f(pressure, speed);
   -roughness = f(power, pressure), roughness = f(power, speed), roughness = f(pressure, speed);
   - Kerf = f(power, pressure), Kerf = f(power, speed), Kerf = f(pressure, speed);
10. determination of all these relationships in both linear and quadratic versions;
11. identification of the most influential predictor for roughness, hardness and Kerf in parts made of raw material products having the thickness of 8 and 10 mm;
12. identification of the most sensitive output quantity when changing the values of the predictors;
13. validation of results through case studies;
14. validation of some of the mathematical relationships determined by applying alternative methods (Lagrange interpolation).

7.3 Valorisation and dissemination of scientific research results

The paper joins the doctoral theses that studied the processing of materials by the laser. The final results obtained within the research activity can be applied in the industrial field. The theoretical and practical results can be applied in teaching processes and in production.

As part of the dissemination and valorisation of scientific research results, the author has published a series of articles in the country and abroad to support theoretical and practical training in the field of using the CO_2 laser for the manufacture of industrial products from materials in HARDOX range. Research and studies published and/or presented at scientific conferences are structured in the list of published works:

List of papers published during the doctoral internship

1.Articles published in indexed journals Web of Science:

1.1 Mileșan M, Gîrdu C. C., Cîrțînă L., Rădulescu C., Mathematical Modelling Study of Hardox 400 steel parts Roughness and Hardness, Cut with CO_2 laser, Strojniski Vestnik Journal of Mechanical Engineering, 66(2020)2, 127-141, https://doi.org/10.5545/sv-jme.2019.6320. (IF=1,554), https://www-webofscience-com.am.e-nformation.ro/wos/woscc/full-record/WOS:000513872300005

1.2 Girdu C. C., Gheorghe C., Raulescu C., Cirtina D., Influence of process parameters on cutting width in CO_2 laser processing of Hardox 400 steel, Appl. Sci. 2021, 11(13), 5998; https://doi.org/10.3390/app11135998. (IF=2,474), https://www-webofscience-com.am.e-nformation.ro/wos/woscc/full-record/WOS:000672334200001

2.Articles published in journals:

2.1 Girdu C. C., and Gheorghe C., Energy efficiency in CO_2 laser processing of Hardox 400 material, (IF=3,74), Materials, 2022 https://doi.org/10.3390/ma15134505

3.Works indexed in BDI International Databases:

3.1 Gîrdu C. C, Mihail L. A, Drăgoi M. V.,, Estimation of laser cutting process efficiency, IRMES Research and Development of mechanical elements and systems, KRAGUJEVAC, Serbia, IOP Conf. Series: Materials Science and Engineering 659 (2019) 012045 IOP Publishing doi:10.1088/1757-899X/659/1/012045.

3.2 Gîrdu C. C., Dragoi M. V., Milesan M., Mihail L. A.., Cirtina L. and Radulescu C., Study of cutting parameters influence on the surface roughness at laser processing of Hardox400 steel, IOP Conf. Series: Materials Science and Engineering 1009 (2021) 011001, doi:10.1088/1757-899X/1009/1/011001.

3.3 Girdu C. C., Lepădătescu B., Experimental research methods for CO_2 laser cutting of HARDOX400 steel, INTERNATIONAL JOURNAL OF SYSTEMS APPLICATIONS, ENGINEERING & DEVELOPMENT DOI: 10.46300/91015.2021.15.8, Volume 15, 2021.

4.Other works:

4.1 Gîrdu C. C., Mathematical modeling for soft laser beam processing, International Journal of Applied Physics, Volume 3, 2018. http://www.iaras.org/iaras/journals/jap pg 20-25, www.semanticscholar.Org.

4.2 Gîrdu C. C., Management and Resources in the Research project: Carbon dioxide Laser with Applications in Industrial Engineering, International Journal of Economics and Management Systems, http://www.iaras.org/iaras/journals/ijems, Dubrovnik, Croația, 2018.

List of citations of published works

Some of the articles presented above have aroused the interest of some researchers acquiring citations as shown in table 7.1.

Dissemination of the results of scientific research was achieved with the publication of articles in the ISI-indexed journal Strojinski and Applied Science. Other authors studied ISI papers recently published on WEB OF SCIENCE and used them in their study. They appreciated the results obtained on the roughness Ra and the cutting width Kerf on the HARDOX400 blank. Established authors listed in the introduction and bibliography of the work a brief description of the results obtained with HARDOX400 steel on the occasion of the publication of research in the field of laser processing. The doctoral student's articles were cited by 4 foreign authors and collaborators, respectively 1 doctoral thesis. They are presented in table 7.1:

Table 7.1 *List of citations*

Article	Quoted in:
Mathematical Modelling Study of Hardox400 Steel Parts' Roughness and Hardness, Cut with CO2 Laser	**Experimental investigation to optimize laser cutting process parameters for difficult to cut die alloy steel using response surface methodology** **Patel, Amit**; **Bhavsar, Sanket N.** **Conference: 1st International Conference on Energy, Materials Sciences and Mechanical Engineering (EMSME) Location: Delhi, INDIA Date: OCT 31-NOV 01, 2020** **MATERIALS TODAY-PROCEEDINGS Volume: 43 Pages: 28-35 Part: 1 Published: 2021**
Influence of process parameters on cutting width in CO_2 laser processing of Hardox 400 steel	Effect of Process Parameters on the Quality of Laser-Cut Stainless Steel Thin Plates Irene Buj-Corral, Lluís Costa-Herrero and Alejandro Domínguez-Fernández **Department of Mechanical Engineering, School of Engineering of Barcelona (ETSEIB), Universitat Politècnica de Catalunya (UPC), Av. Diagonal, 647, 08028 Barcelona, Spain** *Metals* **2021**, *11*(8), 1224; **https://doi.org/10.3390/met11081224**
Influence of process parameters on cutting width in CO_2 laser processing of Hardox 400 steel	Application of a Robust Decision-Making Rule for Comprehensive Assessment of Laser Cutting Conditions and Performance Miloš Madic, Goran Petrovic, Dušan Petkovic, Jurgita Antucheviciene and Dragan Marinkovic **Faculty of Mechanical Engineering, University of Nis, Vilnius Gediminas Technical University, Faculty of Mechanical Engineering and Transport Systems, Technische Universität Berlin,** Machines/2022,10,153. https://doi.org/10.3390/machines10020153
Some applications of CO_2 laser in industrial engineering	Optics and Apparatus for CO_2 and CO Laser Micro-processing. Hohnholz A., Rettschlag K., Desens M., Taschner P.A., Overmeyer L. (2020)

	In: Sugioka K. (eds) Handbook of Laser Micro- and Nano-Engineering. Springer Nature Switzerland AG. Cham. Pp 1-37 https://doi.org/10.1007/978-3-319-69537-2_4-1
Some applications of CO_2 laser in industrial engineering	ΑΝΑΠΤΥΞΗ ΚΑΙ ΕΦΑΡΜΟΓΕΣ ΥΒΡΙΔΙΚΩΝ ΝΑΝΟΫΛΙΚΩΝ ΚΑΙ ΝΑΝΟΔΟΜΗΜΕΝΩΝ ΕΠΙΦΑΝΕΙΩΝ (DEZVOLTAREA ȘI APLICAȚIILE SUPRAFEȚELOR NOROLOGICE ȘI STRUCTURATE HIBRIDE) ΔΙΔΑΚΤΟΡΙΚΗ ΔΙΑΤΡΙΒΗ (TEZĂ DE DOCTORAT) Πάτρα 2020 (Patras 2020) Κανίδη Μαρία Διπλωματούχου Χημικού Μηχανικού (Kanidi Maria Absolventa in Inginerie Chimica) ΠΑΝΕΠΙΣΤΗΜΙΟ ΠΑΤΡΩΝ ΣΧΟΛΗ ΘΕΤΙΚΩΝ ΕΠΙΣΤΗΜΩΝ ΤΜΗΜΑ ΕΠΙΣΤΗΜΗΣ ΚΑΙ ΤΕΧΝΟΛΟΓΙΑΣ ΥΛΙΚΩΝ UNIVERSITATEA DIN PATRAS ȘCOALA DE ȘTIINȚE POZITIVE DEPARTAMENTUL DE ȘTIINȚA ȘI TEHNOLOGIA MATERIALELOR

From the webpage of each journal, the data regarding the counting of the article was observed (table 7.2)

Table 7.2 *Access list of ISI articles*

journal	Article	Views	Downloads	Date	Impact Factor
Strojinski **2020**	**Mathematical Modelling Study of Hardox400 Steel Parts' Roughness and Hardness, Cut with CO_2 Laser**	1302	1603	17.04.2022	1,554
MDPI **Applied Sciences 2021**	**Influence of process parameters on cutting width in CO_2 laser processing of Hardox 400 steel**	570	558	17.04.2022	2,474

Three articles were published in ISI indexed journals, 1 article in ISI Proceedings Conferences, 2 articles in BDI indexed conferences.

7.4 Research development directions

Concerns for the future are to develop experimental projects and research studies based on laser cutting of parts from HARDOX500, HARDOX550, HARDOX600. The previously stated reasons led to the following research directions:

D1: Extension of research to other materials in the same category - H500, H550, H600.

D2: Determination of mathematical relationships to characterize the dependence of laser cutting results on predictors for the new materials studied

D3: Research focus towards identifying a systematic influence of any predictor on flank slope.
New mathematical relationships will be identified to establish new output responses depending on input parameters (laser power, assist gas pressure, cutting speed, nozzle diameter, nozzle-workpiece distance, focal position) for other thicknesses and HARDOX models or other materials.

The research aims to make new scientific contributions to the manufacture of industrial products processed with new types of fiber and CO_2 installations.

The research directions will impose the development of new scientific contents that enrich the specialized literature in the field of materials processing with the help of laser.

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