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INVESTIGATION OF THE DEPENDENCE OF THE TECHNOLOGICAL PARAMETERS OF LASER CUTTING TO MINIMIZE THE DEVIATION FROM THE NOMINAL DIMENSIONS OF THE PARTS

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Abstract: The purpose of the published research is to investigate the dependence of the technological parameters (cutting speed, focal length, and gas pressure) of fiber laser cutting to obtain the minimum deviation of the diameters of the parts from the nominal dimensions. The result is a mathematical model and optimized values for setting the fiber laser cutting machine's technological parameters for the given material type. The optimized laser cutting parameters also depend on the kind of material. The entire research is focused on developing a global auto-calibration system for optimizing laser cutting parameters for different thicknesses and types of materials.

KEYWORDS: fiber laser, optimization, mathematical model, laser power, laser focal length, laser cutting speed

1 Introduction

Customer demands for the accuracy of laser cutting machines and their quick and efficient adjustment control are increasing. High production with maintenance or an increase in the accuracy of cut parts is required. The aim is to obtain a finished, final part by laser cutting without the need for further processing. For this reason, the investigation of the influence of the technological parameters of laser cutting on the resulting accuracy or the size of the deviation of the nominal dimensions is a broad scientific field. From the scientific articles [1], [2], [3], [4], [5], [6], [7], [8] and [9], it follows that the machine parameters recommended by the manufacturer for cutting the specified thickness or type of material, are not always optimal.

In the article [1], they investigated the suitability of using GRA (Gray Relational Analysis) to determine the optimal parameters of laser cutting with multi-performance characteristics. In the conducted experiment, they investigated the effect of laser power and cutting speed on surface roughness, gap width, and HAZ (heat-affected zone) size. The independent variables (laser power and cutting speed) were varied in four levels. In conclusion [1], the authors state that from the results of GRA, it is possible to observe that the change in laser power has a greater effect on the quality parameters than on the cutting speed. It proved the suitability of using GRA. Thus, the technological parameters of laser cutting can be effectively improved with the help of GRA. [1].

One of the main problems with laser cutting machines is related to the incorrect setting of the cutting parameters. The discrepancy between these parameters leads to a loss of the quality of the cutting surface. This loss of quality is usually associated with the burr problem. The study [2] is aimed at improving and optimizing the cutting process using a fiber laser machine. The authors of the study [2] designed the experiment based on the parameters recommended by the

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manufacturer: laser power, cutting speed, and gas pressure. The first samples were cut with parameters using the values according to the manufacturer's recommendations, i.e. for stainless steel: laser power 4 kW, cutting speed 20 m.min-1, and gas pressure 15 bar. The cut samples were made of two materials, AISI 316L stainless steel and cold-rolled St12 low carbon steel. For other cuts, the values of the performance parameters were adjusted against the recommended values of the machine manufacturer. While the laser power could not be increased above the value recommended by the manufacturer, it was proportionally reduced in two levels. The cutting speed could be increased and it was also increased in two levels. The gas pressure was reduced by only one level because the quality of the cutting surface was too poor to reduce by one more level, [2]. The results of the study show that the best and most accurate results are not always achieved concerning the quality of the cutting surface at the values of the parameters that are recommended by the manufacturer. From the conclusions of the analysis, it is possible, in this case, to state that when cutting stainless steel AISI 316L, about the elimination of burrs, the optimal values of the parameters are: gas pressure 15 bar, cutting speed 10 m.min-1 and laser power 3.5KW. While the parameter with the greatest influence on the burr is the gas pressure. When cutting the same material, but taking into account the roughness of the cutting surface, the parameter with the greatest influence is the cutting speed. Compared to the optimal setting for deburring, for roughness, it is necessary to increase the cutting speed to a value of 25 m.min-1.

The study [3] deals with the same type of cutting parameters that we investigated in the paper. However, it focuses on optimizing the parameters of the quality of roughness, the surface of the cut, and the width of the slot. In the optimization process, 18 optimization solutions were implemented, and it was shown that it is possible to achieve a minimum gap width of 0.124 mm at the following parameter values: P = 420W, V = 15 mm/s, p = 10 bar, and f = -1 mm. The minimum surface roughness of 35.726 μm can be achieved with the following parameters: P = 420W, V = 10 mm/s, p = 8 bar, and f = -1 mm. The results were mutually limited and the optimal solution could not be obtained simultaneously for the slot width and the surface roughness.

The authors [4] focused on the analysis and optimization of the surface quality of stainless steel miniature gears produced by CO2 laser cutting. Again, laser power, cutting speed, focus position, and gas pressure were specified as variable, independent variables. A Trumatic L3020 machine from Trumpf with a maximum power of 3.2 kW was used and nitrogen was used as the auxiliary gas. The optimal value of laser process parameters for miniature gears was evaluated as follows: for laser power 2407 W, cutting speed 1.25 m/min, focus position -2.40 mm, and gas pressure 12.5 bar. In this setting, the smallest average roughness of 0.43 μm was achieved.

Similarly, works [5], [6], [7], [8], [9] and [13] are aimed at investigating the influence of technological parameters on surface roughness, gap width, or HAZ size. These are valuable scientific conclusions. In this article, we focused on the investigation of dimensional accuracy, which is closely related to the mentioned investigated parameters.

The aim of the research is not only to find the parameters for the optimal machine setting but also to find out the dependence of the machine parameter setting on the resulting accuracy of the part.

2 Material and methods

The experiments were carried out on a laser cutting machine with fiber laser technology labeled Fiber laser MFSCo 1001.20L (fig. 1). Technical parameters of the machine: max. movement speed of the X (Y) axis 130 m/min, max. the synchronous speed of the X and

Y axes is 183 m/min, max. axis acceleration 10 m/s^2, max. acceleration usable during cutting 2 m/s^2, repeatable positioning accuracy 0.03 mm, effective cutting area (1.5 x 3) m, and weight of support with cutting head 80 kg. The machine has installed a direct cutting head from the manufacturer HighYag-FSC-Bimo2. The source of the fiber laser is the company IPG Photonics with the designation YLS-6000-CUT.

Fig. 1 Fiber laser MFSCo 1001.20L.

A technical drawing was created with the nominal dimensions of the part (fig. 2). Subsequently, a dxf format file was generated to create a cutting plan for laser cutting in the Asper program.

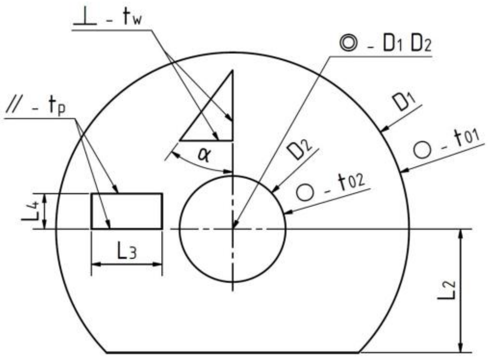


Fig. 2 Graphical representation of the cut part and dependent variables.

The material of part S235JRG2 is non-alloy structural steel of usual quality and weldable. It is used, for example, in the production of welded structures, for the construction of halls, buildings, bridges, etc., less stressed machine parts, and it is also used for supporting structures of machines. The chemical composition of the material is shown in tab. 1.

Tab. 1 Chemical composition of material S235JRG2 for thickness ≤ 16 mm [10]

Chemical elements max. %	C	Mn	Si	P	S	N
	0,17	1,40	-	0,045	0,045	0,009

The factors (cutting speed, gas pressure, and focal point position) were determined in three levels, tab. 2. The experiment was carried out using design 3^3, i.e. the experimental layout using the L27 orthogonal field, tab. 2. When choosing the levels of the factors, the initialization of the cutting process and a minimal but sufficient cutting gap needed to be created.

Table 2 Proposed levels of the independent variables

FACTORS		FACTOR LEVELS		
		-1	**0**	**+1**
Cutting speed (mm/min)	**C**	2900	3200	3400
Gas pressure (bar)	**B**	0.50	0.60	0.70
Location of focus (mm)	**A**	6	7	9

Constants:

- Material thickness: 5 mm
- Material type: steel S235JRG2 (11 375)
- Technology: IPG YLS-6000-CUT laser
- Power: 3 kW
- Gas type: oxygen purity 99.95%
- Machine: Fiber laser MFSCo 1001.20L

From the point of view of statistical processing of measured data and their validation, each setup had six replications. Although the experiment was carried out on the same machine, the same type of material was cut, even so, we cannot talk about repeating the setup. This is because we are not able to guarantee, for example: the absolute homogeneity of the material in the entire volume. So, in such a case, we are not talking about repetitions of settings, but about their replications, Fig. 3.

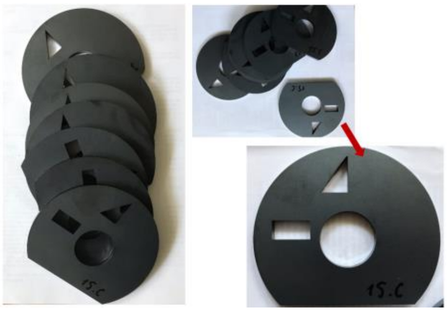


Fig. 3 Experimentally produced sample at setting no. 15 levels of factors.

3 Analysis of measured data

The measurements were carried out using a digital measuring system 7500 with an IM-7030 measuring head from Keyence. The system enables image measurement and light probe measurement. The field of view for image measurement can be set in two modes: wide field of view mode (300mm x 200mm or 4 x R50) and high precision measurement mode (225mm x 125mm). When measuring the image, the minimum displayed unit is 0.1 μm. The measurement accuracy (±2σ) for the wide field of view mode is ± 5 μm, the repeatability is ± 1 μm, and in the high precision measurement mode ± 2 μm, the measurement repeatability is ± 0.5 μm. [11], [12] When measuring responses, the image measurement mode was selected without moving the inspection surface. The responses of each experimental sample were measured separately in high-precision measurement mode without movement of the inspection surface.

The diameter of the outer circle has a nominal dimension of 100 mm, designation D1, fig. 4. In the measuring program, 130 reference points at approximately equal intervals were selected. Using the method of least squares, the software automatically evaluates the diameter of the circle.

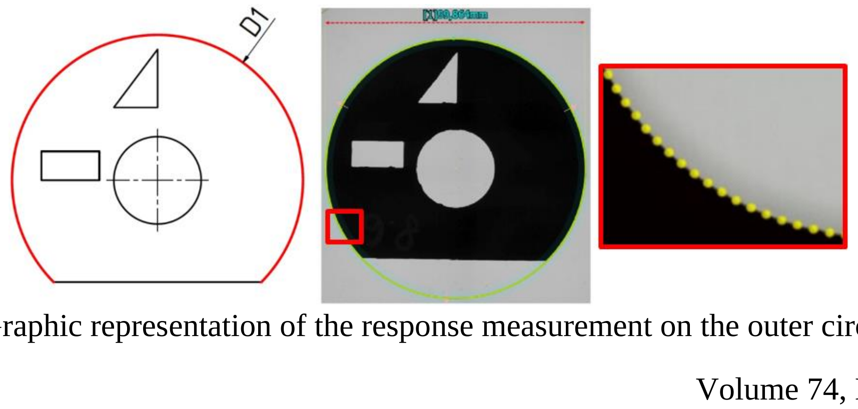


Fig. 4 Graphic representation of the response measurement on the outer circle D1.

The maximum value of the deviation of the diameter D1 of the outer circle was measured at setting no. 26, replication 1, at -0.249 mm. Where the experiment factors were set as focus position 9 mm (level 1), gas pressure 0.70 bar (level 1), and cutting speed 3200 mm/min (level 0). The highest positive deviation has a value of 0.073 mm and was measured at setting no. 7, replication no. 6. At this setting, the factors were: focus position 6 mm (level -1), gas pressure 0.70 bar (level 1), and cutting speed 3400 mm/min (level 1).

The diameter of the inner circle has a nominal size of 30 mm, designation D2, fig. 5. In the measurement program, 15 reference points were selected at approximately equal intervals.

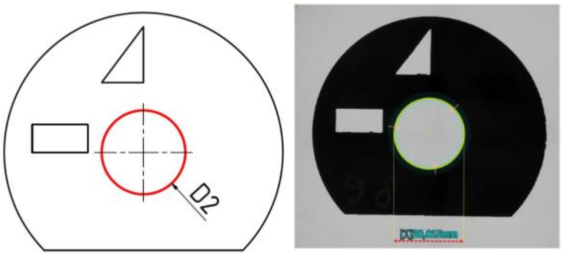
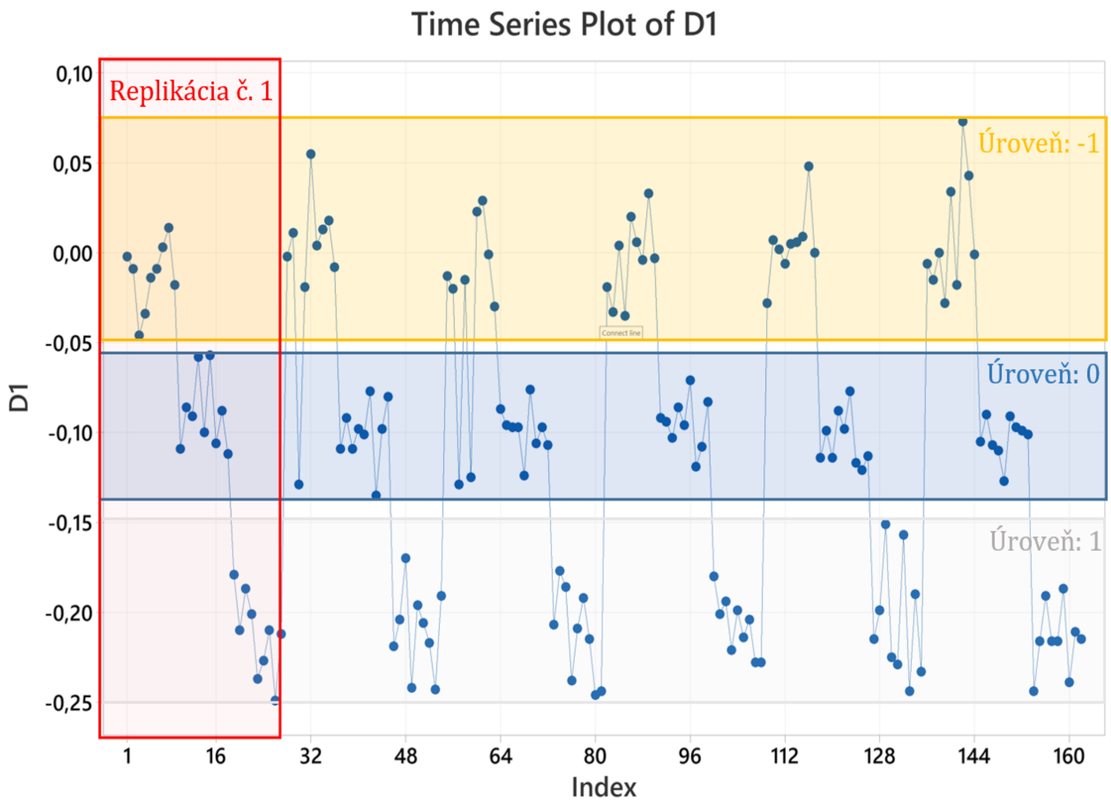


Fig. 4 Graphic representation of the response measurement on the inner circle D2.

The maximum value of the deviation of the diameter D2 of the inner circle was measured at setting no. 12, replication 6, at -0.232 mm. Where the experiment factors were set as focus position 7 mm (level 0), gas pressure 0.50 bar (level -1), and cutting speed 3400 mm/min (level 1). The highest positive deviation has a value of 0.125 mm and was measured at setting no. 25, replication no. 6. At this setting, the factors were: focus position 9 mm (level 1), gas pressure 0.70 bar (level 1), and cutting speed 2900 mm/min (level -1).

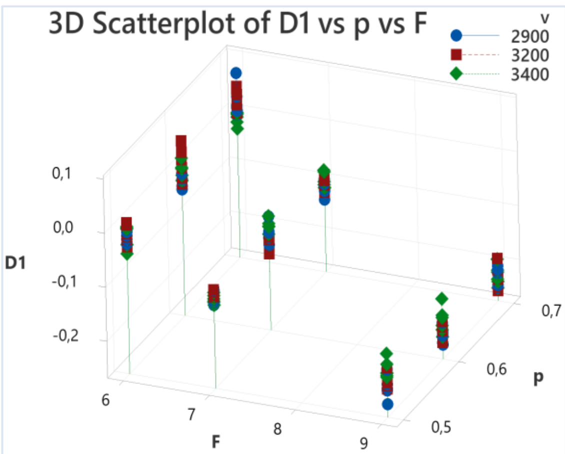
It is interesting to observe the responses when the factors are set at the O level, which is the manufacturer's recommendation for optimal machine settings. For example, when evaluating the deviation of the diameter D1 of the outer circle (graph 1), when setting the factors at level O, the deviations oscillated around the value of -0.10 mm.



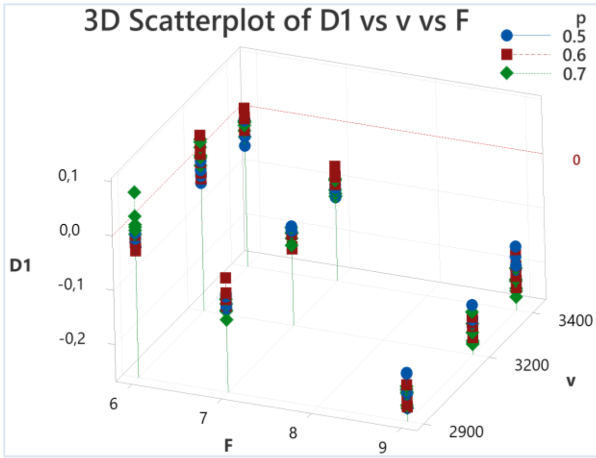
Graph 1 Observation of measurement results at response D1.

Before the investigation itself, with the help of statistical evaluation, it is possible to follow the connections between the response values and the individual levels of setting the factors, using 3D graphs. The focus position factor is denoted as **F**, the gas pressure is **p** and the cutting speed is denoted by the letter **v**. The values of the setting of the third factor, to which we can relate the visualized data and observe the dispersion of the data concerning this parameter, are distinguished by color. The blue color shows the parameter setting at the lowest level of -1, and the green color is the highest setting level of +1.

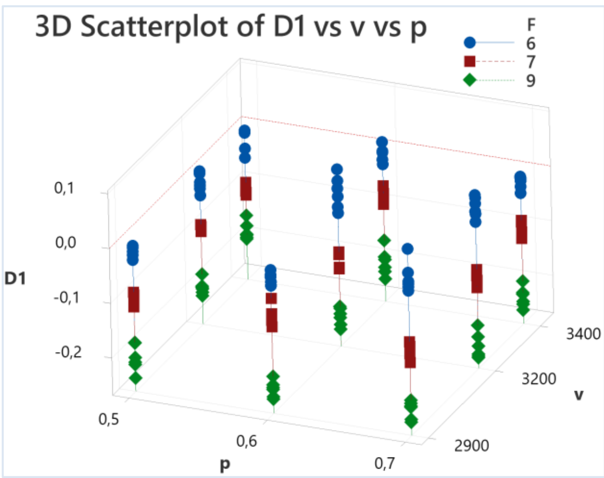
When observing the results of the deviations D1 of the diameter of the outer circle (graph 2), we see that the greatest dispersion of data is observed in the evaluation concerning the F factor – the position of the focal point (graph 15 c). It is also possible to observe that concerning the cutting speed (graph 2 a), the lowest values of deviations are recorded at the focus position of 6 mm, and as the distance of the focus position increases, the deviation increases in the negative direction. The smallest dispersion of data concerning the cutting speed is observed at a focus position of 7 mm and a gas pressure of 0.50 bar. If we look at the data (deviations D1) concerning the gas pressure (graph 2 b), then the smallest data dispersion is visible when the focus position is set to 7 mm and the cutting speed is 3200 mm/min. At the same time, however, with this setting, the deviations of D1 are not at their lowest values. The lowest values of deviations are observed again when the focus position is set to 6 mm. If we complete the overall picture by distributing the data concerning the position of the focus (graph 2 c), when the data has the largest dispersion, we can conclude that with the increasing value of the position of the focus, the size of the deviation D1 of the outer circle increases.



a



b



c

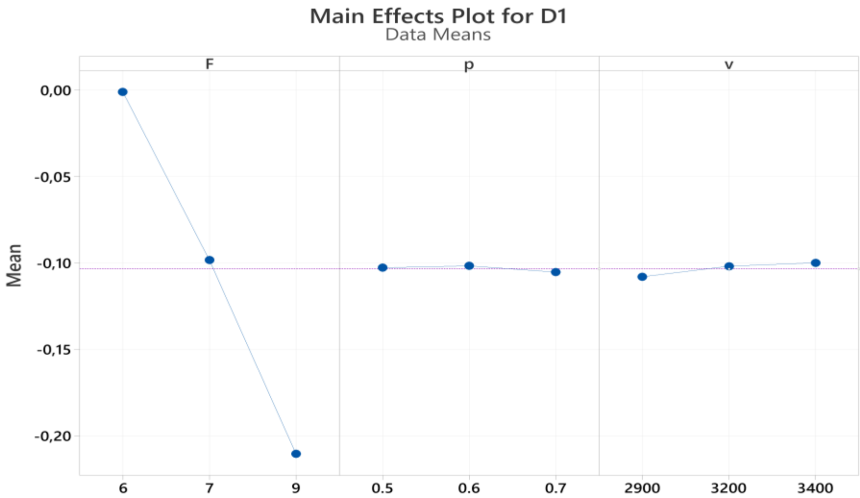
Graph *2* Observation of measurement results at response D1

Data were analyzed using a full factorial design, table 3. With six replications in one run, the total number of runs is 162.

Table 3 Summary of the full factorial design of the data evaluation

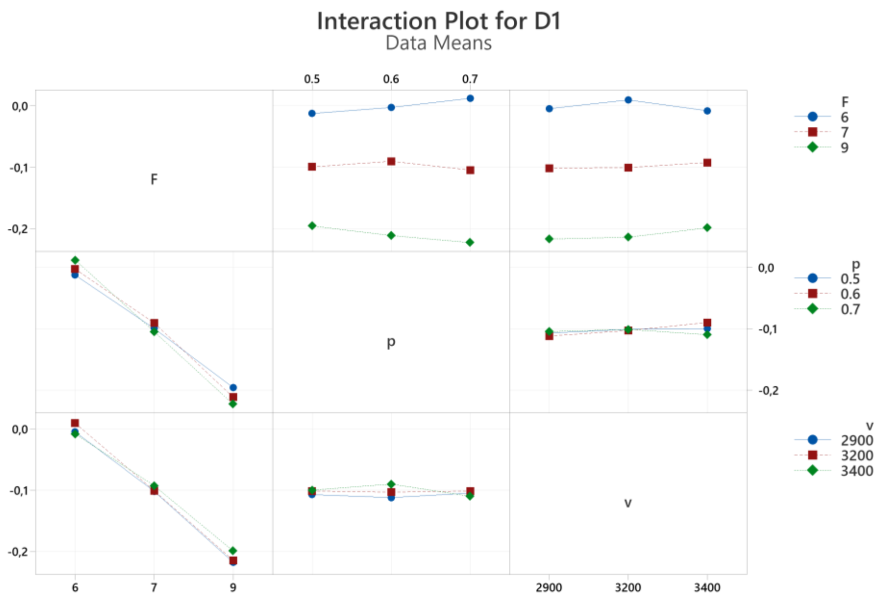
Factors:	3	Replicates:	6
Base runs:	27	Total runs:	162
Base blocks:	1	Total blocks:	6

Graph 3 shows the average value of the response and also the main effects of the individual factors of the experiment for the response D1, i.e. the diameter of the outer circle. As can be seen, the factor F has the greatest influence. When evaluating this factor, it turns out that the smallest values of the deviation D1 of the outer circle were achieved approximately at the setting of F = 6 mm.



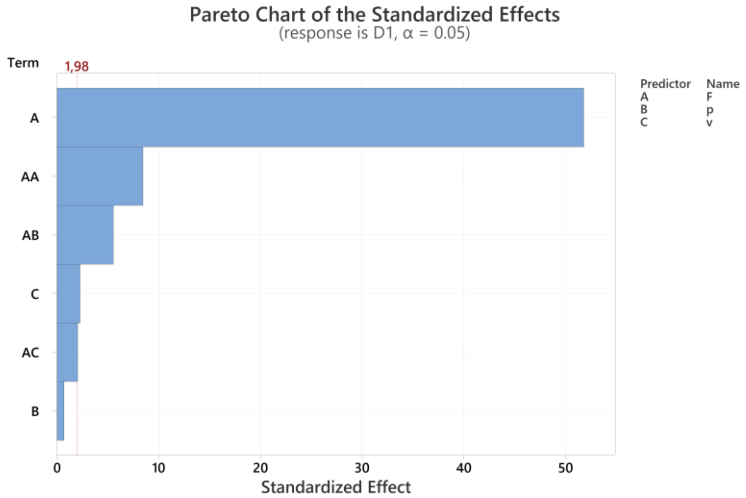
Graph 3 Main effects plot for response D1

The effects of the interactions of the factors can be observed from the graph of 4 interactions of the investigated factors. For the D1 response, it can be seen that factor F has a clear influence on the response, while the interactions between the factors are low. Interactions of factors F*p and F*v are observable.



Graph 4 Factor interaction effects for the D1 response

To compare the relative size and statistical significance of the factors, the Pareto diagram was used (graph 5). The reference value in Chart 5 indicates which factors or their interactions are significant. While the significance level for drawing a reference line is α=0.05.



Graph 5 Pareto diagram of standardized effects for response D1

As seen in Table 4, the p-value (p=0.493) for the p-factor gas pressure is greater than the significance level, indicating that there is no statistically significant association between the D1 response and the p-factor gas pressure. However, it is not possible to exclude this factor from the model and claim that it is not significant due to the influence on the observed response when in the interactions from the focus positions (F*p) we can conclude that there is a statistically significant connection between the response D1 and by F*p interaction.

Table 4 Statistical significance of factors and their interactions

Term	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant	-0.12470	0.00295	(-0.13052, -0.11888)	-42.31	0.000	
F	-0.09302	0.00180	(-0.09657, -0.08947)	-51.79	0.000	1.41
p	-0.00104	0.00151	(-0.00403, 0.00195)	-0.69	0.493	1.00
v	0.00340	0.00151	(0.00041, 0.00638)	2.25	0.026	1.00
F*F	0.02155	0.00255	(0.01651, 0.02658)	8.46	0.000	1.41
F*p	-0.00840	0.00152	(-0.01140, -0.00540)	-5.54	0.000	1.00
F*v	0.00307	0.00152	(0.00007, 0.00606)	2.02	0.045	1.00

You can use a regression equation to describe the relationship between the response and the terms in the model (equation 1).

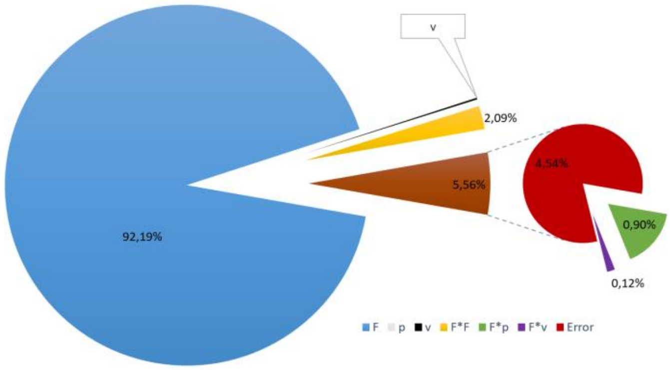
$$D1 = 1{,}032 - 0{,}2647 \cdot F + 0{,}589 \cdot p - 0{,}000071 \cdot v + 0{,}01377 \cdot F^2 - 0{,}0820 \cdot F \cdot p + 0{,}000012 \cdot F \cdot p \tag{1}$$

Table 5 contains a summary of the model, from which it is possible to find out how well the model fits the measured data.

Table 5 Summary of the model

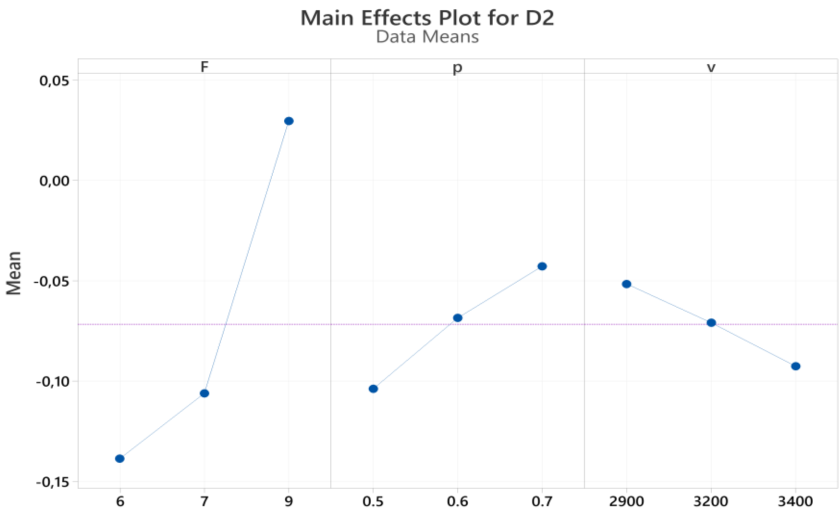
S	R-sq	R-sq(adj)	PRESS	R-sq(pred)	AICc	BIC
0.0191844	95.46%	95.28%	0.0624574	95.03%	-811.46	-787.70

From the summary table of the model (table 5) it can be seen that the coefficient of multivariate determination R2 = 95.46%, so we can conclude that at the level of significance α=0.05 the regression model fits the response data D1 to 95.46%, graphically shown on graph 6.



Graph 6 Graphical representation of the results of the variance analysis for response D1

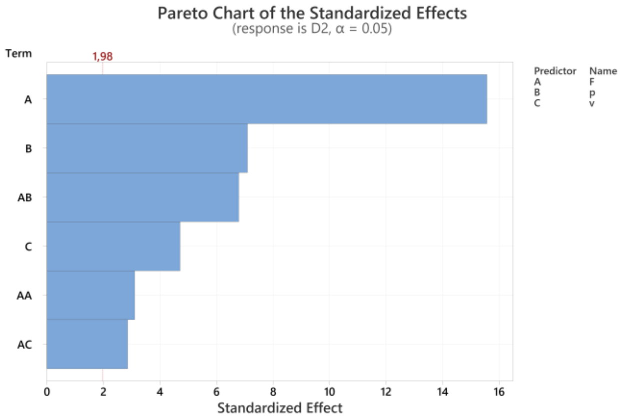
As can be seen from Graph 7, even with this response, the F factor has the greatest influence. It turns out that there is a more pronounced effect between the 7mm and 9mm focal position settings than between the 6mm and 7mm settings. The other two factors p and v also affect the D2 response. The lowest values of deviation D2 were recorded at the setting of p=0.70 bar and v=2900mm/min.



Graph 7 Main effects plot for response D2

Graph 8 Factor interaction effects for D2 response

From graph 8 of the interactions of the examined factors, in response to D2, it can be seen that factor F has a clear influence, while it is possible to observe the interactions of factors F*p and F*v. The Pareto diagram (graph 9) shows which factors and factor interactions are statistically significant at α=0.05.



Graph 9 Pareto diagram of standardized effects for response D2

Regression equation for response D2, (equation 2):

$$D2 = 0{,}356 - 0{,}1373 \cdot F - 1{,}413 \cdot p + 0{,}01177 \cdot F^2 + 0{,}2343 \cdot F \cdot p - 0{,}000039 \cdot F \cdot v \tag{2}$$

Table 6 Model summary for response D2

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)	AICc	BIC
0.0447480	78.18%	77.34%	0.337969	76.24%	-537.05	-513.29

4 Results and discussion

From the statistical analysis of the data, a regression equation (1) was determined for the response D1, the diameter of the outer circle. The regression model at the level of significance α=0.05 covers 95.46% of the investigated data of response D1. It was proven that the gas pressure factor "p" is not statistically significant (p=0.493), we will recalculate the approximation equation (3), then:

$$D1 = 0{,}9408 - 0{,}2396 \cdot \mathrm{F} + 0{,}01377 \cdot F^2 + 0{,}492 \cdot p - 0{,}0820 \cdot F \cdot p + 3{,}9693 \cdot 10^6 \cdot F \cdot v \tag{3}$$

The statistical significance of the interaction of the factors focus position and cutting speed F*v at the significance level α=0.05 is p=0.044. The percentage contribution of the influence of the F*v interaction on the regression model is 0.12%. Thus, it can be argued that the value of the coefficient is small and also has little influence on the values. For this reason, we will neglect the influence of the interaction F*v, and we can recalculate the regression equation (4):

$$D1 = 0{,}9408 - 0{,}2396 \cdot \mathrm{F} + 0{,}01377 \cdot F^2 + 0{,}492 \cdot p - 0{,}0820 \cdot F \cdot p \tag{4}$$

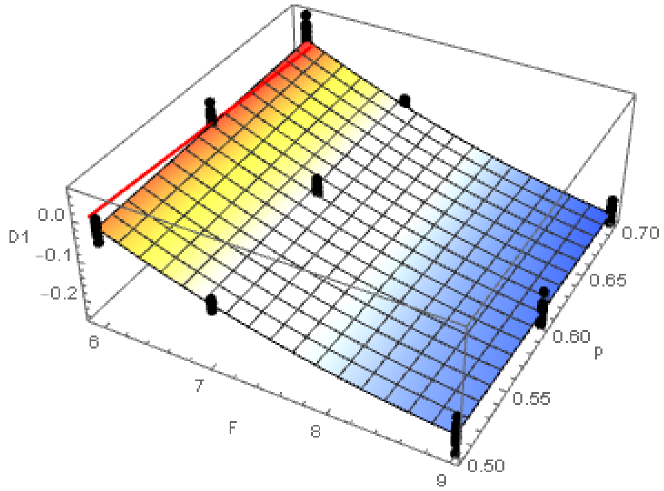
Then, the zero deviation of the response D1 occurs at dependence (5):

$$p = \frac{0{,}9408 - 0{,}2396 \cdot \mathrm{F} + 0{,}01377 \cdot F^2}{0{,}492 - 0{,}0820 \cdot F} \tag{5}$$

From the dependence, within the approximate data, it is possible to determine the value of setting the experiment factors to achieve zero deviation of the diameter D1, as follows:

focus position F = 6 mm, gas pressure p=0.61 bar.

The dependence for zero deviation D1 is represented by the red curve on graph 10 of the approximate mathematical model with parametric lines for the response deviation D1 - the diameter of the outer circle of the experimental sample with nominal size D1=100 mm. The graph shows all the response data of D1 concerning the cutting speed, the influence of v is negligible. We can also observe a small influence of the gas pressure P. The most significant influence on the size of the deviation of the nominal diameter D1 is the position of the focus F. As the distance of the focus position F increases, the deviation D1 increases in the negative direction.

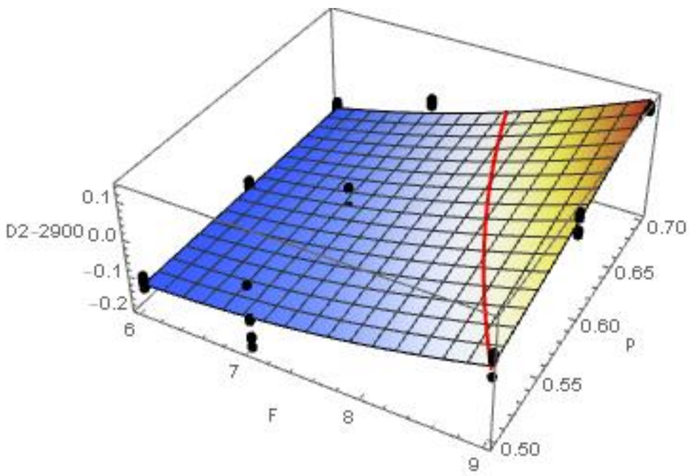


Graph 10 Graphic representation of the mathematical model of the approximate response data D1

The regression model (2) for the response D2, the diameter of the inner circle, at the level of significance α=0.05 covers the investigated data of the response D2 to 78.18%. After adjusting the equation (2), the zero deviation of the D2 response occurs at dependence (6):

$$p = \frac{-0{,}356 + 0{,}1373 \cdot \mathrm{F} - 0{,}01177 \cdot F^2 - 0{,}000206 \cdot v + 0{,}000039 \cdot F \cdot v}{-1{,}413 + 0{,}234 \cdot F} \tag{6}$$

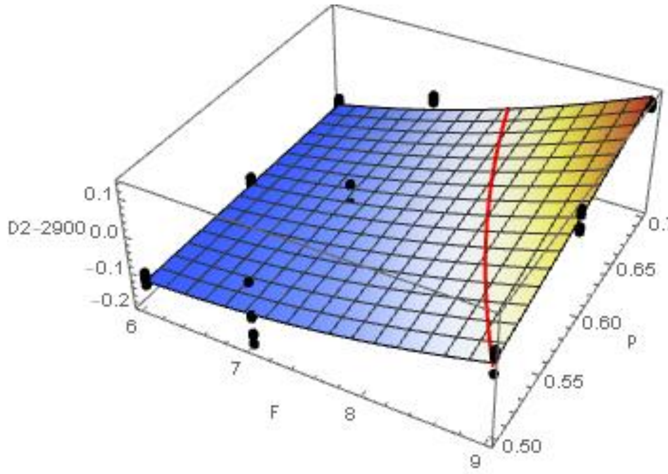
If the variability of the data increases, it affects the entire regression model. The influence of the factor must take into account the internal variability. For better readability of the resulting mathematical model, the data were divided into groups based on the levels of the cutting speed setting.



Graph 11 Graphical representation of the mathematical model of the approximate response data D2 for the set of data in the setting v=2900 mm/min

From the dependence, within the approximate data, it is possible to determine the value of setting the experiment factors to achieve zero deviation of the average D2, according to graph 11, as follows:

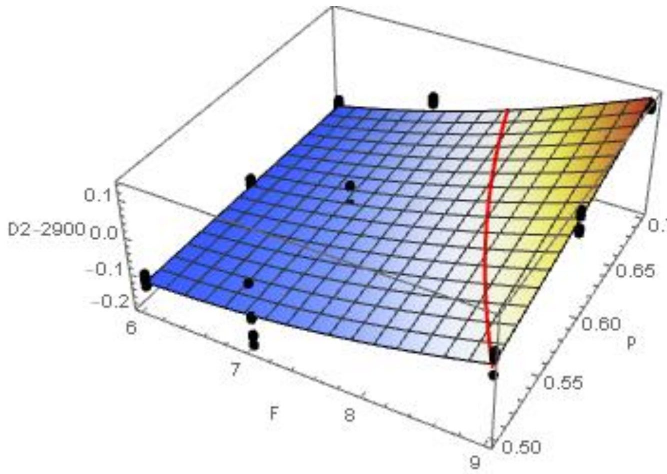
focus position F=8 mm, gas pressure p=0.64 bar, at cutting speed v=2900 mm/min.



Graph 12 Graphical representation of the mathematical model of the approximate response data D2 for the group of data in the setting v=3200 mm/min

From the dependence, within the approximate data, it is possible to determine the value of setting the experiment factors to achieve a zero deviation of the average D2, according to graph 12 as follows:

focus position F=8,5 mm, gas pressure p=0.63 bar, at cutting speed v=3200 mm/min.



Graph 13 Graphical representation of the mathematical model of the approximate response data D2 for the set of data in the setting v=3400 mm/min

From the dependence, within the approximate data, it is possible to determine the value of setting the experiment factors to achieve zero deviation of the average D2, according to graph 13, as follows:

focus position F=8,5 mm, gas pressure p=0.67 bar, at cutting speed v=3400 mm/min.

The dependence for zero deviation D2 is represented by the red curve on graphs 11, 12, and 13 of the approximate mathematical model with parametric lines for the response D2 – the diameter of the inner circle of the experimental sample with nominal dimension D1=30 mm. The graphs show groups of D2 response data concerning cutting speed. It can be concluded that within the ranges of setting the experiment factors when cutting a circle with a diameter of 30 mm, the size of the deviation of the nominal dimension is influenced by the cutting speed. With the increasing cutting speed and the requirement of zero deviation, the diameter also increases, the distance of the focus position increases, and the value of the gas pressure increases.

We found that the settings recommended by the machine manufacturer for cutting S235JRG2 non-alloy structural steel, namely: cutting speed 3200 mm/min, gas pressure 0.60 bar, and focal position 7 mm, can be optimized to achieve zero deviation as follows:

- for a diameter of 100 mm (larger holes, contours), the cutting speed remains at the value v=3200 mm/min, increase the gas pressure slightly to the value p=0.61 bar and change the focus position to F=6 mm,
- for a diameter of 30 mm (smaller holes) with the maintained cutting speed v=3200 mm.min-1, it is necessary to slightly increase the gas pressure to the value p=0.63 bar and change the focus position to F=8.5 mm. It is also possible to increase the cutting speed to the value v=3400 mm.min-1 and then change the gas pressure to p=0.67 bar, while the focus position remains at the value F=8.5 mm.

CONCLUSION

The obtained functions of dependence on the parameters of the machine are the basis for the creation of the correction of the control system of the machine. This contributes to expanding the knowledge base when testing the accuracy of newly produced fiber laser-cutting machines. And it can be machines with different kinematics. And it is also a contribution to the solution of the strategic long-term goal, which is the creation of a global auto-calibration system. Such a system should enable the automatic, optimal setting of the machine before cutting about the thickness of the sheet metal, the size, and the shape of the part to be cut so that its resulting accuracy meets the defined standard. The results of the investigation can be particularly significant in the production of large-scale machines, used for example in shipyards, which are intended for cutting welded sheets of various thicknesses.

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