

EXPERIMENTAL INVESTIGATION AND OPTIMIZATION OF FIBER LASER CUTTING PARAMETERS FOR STAINLESS STEEL AISI 304

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Abstract: The aim of this study is to analyze the effect of selected technological parameters in fiber laser cutting, specifically cutting speed, focal position, and assist gas pressure, on the dimensional and geometrical accuracy of thin stainless steel sheets. An experimental design methodology is applied to determine parameter combinations that reduce deviations from the desired dimensions. Using statistical evaluation and regression modelling, optimal process settings for the given material are established. The findings indicate that cutting speed and focal position play a key role in determining cutting accuracy, while their mutual interaction has a significant impact on process stability. The presented methodology provides a foundation for the systematic optimization of fiber laser cutting conditions.

KEYWORDS: fiber laser cutting, process parameter optimization, cutting speed, laser power, laser focal length, dimensional deviation

1 Introduction

Laser cutting represents a commonly applied technology in contemporary manufacturing, mainly due to its high accuracy, operational flexibility, and capability to process various metallic materials with minimal mechanical influence on the workpiece. Nevertheless, the resulting quality of laser-cut components largely depends on the correct adjustment of process parameters, including laser power, cutting speed, assist gas pressure, and focal position. Inadequate parameter settings may lead to increased surface roughness, excessive kerf width, dimensional inaccuracies, or an enlarged heat-affected zone, which negatively affect the functional and aesthetic properties of the manufactured components.

Based on the scientific studies presented in [1], [2], [3], [4], [5], [6], [7], [8] and [9], it can be concluded that the machine parameter settings recommended by manufacturers for a given material type or thickness do not always ensure optimal cutting performance.

In the cutting of stainless steel using a CO₂ laser [1], researchers have applied design of experiments (DOE) combined with quantitative statistical tools, namely the analysis of variance (ANOVA) and response surface modelling techniques (RSM) to analyse the influence of laser power, cutting speed, and gas pressure on surface roughness and kerf geometry. The findings indicate that laser power and cutting speed are the primary factors influencing surface quality, whereas assist gas pressure exerts a secondary, yet still significant, effect on kerf width and the removal of molten material.

Similar optimization approaches have been applied to aluminium laser cutting processes [2]. Using the Taguchi method and orthogonal arrays, studies have examined the effects of laser power, cutting speed, pulse frequency, and assist gas pressure on key quality indicators,

including kerf width, surface roughness, and heat-affected zone. Experimental results confirmed that appropriate parameter optimization leads to a significant reduction in all quality indicators compared to initial machine settings, highlighting the effectiveness of statistical optimization methods in laser cutting applications.

One of the major challenges in laser cutting is the improper adjustment of technological parameters, which can significantly deteriorate surface quality of the cut. Inappropriate parameter combinations often result in surface defects, most commonly the formation of burrs. Study [3] focuses on the optimization of the fiber laser cutting process using parameters initially recommended by the machine manufacturer, specifically laser power, cutting speed, and assist gas pressure. The initial trials were carried out using recommended parameter values for stainless steel (laser power of 4 kW, cutting speed of $20 \text{ m} \cdot \text{min}^{-1}$, and gas pressure of 15 bar). The experimental study focused on AISI 316L stainless steel and cold-rolled St12 low-carbon steel. Subsequently, the cutting parameters were systematically modified relative to the manufacturer's recommendations. While the laser power was reduced in two levels due to machine limitations, the cutting speed was increased in two steps. The gas pressure was reduced to the next lower level, as further reduction led to unacceptable cut quality. The results demonstrated that the highest cutting surface quality is not necessarily achieved using manufacturer-recommended parameter values. For AISI 316L stainless steel, optimal burr reduction was obtained at a gas pressure of 15 bar, cutting speed of $10 \text{ m} \cdot \text{min}^{-1}$, and laser power of 3.5 kW, with gas pressure identified as the most influential parameter. In contrast, when surface roughness was considered, cutting speed had the dominant effect, requiring an increase to $25 \text{ m} \cdot \text{min}^{-1}$ for optimal results.

Further research [4] employing the Taguchi method has investigated the influence of laser cutting parameters on surface roughness during CO_2 laser cutting of stainless steel. These studies identified cutting speed as the most significant factor affecting surface roughness, followed by laser power and focal position, while the influence of assist gas pressure was found to be negligible within the investigated parameter range. In addition, interaction effects between process parameters were shown to have a substantial impact on surface quality, in some cases exceeding the influence of individual parameters.

Although numerous studies have addressed surface roughness, kerf geometry, and heat-affected zones in laser cutting, relatively less attention has been paid to the systematic evaluation of dimensional and geometric accuracy of laser-cut parts, particularly in the context of fiber laser cutting. Moreover, existing research confirms that the significance of individual process parameters strongly depends on the material type, thickness, and laser source used. Therefore, further experimental investigations are required to establish optimized parameter settings that ensure high dimensional accuracy and process stability.

This study seeks to address the identified research gap by examining the effect of selected technological parameters in fiber laser cutting on the dimensional accuracy of thin stainless steel sheets. A statistically designed experimental approach, combined with a quantitative assessment of dimensional deviations, is employed to determine optimal process settings. The obtained results are intended to enhance cutting precision and provide support for the systematic optimization of parameters in industrial laser cutting applications.

2 Material and methods

The experimental study was carried out using a fiber laser cutting system identified as Fiber Laser MFSCo. 1001.20L from company MicroStep a.s. [11], shown in Fig. 1. The machine is characterized by a maximum travel speed of $130 \text{ m} \cdot \text{min}^{-1}$ along the X and Y axes, while the maximum synchronized speed of both axes reaches $183 \text{ m} \cdot \text{min}^{-1}$. The maximum axis

acceleration is $10 \text{ m}\cdot\text{s}^{-2}$, with an effective acceleration during cutting limited to $2 \text{ m}\cdot\text{s}^{-2}$. The system provides a repeatable positioning accuracy of 0.03 mm and an effective working area of $1.5 \times 3 \text{ m}$. The mass of the cutting head assembly is 80 kg . The machine is fitted with a direct cutting head provided by HighYag (type FSC-Bimo2). The fiber laser source, produced by IPG Photonics, is designated as YLS-6000-CUT.



Fig. 1 Fiber laser MFSCo 1001.20L

First, a technical drawing with the specified nominal dimensions of the part was developed (fig. 2). Based on this, a DXF file was produced and subsequently utilized to define the cutting layout within the Asper program.

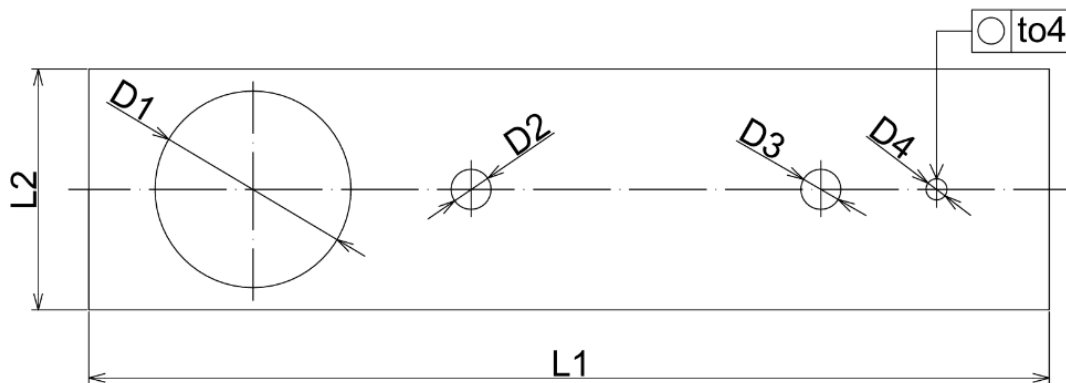


Fig. 2 Graphical representation of the cut part and dependent variables

AISI 304 belongs to the group of widely applied austenitic stainless steels, valued for its excellent resistance to corrosion and solid mechanical performance. The alloy contains about 18% chromium and 8% nickel, contributing to its enhanced resistance to oxidation and aggressive chemical environments. The material exhibits good formability and weldability, making it suitable for a wide range of industrial applications. AISI 304 is commonly used in the food, chemical, and automotive industries, as well as in structural and decorative components. The steel maintains good toughness and ductility over a wide temperature range.

Therefore, careful optimization of laser cutting parameters is required to achieve high-quality cut edges when processing AISI 304 stainless steel.

The factors (cutting speed, gas pressure, and focal point position) were determined in three levels, tab. 1. The experiment was carried out using design 3^3 , i.e. the experimental layout using the L27 orthogonal field, tab. 1. 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 1 *Defined levels of the input variables*

FACTORS		FACTOR LEVELS		
		-1	0	+1
Cutting speed (mm/min)	C	10 000	20 000	30 000
Gas pressure (bar)	B	6	10	14
Location of focus (mm)	A	0	0.5	1

Constants:

- Material thickness: 1 mm
- Material type: AISI 304
- Technology: IPG YLS-6000-CUT laser
- Power: 3 kW
- Gas type: oxygen purity 99.95%
- Machine: Fiber laser MFSCo 1001.20L

From the viewpoint of statistical evaluation of the measured data, each parameter setting was tested using six replications. Even though all experiments were performed on the same machine and the same type of material, the tests cannot be considered exact repetitions. This is mainly due to the fact that material homogeneity cannot be guaranteed throughout the entire volume. Therefore, the individual tests represent replications of the settings rather than true repetitions. Fig. 3 shows the cut-out material.



Fig. 3 Cut part

3 Analysis of experimental data

The measurements were carried out using a Keyence IM-7500 digital measuring system equipped with an IM-7030 measuring head. [10]. The system enables both image-based and light probe measurement techniques. Image measurements can be performed in two modes: a wide field-of-view mode covering an area of 300 mm × 200 mm and a high-precision mode with a measurement area of 225 mm × 125 mm. In image measurement, the minimum display resolution is 0.1 μm. In the wide field-of-view mode, the measurement accuracy is ±5 μm with

a repeatability of $\pm 1 \mu\text{m}$, whereas the high-precision mode achieves an accuracy of $\pm 2 \mu\text{m}$ and a repeatability of $\pm 0.5 \mu\text{m}$ [10]. For response evaluation, image-based measurement was applied without repositioning the inspected surface. Each experimental specimen was measured separately using the high-precision mode.

The length of side L1 has a nominal size of 200 mm, Fig. 4. For setting No. 19, replication 2, the maximum negative deviation of the L1 length was measured, with a value of -0.131 mm . In this setting, the experimental factors were set to a focal position of 1 mm, gas pressure of 6 bar, and cutting speed of $10,000 \text{ mm}\cdot\text{min}^{-1}$. In contrast, the highest positive deviation of 0.055 mm was recorded for setting No. 9, replication 2. In this case, the focal position was 0 mm, gas pressure was 14 bar, and cutting speed was $10,000 \text{ mm}\cdot\text{min}^{-1}$.

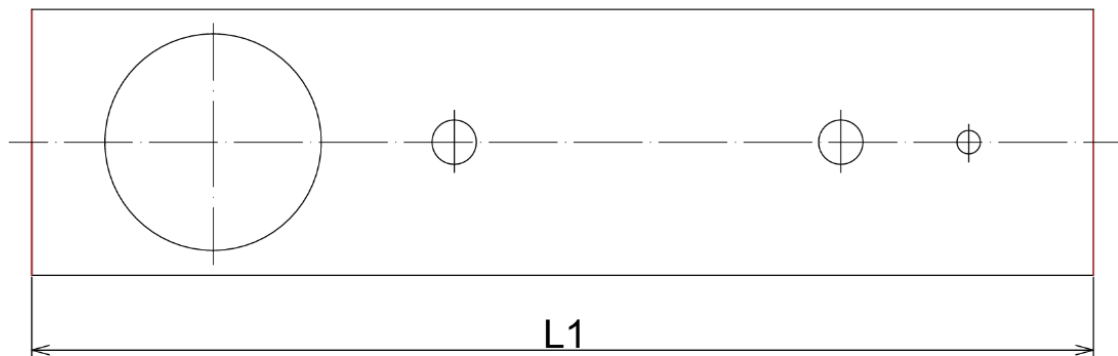


Fig. 4 Visual representation of the L1 response measurement

The largest circle has a nominal diameter of 40 mm, denoted as D1, as shown in fig. 5. For parameter setting No. 1, replication 2, the greatest negative deviation of the D1 diameter was observed, reaching -0.046 mm . Under these conditions, the process parameters were a focal position of 0 mm, assist gas pressure of 6 bar, and a cutting speed of $10,000 \text{ mm}\cdot\text{min}^{-1}$. Conversely, the maximum positive deviation, equal to 0.051 mm , was obtained for setting No. 24, replication 5. In this case, the focal position was set to 1 mm, the gas pressure to 10 bar, and the cutting speed to $30,000 \text{ mm}\cdot\text{min}^{-1}$.

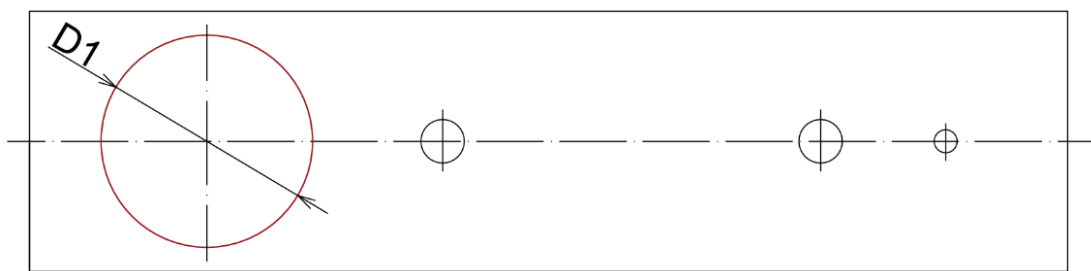


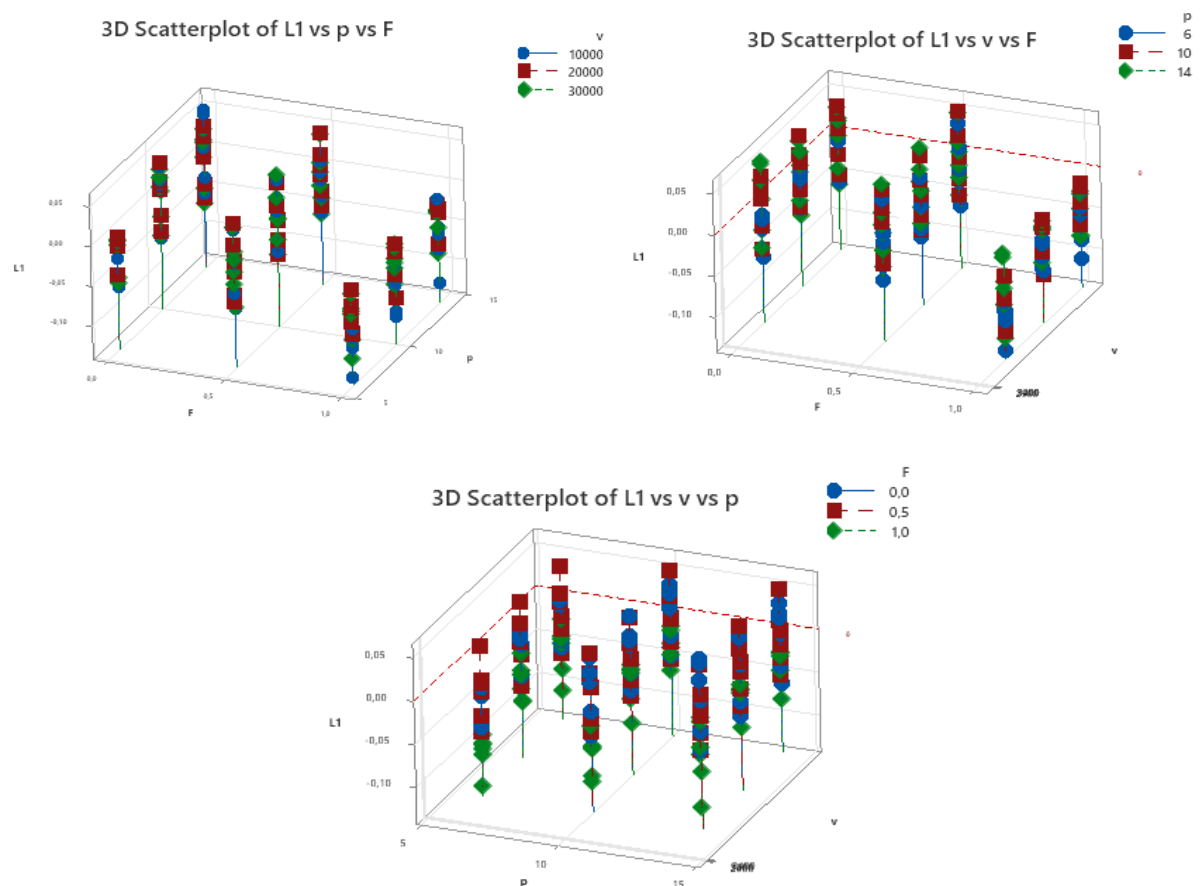
Fig. 5 Graphical illustration of the response for the largest circle D1.

Although both the diameter D1 and the length L1 were evaluated, the length L1 is used as a representative example for describing the evaluation procedure. This approach was chosen due to the large amount of measured data. The complete results for both measured characteristics, D1 and L1, are presented and discussed in the Results and discussion section.

Prior to the main analysis, statistical evaluation enables the identification of relationships between the response variables and the individual factor levels through the use of 3D graphical

representations. The focal position is denoted by **F**, gas pressure by **p**, and cutting speed by **v**. The levels of the third factor, which serve as a reference for interpreting the displayed data and observing their variability with respect to this parameter, are indicated by colour. The blue colour corresponds to the lowest level -1 , while the green colour represents the highest level $+1$.

Based on the deviation measured results of L1 length (graph 1), the largest data dispersion is observed in relation to factor F, which represents the focal position. It can also be seen that, with respect to cutting speed, the lowest deviation values occur at a focal position of 0 mm, while increasing the focal distance leads to an increase in negative deviations. When evaluating the data with respect to gas pressure, the smallest data dispersion is observed at a focal position of 1 mm and a cutting speed of $20,000 \text{ mm} \cdot \text{min}^{-1}$. Under these conditions, the L1 deviations reach their lowest values. Overall, when the results are summarized with respect to the focal position, it can be concluded that an increase in the focal position results in an increase in the deviation of the L1 length.



Graph 1 Analysis of measurement results for response L1

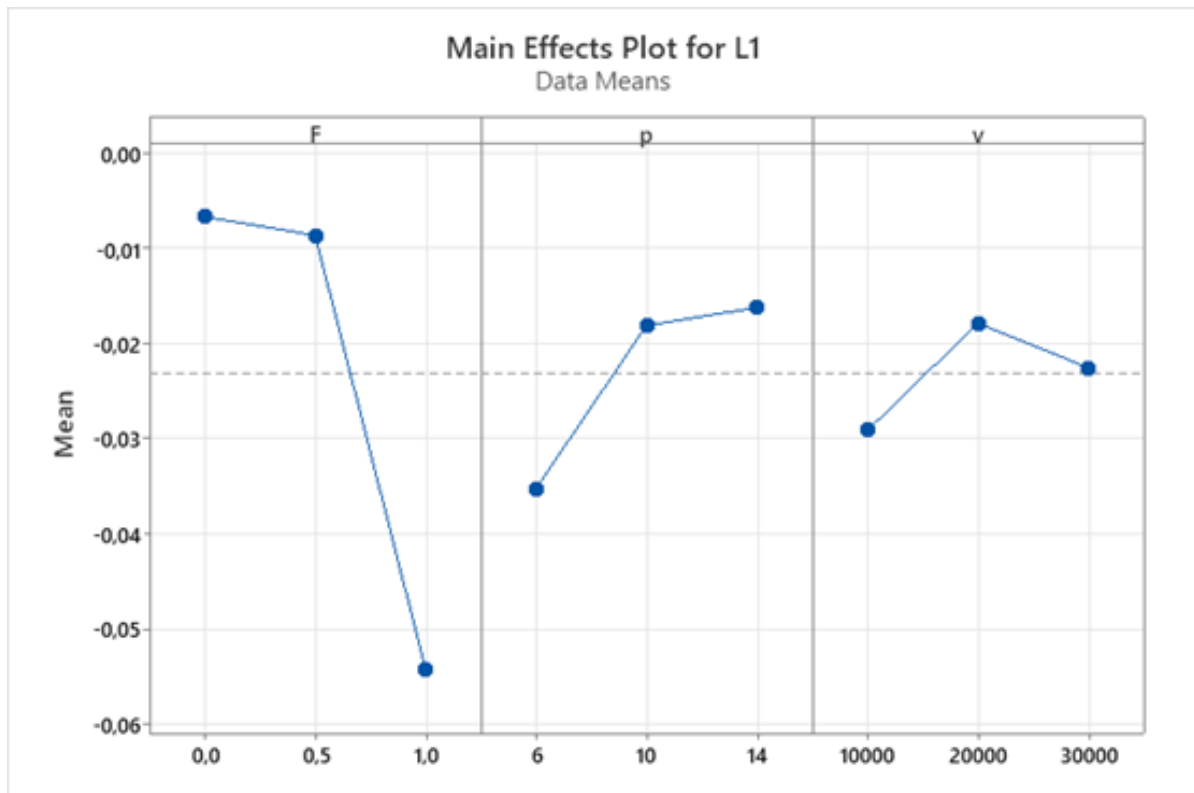
The data were evaluated using a full factorial experimental design, as presented in Table 2. With six replications per run, the total number of experiments amounted to 162.

Graph 2 presents the mean response values together with the main effects of the individual experimental factors for the L1 length. It is evident that factor F has the most significant impact on the response L1. Analysis of this factor shows that the lowest deviations in L1 length were obtained at a focal position of $F = 0 \text{ mm}$.

Table 2 Overview of the full factorial design used for data evaluation

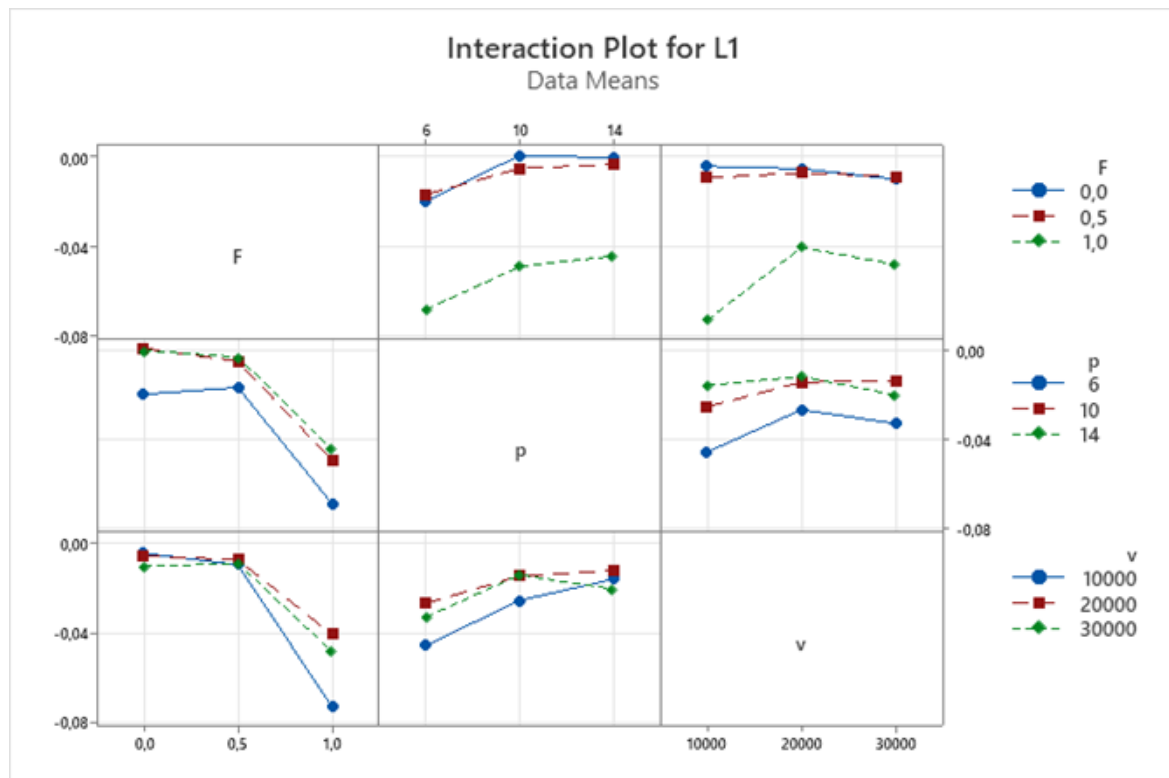
Factors:	3	Replicates:	6
Base runs:	27	Total runs:	162
Base blocks:	1	Total blocks:	6

The influence of factor interactions is illustrated in the interaction plot presented in Graph 5. For the L1 length, factor F can be identified as having the most pronounced effect on the response. At the same time, the results suggest that the overall quality is influenced by all combinations of the examined factors.

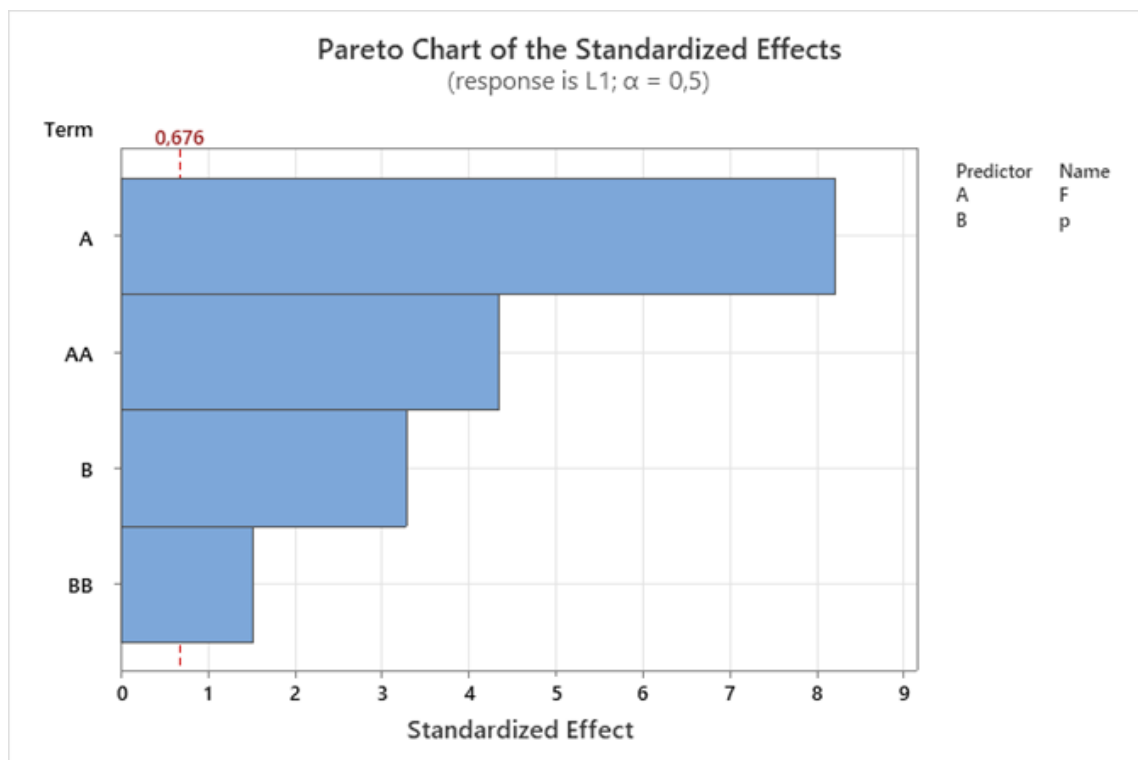


Graph 2 Plot of main effects for L1

A Pareto chart was employed to assess the relative importance and statistical significance of the individual factors.. In the chart, the factors and their interactions are arranged in descending order according to their absolute values. The reference line indicates which factors and factor interactions are statistically significant. The significance level used to define the reference line was $\alpha = 0.5$. From Graph 4, it can be seen that parameter F, representing the focal position, has the greatest effect in the regression model. The remaining parameters and their interactions show smaller, but still significant effects, as they are located beyond the significance reference line.



Graph 3 Effects of factor interactions on response L1



Graph 4 Pareto diagram of standardized effects for the L1 response

As shown in Table 3, the p-value associated with factor F (focal position) is $p = 0.000$, which is lower than the selected significance level ($\alpha = 0.5$). This confirms a statistically significant effect of factor F on response L1. Similarly, factor p (gas pressure) shows a statistically

significant effect on the L1 response with a p-value of 0.001. The interaction FF is also statistically significant, as its p-value equals 0.000, confirming its influence on the response L1. Based on these results, factor F has the strongest impact on the response L1, while gas pressure also contributes significantly to the observed deviations.

Table 3 Statistical significance of factors and their interactions

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	-0.00349	0.00530	-0.66	0.511	
F	-0.01949	0.00238	-8.20	0.000	1.00
p	0.00780	0.00238	3.28	0.001	1.00
F*F	-0.01466	0.00337	-4.35	0.000	1.00
p*p	-0.00512	0.00337	-1.52	0.131	1.00

The relationship between the response variable and the model terms can be described using a regression equation (Equation 1).

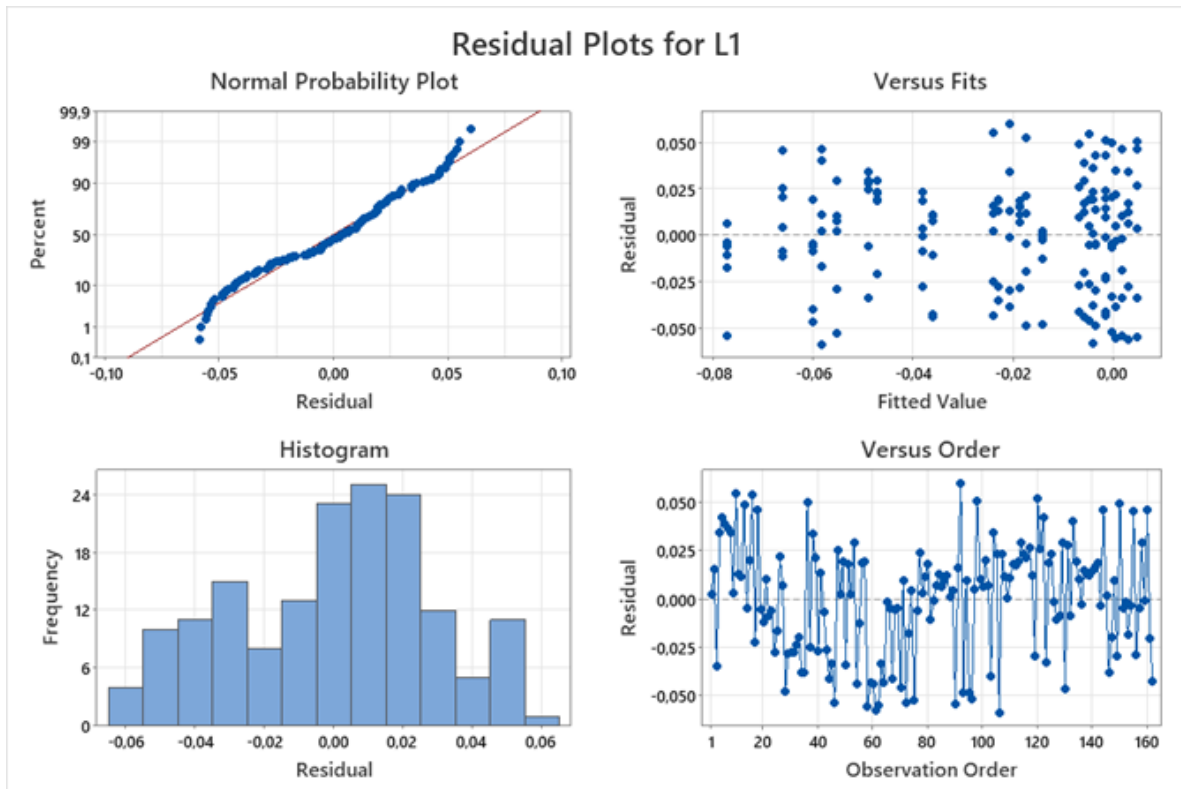
$$L1 = -0.0730 + 0.0398 \cdot F + 0.1192 \cdot p - 0.0874 \cdot F^2 - 0.000477 \cdot p^2 \quad (1)$$

Table 4 contains a summary of the model, from which it is possible to find out how well the model fits the measured data.

Table 4 Model summary

S	R-sq	R-sq(adj)	R-sq(pred)
0,0301487	38,74%	37,17%	34,77%

Graph 5 illustrates the residual plots applied to assess the suitability of the regression model. The residuals are randomly scattered without any evident pattern, suggesting a good fit between the model and the experimental results. The normal probability plot further indicates that the residuals are approximately normally distributed.



Graph 5 Residual graphs for L1

4 Results and discussion

Based on the statistical evaluation of the experimental data, a regression equation was established for response L1, which represents the length of the longest side. In this model, the cutting speed factor v was omitted, as it did not show statistical significance. The resulting regression equation for response L1 is expressed as follows:

$$L1 = -0.0730 + 0.0398 \cdot F + 0.1192 \cdot p - 0.0874 \cdot F^2 - 0.000477 \cdot p^2 \quad (2)$$

Based on the regression model, the condition for zero deviation of the response L1 can be expressed by the following dependence:

$$p = -0.01192 \pm \frac{\sqrt{(-0.01192)^2 - 4 \cdot (0.000477) \cdot (0.0730 - 0.0398 \cdot F + 0.0874 \cdot F^2)}}{2 \cdot (0.000477)} \quad (3)$$

Using the approximated data, it is possible to determine the parameter settings that lead to zero deviation of the L1 length. The derived relationship enables the determination of appropriate combinations of focal position and gas pressure that minimize the deviation from the nominal length L1.

To achieve zero deviation, the parameter settings were determined using the approximated data as follows: focal position $F = 0$ mm and gas pressure $p = 6.122$ bar.

Based on the regression analysis, an equation was derived for response D1, which represents the largest diameter. In this model, the cutting speed factor v was not included, as it lay beyond the significance threshold and was therefore not considered statistically significant. The resulting regression equation for response D1 is expressed as follows:

$$D1 = -0.0379 - 0.0057 \cdot F + 0.0067 \cdot p + 0.04411 \cdot F^2 - 0.00037 p^2 - 0.000569F \cdot p \quad (4)$$

Based on this regression model, the condition for zero deviation of the response D1 can be expressed by the following dependence:

$$p = -0,0067 \pm \frac{\sqrt{(0,0067)^2 - 4 \cdot (-0,00037) \cdot (-0,0379 + 0,04411 \cdot F^2 - 0,0057 \cdot F - 0,000569)}}{2 \cdot (-0,00037)} \quad (5)$$

To achieve zero deviation, the parameter settings were determined using the approximated data as follows: focal position $F = 0$ mm and gas pressure $p = 18.08$ bar.

CONCLUSION

This study examined the effect of selected fiber laser cutting parameters—focal position, assist gas pressure, and cutting speed—on the dimensional accuracy of components made from AISI 304 stainless steel. The deviations in length L1 and diameter D1 were assessed using high-precision optical measurement techniques.

Regression analysis confirmed that the focus position is the dominant factor affecting both responses, while gas pressure also showed a statistically significant influence. Cutting speed was found to be statistically insignificant within the investigated range and was therefore excluded from the final regression models.

The developed regression equations enabled the determination of parameter settings leading to minimal or zero dimensional deviation. The results demonstrate that manufacturer-recommended parameters are not always optimal for achieving high dimensional accuracy and highlight the need for process-specific optimization.

The presented methodology and obtained models provide a basis for the development of automated parameter correction and calibration systems for fiber laser cutting machines, contributing to improved accuracy and process reliability in industrial applications.

ACKNOWLEDGMENTS

This research was funded by the project VEGA 1/0387/24 “Analysis of the HAZ index of carbon fiber reinforces-plastics (CFRP) composites using a Quasi-Continuous Wave (QCW) fiber laser” of the Scientific Grant Agency MŠVVaM SR and SAV (VEGA) and of the Agency for the Promotion of Science and Research for the project "APVV-23-0619 Research of progressive technology of decomposition of glued layered materials" and are one of the implemented activities of the project and the Ministry of Education, Science, Research and Sport of the Slovak Republic.

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