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Optimization of Steel Laser Cutting Processes Using the Roughness Parameter *Sq* and Response Surface Methodology (RSM)

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Abstract

Laser cutting of steel is among the most advanced and competitive technologies in metal processing, widely employed in the automotive, aerospace, construction, and electronics industries, as well as in the production of precision components. Its advantages over traditional methods stem from its high precision, cutting speed, and ability to process complex geometries without requiring any subsequent finishing operations. This study presents research on the influence of fiber laser control parameters on the surface quality of S355J2C+N steel cuts. The primary objective is to identify which laser cutting parameters significantly affect the surface roughness of the cut. The response surface methodology (RSM) was employed for modeling. The *Sq* roughness parameter was selected as the primary metric to assess surface quality. The investigated process control parameters affecting surface roughness included feed rate, focal point position, and peak power. A 2-level split-plot experimental design was used for data analysis, with the focal point position designated as a hard-to-change factor due to the mechanical complexity of optical realignment. A mathematical model of the cutting process was generated. Based on analysis of variance (ANOVA), the model was found to fit the experimental data with an accuracy exceeding 98%. The results indicated that achieving low surface roughness (*Sq*) requires cutting with the lowest possible feed rate, lowest focal point position, and minimal peak power. The use of RSM facilitates the optimization of control parameter selection, contributing to improved surface quality and process efficiency.

Keywords

laser cutting, RSM, process optimization, structural steel, roughness parameter *Sq*

1 Introduction

The current rapid development of technology has enabled the development of a whole group of modern engineering materials such as bimetals [1–3], cast composites, and steels and cast steels for special applications [4, 5]. The production of the material itself causes certain technological problems that need to be solved, but its further processing and shaping, such as laser cutting, poses an additional challenge.

Laser cutting is one of the fastest-growing technologies and is widely implemented in various manufacturing fields. It effectively competes with other material separation methods, such as flame cutting and plasma cutting [6]. Laser cutting has a broad range of applications, including cutting different types of metals (usually up to 25 millimeters), selected polymers, composite materials, as well as conductive and non-conductive materials [7, 8]. This is due to its ability to precisely cut complex components while maintaining high edge accuracy and surface quality after cutting, with a minimal heat-affected zone [8–10]. The surface quality of the cut depends on several factors, including the material being cut [10, 11], the selected cutting parameters: such as laser beam power, assist gas type, feed rate, lens, and focal length [11–13].

In previous studies, to verify whether the selected laser cutting parameters were appropriate, researchers primarily analyzed surface roughness, perpendicularity, kerf width, and the size of the heat-affected zone [9, 10, 12]. In some cases, relevant standards were also considered [14].

For example, in publication [15], surface roughness parameters *Ra*, *Rz*, *Rp*, *Rv*, and *Rt* were used to analyze surfaces obtained through laser and plasma cutting. These parameters were measured both from the side exposed to

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the cutting system and from the opposite side. The analysis of the results demonstrated the superiority of laser cutting over plasma cutting.

In study [16], the influence of selected laser cutting parameters on the surface quality of S235JR steel samples with thicknesses of 10 and 15 millimeters was examined. The roughness parameters *Ra*, *Rq*, *Rz*, *Rk*, *Rpk*, and *Rvk* were used in the analysis. It was found that the best surface roughness was measured for the sample with the lowest cutting speed and shielding gas pressure.

It should be noted that many researchers analyze the cutting surface primarily using roughness parameters. For example, in study [17], an analysis of the sidewall surface roughness of a kerf after high-pressure water jet cutting of high-alloy stainless steel was conducted. The authors analyzed the *Sq* parameter, as it is a universal texture parameter that is not significantly affected by scratches, contaminants, or measurement noise. This enables reliable statistical analysis and reproducible conclusions.

To develop models and optimize the laser cutting process, the design of experiments (DoE) method can be used. This method enables the generation of a significant amount of information from a small number of conducted experiments. Applying the DoE method reduces the number of required tests and shortens the duration of the analysis, with experiments conducted using a full factorial design. response surface methodology is a technique that combines mathematical and statistical modeling, making it useful for multi-criteria optimization. Additionally, RSM facilitates the observation of the effects of selected parameters on the measured response of the system in the analyzed process.

The response surface methodology is widely used by researchers for data analysis [17–21]. Perec et al. [20] successfully applied RSM to build a model of the abrasive water jet (AWSJ) cutting process for a composite material (phenolic resin reinforced with cotton fabric). The obtained results identified the key factors influencing the cutting process quality, efficiency, and cutting depth. For example, in article [21], RSM was applied as one of the methods for optimizing the plasma arc cutting process of Monel 400 steel.

The discussed requirements are particularly important when selecting optimal cutting parameters for structural steel to minimize subsequent machining operations while maintaining high efficiency. This study investigates the potential for optimizing the laser cutting process of S355J2C+N steel, considering surface quality using the response surface methodology. The roughness parameter *Sq* (root mean square height) was selected as a measure of roughness. This parameter is one of the key metrics in surface metrology and enables an objective assessment of roughness and material processing quality. It is well-suited for surface quality assessment following machining after machining, regardless of the machining direction [19, 22].

2 Research methodology

2.1 Target material

The study was conducted on a 10 mm thick hot-rolled, normalized S355J2C+N steel sheet. This grade of steel is intended for the production of various types of structures, including bridges, cranes, and machine construction elements. It is characterized by good strength (minimum yield strength *ReH* = 355 MPa; tensile strength *Rm* = 490 MPa), ductility (minimum percentage elongation after fracture *A*5 = 20%), weldability, and relatively low cost [18]. Table 1 [23] presents the chemical composition of S355J2C+N steel.

2.2 Cutting method and experiment plan

The cutting process was carried out using an Otinus Fiber Laser VF1530 cutter with a power of 4000 W, equipped with a dual nozzle with a diameter of 1.2 mm. Oxygen was used as the processing gas at a pressure of 0.9 bar during the laser cutting. Samples with dimensions of 52.5 × 25 × 10 mm were cut (Fig. 1) [24].

The cutting parameters along with the codes are presented in Table 2. The selected cutting parameters reflect the extreme ranges provided by the fiber laser manufacturer for the cut material.

For data analysis, a 2-level split-plot experimental design was considered. Each combination of parameters was tested twice to enhance measurement precision and estimate random errors. The experimental design is

Table 1 Nominal chemical composition of S355J2C+N steel [23]

Content	C	Si	Mn	Cr	Mo	P and S
Max. [%]	0.22	0.55	1.60	0.30	0.08	0.035

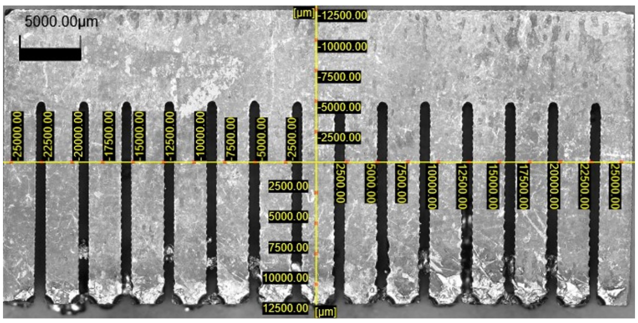


Fig. 1 Shape of cut samples

Table 2 The values of the factors tested at each level and the orthogonal matrix of the experimental design

Tested factors	Encoded variable	Unit of variation	Code	
			–	+
Focus X_1 [mm]	x_1	0.1	0.2	0.3
Feed rate X_2 [m/min]	x_2	0.16	1.52	1.68
Peak power X_3 [W]	x_3	400	3600	4000

presented in Table 3. The parameter analysis was performed using Minitab 21.1.0 software [25] (Pennsylvania State University, Pennsylvania, PA, USA). To determine the effect of cutting parameters on the quality of the side surface and to identify the optimal cutting parameters, analysis of variance (ANOVA), linear regression

Table 3 Factors of the designed experiment

No	Output factors		
	X_1 (Focus)	X_2 (Feed rate)	X_3 (Peak Power)
1, 9	0.2	1.52	3600
2, 10	0.2	1.52	4000
3, 11	0.3	1.52	3600
4, 12	0.3	1.52	4000
5, 13	0.2	1.68	3600
6, 14	0.2	1.68	4000
7, 15	0.3	1.68	3600
8, 16	0.3	1.68	4000

(considering both individual variables and interactions between variables, see Eq. (1)), and an analysis of relationships between variables were conducted.

$$Y = a + \sum_{i=1}^{p} b_i X_i + \sum_{i=1}^{p} \sum_{j=i+1}^{p} b_{ij} X_i X_j + \varepsilon \quad (1)$$

Where:

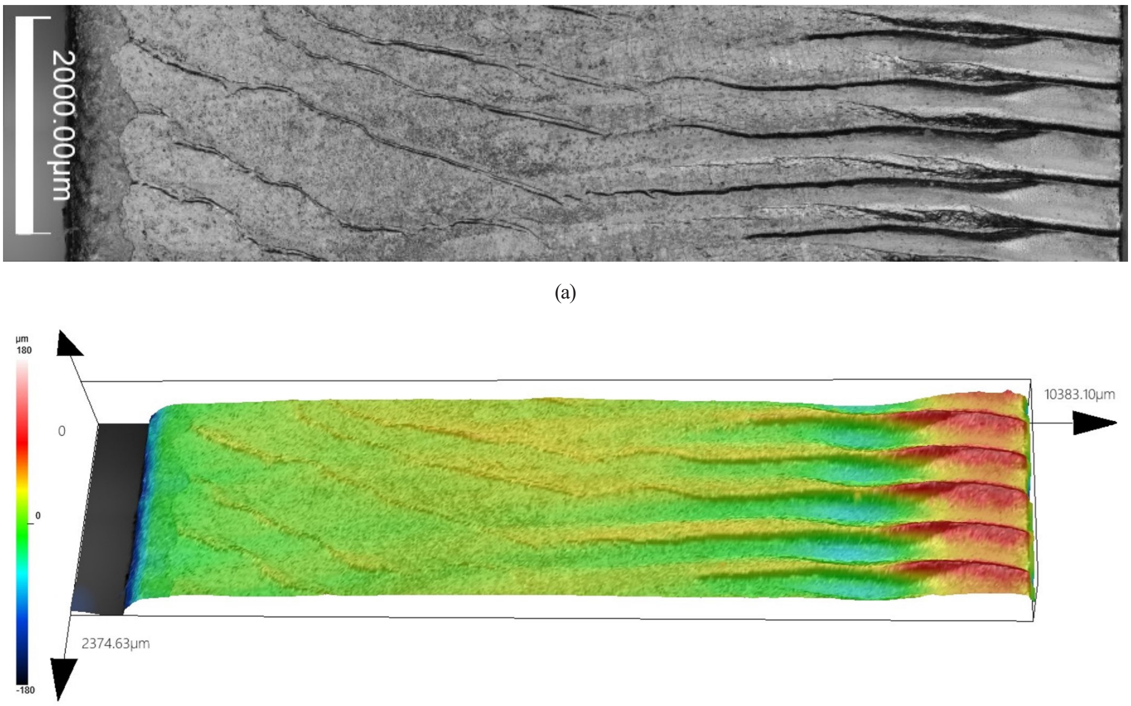
- Y – dependent variable (system response),
- a – intercept (constant term),
- Xi – independent variables (experimental factors),
- b_i – coefficients of the linear effects of factors X_i,
- b_{ij} – coefficients of the interaction effects between factors X_i and X_j,
- ε – random error.

The selected design allowed for a reduced number of experiments. Table 3 presents the factorial experimental design, which planned 16 experiments.

The surface topography analysis of the cut was conducted using an Olympus DSX 1000 digital microscope (manufactured by Olympus Corp., Tokyo, Japan).

3 Results and discussion

The surface topography analysis was performed using an Olympus DSX1000 digital microscope, capturing 3D images. Fig. 2 presents an example of the surface



(a)

(b)

Fig. 2 Cut surface obtained under process parameters: focal length 0.3 mm, feed rate 1.68 m/min, and peak power 4000 W. (a) Side surface, (b) Surface topography

topography for sample no. 8 (Table 3) under the following settings: focus 0.3 mm, feed rate 1.68 m/min, and peak power 4000 W. The observation was conducted on a surface area of 2374 × 10383 µm. Distinct striation lines were observed in the laser entry zone of each examined sample. The surface topography becomes more homogeneous in the middle and trailing zones, which may indicate uniform material removal.

The parameter chosen as a measure of roughness was *Sq* – the root mean square height. This parameter is crucial in surface metrology as it allows for an objective assessment of roughness and the quality of material processing. The *Sq* coefficient defines the average height of surface irregularities relative to the mean surface and can be effectively used to inspect surfaces after processing, regardless of the machining direction.

Fig. 3 presents the *Sq* parameter values for the given laser settings according to Table 2 and Table 3. It can be observed that for samples 1 and 9, with parameters of focus 0.2 mm, feed rate 1.52 m/min, and peak power 3600 W, the roughness was the lowest at 15 and 16 µm. On the other hand, the highest roughness values were observed for the parameters of samples 3 and 11, 4 and 12, 6 and 14, 7 and 15, with respective values of 25 and 25 µm, 25 and 25 µm, 26 and 25 µm, 24 and 25 µm. Based on the analysis of the results, it was determined that increasing the focal length from 0.2 mm to 0.3 mm, along with an increase in feed rate and peak power, leads to a deterioration in roughness.

Table 4 presents the overall ANOVA results regarding the main effects and two-factor interactions. Its analysis was conducted with a 95% confidence level ($\alpha = 0.05$). All main effects significantly impact the quality of the lateral surface: focus $p = 0.006$, feed rate $p = 0$, and peak power $p = 0$. The interaction between these parameters significantly affects the roughness of the lateral surface after laser cutting.

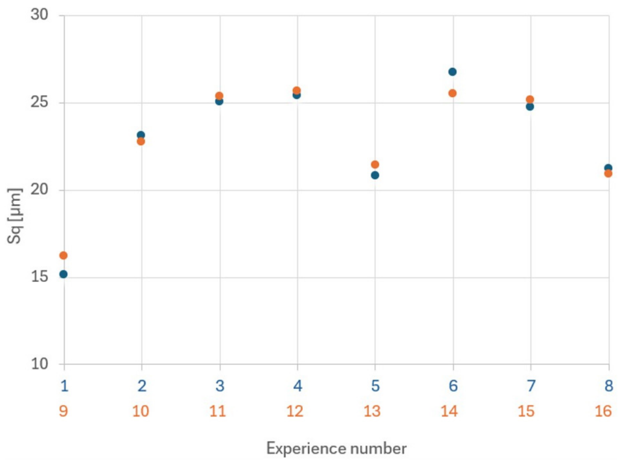


Fig. 3 Impact of control factors on *Sq* surface rough

Table 4 Analysis of variations in the influence of parameters cut on the *Sq*

Source	DF	Adj SS	Adj MS	*F*-value	*P*-value
Model	6	169.565	28.2609	91.37	0.000
Linear	3	52.329	17.4430	56.39	0.000
Focus	1	3.904	3.9036	12.62	0.006
Feed rate	1	18.938	18.9377	61.23	0.000
Power	1	29.488	29.4876	95.33	0
2-way interaction	3	117.237	39.0789	126.34	0
Focus · feed rate	1	10.554	10.5544	34.12	0
Focus· power	1	44.252	44.2542	143.07	0
Feed rate · power	1	62.430	62.4298	201.83	0
Error	9	2.784	0.3093		
Total	15	172.349			

Fig. 4 presents the Pareto chart of standardized effects obtained from the ANOVA analysis, illustrating the main effects and two-factor interactions. The chart shows that the interactions between feed rate – peak power and focus – peak power are statistically the most significant factors.

In the proposed model, the coefficient of determination (R^2) was relatively high at 98.38, close to the adjusted R^2 value of 97.31, indicating the linearity of the regression model (Fig. 5). The model's ability to predict new observations was confirmed by the high predicted R^2 value of 94.90, demonstrating the robustness and predictive validity of the model. The complete regression equation describing the influence of laser settings on roughness can be expressed as follows:

$$\begin{aligned} Sq &= -1017.2 + 966.8X_1 + 32.02X_2 + 0.2459X_3 \\ &-12.19X_1X_2 - 0.1663X_1X_3 - 0.007409X_2X_3. \end{aligned} \quad (2)$$

To optimize the laser cutting process, Response Surface Methodology (RSM) was employed. RSM allows

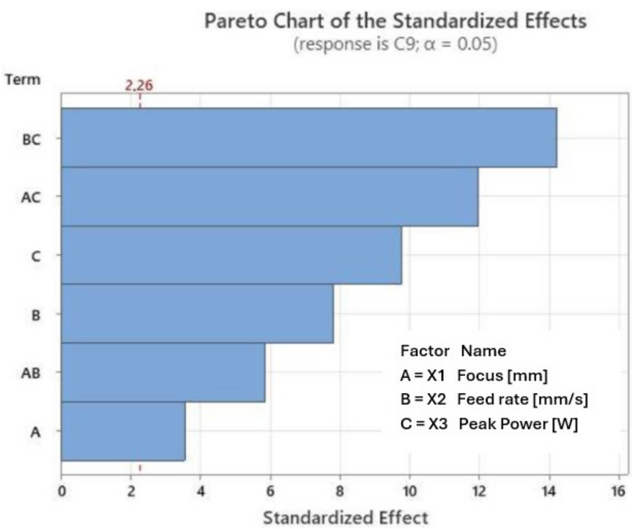


Fig. 4 Pareto chart of the standardized effects (response is *Sq*; $\alpha = 0.05$)

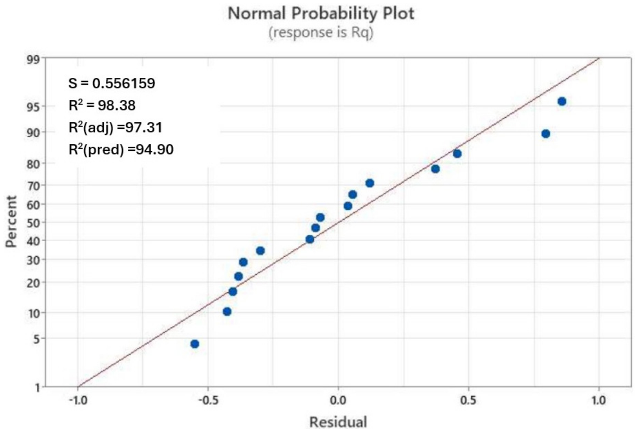


Fig. 5 Normal probability plot of the residuals

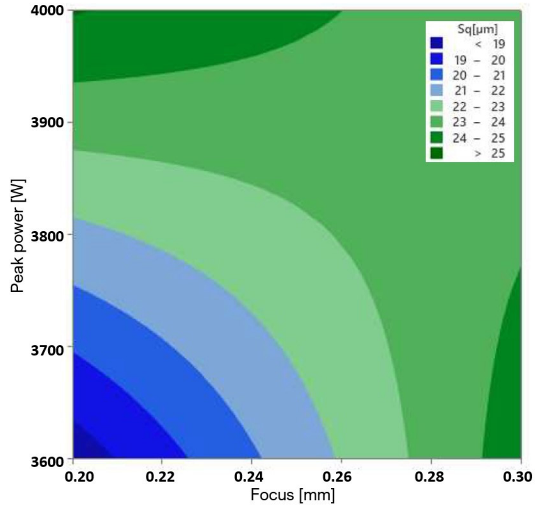
for the determination of suitable combinations of input parameters based on the system's responses. Fig. 6 presents two-dimensional plots illustrating the predictor variables. The analysis of these plots reveals that higher feed rates and peak power result in increased surface roughness (*Sq*). Moreover, the obtained plots for the adopted cutting parameters indicate the gradient of parameter-induced changes. In the case of focal length, an increase in its value was associated with higher *Sq* values.

In laser cutting of structural steel S355J2C+N, technological efficiency may be improved and low surface roughness (*Sq*) maintained by applying low peak power, a reduced focal point position, and a low feed rate, though efficiency in this context should be regarded not as an absolute value but as a process-specific trade-off between surface quality, throughput, and energy consumption dictated by functional and economic requirements.

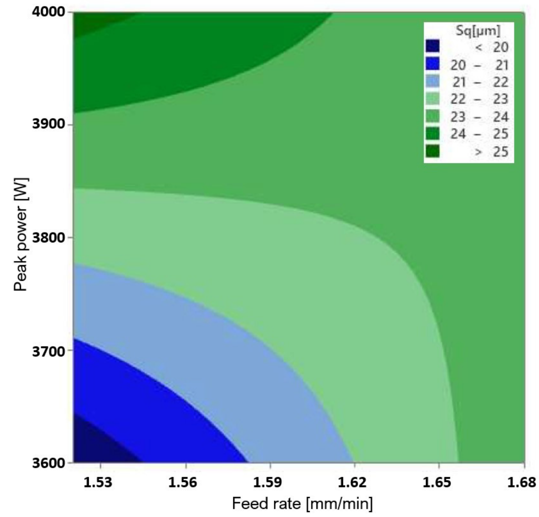
4 Conclusion

The following are a few of the findings concluded from the study:

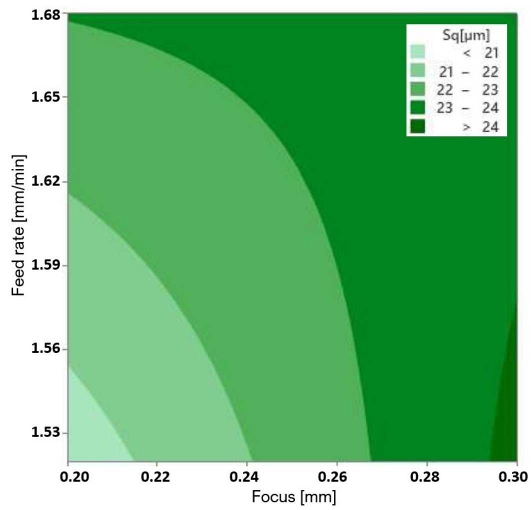
- The application of response surface methodology has proven to be an effective tool for modeling and optimizing the laser cutting process of S355J2C+N structural steel. It enabled the identification of statistically significant process parameters and their interactions affecting surface roughness (*Sq*).
- The most influential factors on surface roughness were found to be feed rate, focal point position, and peak power. All these parameters, as well as their two-way interactions, showed statistically significant effects ($p < 0.05$) on the *Sq* parameter, as confirmed by ANOVA.
- The lowest values of *Sq* surface roughness were obtained under the following conditions: focal point position = 0.2 mm, feed rate = 1.52 m/min, and peak



(a)



(b)



(c)

Fig. 6 The influence of control factors on surface roughness *Sq*:
(a) focus - peak power (hold values feed rate 1.52 m/min); (b) feed rate - peak power (hold values focus 0.25 mm); (c) feed rate and focus (hold values peak power 3800 W)

power = 3600 W. These settings should be considered optimal for minimizing surface irregularities during laser cutting of this steel grade. Importantly, the obtained results are consistent with findings reported by other researchers, confirming that low feed rate, shallow focal position, and moderate laser power are favorable for high-quality laser cuts [9, 12].

- The developed regression model exhibited a high coefficient of determination (R^2 = 98.38%, adjusted R^2 = 97.31%, predicted R^2 = 94.90%), confirming its strong fit and robust predictive performance for new observations.
- These findings offer practical guidelines for improving the efficiency and quality of industrial laser cutting operations. Adjusting process settings within the recommended ranges can significantly enhance surface finish and reduce the need for subsequent machining.
- Although low feed rate and low peak power are favorable for achieving minimal surface roughness, industrial applications may require balancing these parameters with productivity goals. Therefore, RSM can support multi-objective decision-making in manufacturing process optimization.

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