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OPTIMIZATION OF LASER CUTTING PROCESSES IN THE FUNCTION OF SURFACE ROUGHNESS

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Abstract: In today's market–driven manufacturing industry, achieving high productivity, cost efficiency and flexibility without compromising product quality is of paramount importance. Conventional machining methods commonly used for material processing or component manufacturing are reaching their limits in terms of time efficiency and production costs. Therefore, the need for unconventional processes is becoming increasingly apparent, with laser processing emerging as a key alternative. However, there are still problems with the effective implementation and optimization of laser processing that stand in the way of widespread application. By using concentrated light energy, this technique ensures exceptional precision and quality, which depends on the right machine configuration and the use of optimal machining parameters. In this study, we applied the Taguchi method to carefully optimize the parameters of laser cutting to achieve higher processing quality.

Keywords: Laser power, cutting speed, assist gas pressure, surface roughness, Taguchi method

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1. INTRODUCTION

In modern manufacturing, unconventional processing methods and corresponding processing systems are increasingly used alongside conventional ones when cutting sheet metals. By enhancing the quality and precision of these processing systems, the need for multiple subsequent treatments is reduced, while simultaneously achieving satisfactory accuracy, productivity, and cost–effectiveness [1, 2]. The integration of unconventional with conventional machining methods in modern sheet metal processing not only improves overall quality and precision, but also minimizes the need for multiple post–treatments. This approach achieves a balance between accuracy, productivity and cost efficiency, which illustrates the continuous development and efficiency of modern manufacturing processes.

Unconventional processing methods involve cutting processes where material removal is achieved through various physical and chemical mechanisms. Unlike conventional methods, there is no direct contact between the tool and the workpiece, resulting in no chip formation. Instead, material is removed through melting, vaporization, chemical etching, etc. [3].

In contemporary industry, laser processing has become an indispensable procedure, adopted by nearly every company. This is particularly true in the realm of cutting thin sheets with complex contours and obtaining blanks for further processing or components for integration into the final product.

Laser cutting provides a high level of precision and efficiency due to the concentrated energy of laser light [4]. Decision–making regarding parameters such as laser power, speed, and the type of assist gas is crucial for the final quality. Improper parameters can result in material damage or unreliable outcomes.

For instance, fiber laser processing offers high–quality results that meet even the strictest standards. Such processing depends on numerous parameters, including the selection and positioning of nozzles or tips, which can be sensitive to damage if not correctly set. The geometry and depth of the cut can also vary significantly depending on the chosen parameters [3, 4].

To achieve optimal results, it is essential to understand the machine and its operating parameters, along with careful maintenance [5, 6]. The quality of the cut depends on factors such as the cleanliness of the laser lens, proper functionality, correct assist gas flow, and appropriate cutting speed.

Modern machining processes are characterized by the need for economical parameters and high system reliability. The selection of optimal processing parameters becomes crucial for achieving the desired quality, taking into account factors that can influence processing performance.

A team of authors led by Vikas et al. conducted a study on the impact of input parameters on the surface roughness of laser–treated 304 stainless steel [7]. The combination of experimental analyses and the application of the Response Surface Methodology (RSM) allowed for a detailed investigation of the relationships between processing parameters. The results indicated a significant influence of pulse frequency, laser power, cutting speed, and the interaction between certain parameters on surface roughness.

A study on the laser processing of 5 mm thick SS–314 stainless steel was conducted using a CO2 laser system in operation [8]. By optimizing process parameters such as laser power, cutting speed, and gas pressure through the Response Surface Methodology, a minimum surface roughness of 2.132 μm was achieved. This research underscores the importance of optimizing process parameters in achieving precise and high–quality laser processing of stainless steels, paving the way for advancements in various applications of this material in the industry.

Further research on laser cutting of SS–304 stainless steel conducted by author K. Rajesh et al. highlighted key parameters such as laser power, gas pressure, and cutting speed, significantly influencing the kerf width (Kw) and surface roughness (Ra). Developed predictive models provide valuable guidelines for optimizing the laser cutting process of SS–304 stainless steel [9].

By applying a multi–criteria optimization method based on grey relational analysis in the study [10], cutting parameters for fiber laser cutting of AISI 304L stainless steel with a thickness of 20 mm were investigated. Using the Taguchi technique, cutting speed, focal position, frequency, and duty cycle were individually optimized, with simultaneous optimization of surface roughness and kerf width. Analysis of variance (ANOVA) revealed that the most critical parameters for surface roughness and kerf width were the duty cycle (49.01%) and frequency (31.2%). These findings contribute to the understanding of the laser cutting process for thick stainless steel materials and may have significant applications in the industry.

In the study [11], the application of artificial intelligence (AI) in optimizing and modeling the qualitative characteristics of laser material processing (LBM) was investigated. The authors emphasize that AI techniques, including artificial neural networks, fuzzy logic, metaheuristic algorithms, and hybrid approaches, successfully predict and enhance the characteristics of processed materials, providing a powerful tool for creating comprehensive models and optimal settings for LBM processes. This research highlights the potential of AI technologies in improving efficiency and performance in manufacturing.

In the study [12], the authors analyzed the impact of various laser cutting parameters on the surface quality and kerf width of metals. The focus was on key factors of this technological process, exploring how variations in parameters can affect the final properties of processed materials. Examining aspects of laser cutting such as cutting speed, radiation power, and material characteristics, the study analyzed how to achieve an optimal balance between cutting precision, surface quality, and kerf width. Additionally, the paper provides insights into potential challenges and limitations encountered in the metal laser cutting process. Overall, this study contributes to understanding the complexity of laser cutting and provides relevant information for engineers and researchers involved in optimizing metal processing processes.

Literature analysis has revealed that in the majority of studies, the impact of two, three, or four process factors (most commonly laser power, cutting speed, and auxiliary gas pressure) on one, two, or three process characteristics is analyzed. The most common characteristics under investigation are the quality of the cut (kerf width, surface roughness, and heat–affected zone – HAZ). Experimental results show that process factors have varying effects on process performance within different ranges of variation. Previous research has mainly focused on analyzing the impact of process factors on cutting metals, polymers, composite materials, and ceramics. In most works, the problem of single–criteria optimization has been addressed, identifying optimal values for process factors. Statistical methods such as regression analysis, classical optimization methods, and the Taguchi optimization method have been employed for this purpose.

Based on the results of previous studies, it is becoming increasingly clear that the use of the Taguchi method for optimization purposes is not only justified, but also brings considerable benefits. This methodological approach is known for its effectiveness in systematically improving processes and results. Based on this knowledge, the Taguchi method is to be used in the current study to improve the quality of surfaces when cutting metal plates. To improve surface quality, the focus of this study is on determining and applying the optimal processing parameters. These parameters include crucial variables such as laser power, cutting speed and support air pressure. The overall goal is to determine the specific combination of these factors that will result in a machined surface with minimal roughness. This research makes an important contribution to the topic by proving and demonstrating the successful application of the Taguchi method in the sheet metal cutting industry. By showing that this method leads to a noticeable improvement in surface quality, the study not only confirms its relevance, but also underlines its potential as a valuable tool for optimizing processes in the industry.

2. MATERIAL AND METHODS

Material cutting was performed on the "Bystar 3015" laser machine, well–known in the industry for its precision and efficiency, as depicted in Figure 1. The basic characteristics of the machine include a working space size of 3000 x 1500 mm, a maximum workpiece weight of 890 kg, maximum workpiece thickness of 20 mm, and a laser power of 3500W. The machine operates based on fiber technology, differing from the traditional laser beam guidance through mirrors to the melting point. Instead, this technology operates by reflecting the beams off the walls within the optical cable [13].

The experiments were conducted on hot–rolled low–carbon steel sheet, commonly known as black sheet, with the designation S235JR (1.0330) according to SRPS EN 10130:2011. The basic mechanical characteristics of this steel are: tensile strength 360–510 MPa, yield strength 235 MPa, hardness 104–154 HB, and modulus of elasticity 210 GPa. The basic chemical composition is: Fe (≤98,5%), C (0,17–0,20%), Mn (≤1,4%), Si (≤0,035%), P (≤0,045%), S (≤0,045%).

Figure 1. Display of the working space for laser cutting – Bystar 3015

Cold–rolled sheets of low–carbon steels are suitable for welding and coating applications (metal coatings, painting) [14]. They are used in the automotive industry, production of white goods, metallurgy, and packaging. Additionally, they find applications in various sectors of industry and construction, including machinery manufacturing, vehicle production, construction, shipbuilding, industrial equipment manufacturing, and metal processing [15].

Due to the complexity of the laser cutting process, various factors can impact the quality of the cut [16, 17]. Based on information from the literature and operator experience, the following crucial parameters were identified: laser power, cutting speed, and auxiliary gas pressure [17, 18]. When selecting values for these parameters, manufacturer recommendations, machine constraints, and the characteristics of the material being cut were taken into consideration. Assuming the existence of complex and nonlinear relationships between input parameters and cutting characteristics, three levels of variation were chosen for each input factor, with the condition that complete material cutting (3 mm thickness) is achieved for each combination, as shown in Table 1.

Table 1. Process factors by levels

Process factors	Unit	Level		
		1	2	3
Cutting speed, Vf	(m/min)	3000	3400	3800
Laser power, Pl	(kW)	1	1.5	2
Assist gas pressure, P	(MPa)	0.5	0.7	1.0

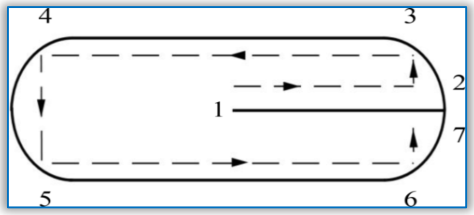


Figure 2. Representation of the cutting path for the samples

The laser cutting process begins with piercing holes by moving the cutting head downward, with the laser operating in pulse mode. Subsequently, the laser transitions into continuous mode and cuts the sheet along the specified contour, as illustrated in Figure 2.

In Figure 3, the cutting process and the appearance of samples after cutting from the sheet metal are depicted.

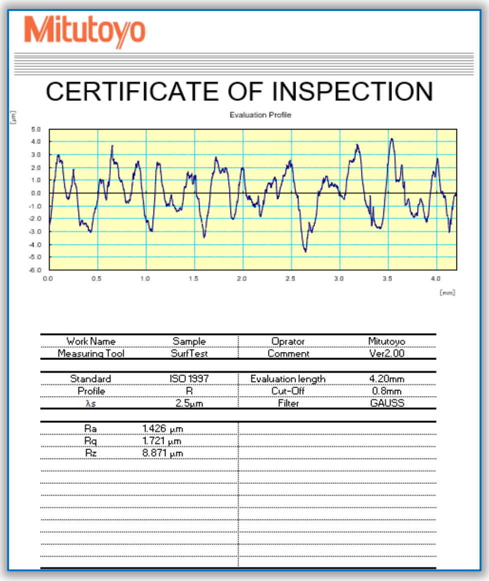
The process will be carried out on nine samples with varying parameters: cutting speed, laser power and assist gas pressure. Before starting, the machine must be thoroughly checked, including gas flow, cooling and the condition of the lens. After the check, the machine setup for processing follows. The machine is connected to a control screen with an operating system, allowing for visualization of the model and optimization of the workflow. The goal is to achieve maximum material utilization [19].

Figure 3. Illustration of the laser cutting process and the appearance of the sample after cutting from the sheet metal

Figure 4. Presentation of the measurement of surface roughness on samples using the Mitutoyo Surftest SJ–210 instrument

To investigate the impact of input factors on the cut quality, a measurement and quantification of the cut surface roughness were performed. The surface roughness was assessed using the average arithmetic deviation of the profile, Ra. Measurements were carried out using the Mitutouo Surfest SJ–210 instrument, which operates based on dragging a measuring stylus across the cut surface and detecting irregularities, Figure 4. These results can be easily processed and categorized by connecting the device to a computer. The machine consists of a clamp for securing the material, the basic structure of the machine, a measuring column and a device with a measuring stylus.

Figure 5 shows the appearance of the results for the first sample loaded into the software on the computer.



Mitutoyo

CERTIFICATE OF INSPECTION

Work Name	Sample	Oprator	Mitutoyo
Measuring Tool	SurfTest	Comment	Ver2.00

Standard	ISO 1997	Evaluation length	4.20mm
Profile	R	Cut-Off	0.8mm
λs	2.5μm	Filter	GAUSS

Ra	1.426 μm	
Rq	1.721 μm	
Rz	8.871 μm	

Figure 5. Example of measurement results for Experiment 3

The Taguchi method, applied in this study and named after the Japanese engineer–statistician Dr. Genichi Taguchi, is employed for product and process design optimization to enhance quality and reduce costs. It focuses on adjusting quality parameters around nominal values. This method gained significant popularity in the 1970s and 1980s by integrating statistical methods into engineering processes, making it one of the key tools for quality planning today [19].

3. RESULTS AND DISCUSSION

Japanese scientist Genichi Taguchi advanced the concept of experimental design through an optimization approach, dividing the problem into two categories. This approach uses the signal–to–noise (S/N) ratio as the target optimization function. There are three approaches to static optimization: smaller is better, larger is better and nominal is better. In the study, the primary goal was to minimize all output performances, using the "smaller is better" method according to the given equation 1:

$$(S/N)_J = -10\, log\, \frac{1}{n}\sum_{i=1}^{n}[yij\ 2]\ ,\ j = 1\ldots m \qquad (1)$$

In this study, the Taguchi method was employed for single–criterion optimization of input parameters in laser cutting, analyzing the output performance. This method is used in product and process design to enhance quality and reduce costs. The Taguchi method is based on narrowing the parameters of properties and quality characteristics around nominal values. It represents a novel design optimization methodology that improves the quality of existing products and processes while simultaneously reducing their cost. Additionally, it provides a simple and systematically efficient approach to optimization without requiring a mathematical model [20].

The method is based on the loss function (Taguchi function), representing the deviation of the functional characteristic from the nominal value. To achieve this, a completely new experimental planning system was developed: orthogonal arrays. These arrays enable designers to study multiple process parameters simultaneously and can be used to assess the impact of each parameter independently. For optimization, the Taguchi orthogonal array $L_9(3^4)$ was applied to laser cutting of 3 mm thick black sheet metal [19]. Table 2 displays organized parameters such as laser power, cutting speed, and auxiliary gas pressure that were varied to investigate their influence on cut quality. Analyses were conducted using Minitab 17 software, with optimization results indicating the impact of input factors within a 95% confidence interval.

Table 2. Taguchi Orthogonal Array L9 Experimental Design Plan and Measurement Results

No.	Factor			
	v_f (mm/min)	P_L (kW)	P (bar)	Ra
1.	3000	1	0.5	0.683
2.	3000	1.5	0.7	1.102
3.	3000	2	1.0	1.426
4.	3400	1	0.7	0.956
5.	3400	1.5	1.0	1.498
6.	3400	2	0.5	1.480
7.	3800	1	1.0	0.888
8.	3800	1.5	0.5	1.311
9.	3800	2	0.7	3.052

Table 3. S/N values for factors related to the surface roughness.

Serial number	Factors	S/N ratio			max–min	Rank
		Levels				
		1	2	3		
1.	C1– Cutting speed, *Pl*	1.578	–2.235	–5.393	6.971	1
2.	C2– Laser power, *Vf*	–1.178	–1.201	–3.671	2.492	2
3.	C3– Assist gas pressure, *P*	–1.789	–2.408	–1.854	0.619	3

In accordance with Table 2 and using Minitab software, the effects of the laser cutting process input parameters on the S/N values for the average arithmetic cut roughness were analyzed. The obtained results were first presented in a tabular form in Table 3. and then in the form of main effects plots, Figure 6. Based on the results from Table 3 and Figure 6, it can be concluded that the optimal combination of factor levels that minimizes the average arithmetic roughness of the cut is approximately at the minimum value C1 (level 1), C2 (level 1), C3 (level 1), Table 4.

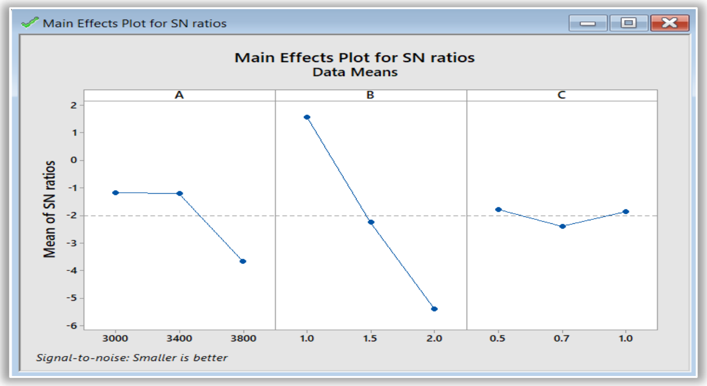


Figure 6. Main effects plot for S/N ratio values of factors related to the surface roughness

Table 4. Optimal settings of input factors for surface roughness

Input parameters	Level	Adjust	Predicted
C1 Cutting speed, Vf	1	3000	S/N= 2,64
C2 Laser power, Pl	1	1.0	Ra= 0.498
C3 Assist gas pressure, P	1	0.5	

4. CONCLUSION

This study emphasizes the importance of laser processing in the modern industrial environment, especially in the processing of specific and complex materials. The study underlines the crucial role of adjusting laser parameters such as power, cutting speed and auxiliary gas pressure in order to achieve optimum processing quality. It has been shown that the application of the Taguchi method in optimizing the input parameters for laser cutting leads to an increase in performance. Data analysis has identified the most important factors influencing cutting quality. The optimal combination of factors to minimize the mean arithmetic roughness was determined with a power of 1 kW, a cutting speed of 3000 m/min and a pressure of 0.5 MPa.

The results suggest that with careful adjustment and optimization, laser processing can deliver consistently high–quality results for complex materials to meet the dynamic demands of the market. In conclusion, the study argues for a proactive and adaptive approach to fully exploit the potential of laser processing and meet the challenges of the modern industrial landscape. Future research in laser processing should focus on parameter optimization, real–time monitoring and interdisciplinary collaboration to improve efficiency, sustainability and adaptability to new industrial demands.

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