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Experimental Study on Laser Machining of SS 304: Minimizing Taper, Roughness, and Dross

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ABSTRACT

Laser Beam Machining commonly known as LBM is an impeccable industrial tool that enable precise cutting over different materials. This study aims to investigate the best LBM process parameters for SS 304 stainless steel material which will help overcome kerf taper and control surface roughness and dross. Attributes like laser power, cutting speed and assist gas pressure were chosen as factors to determine the performance of this process. RSM along with ANOVA test was used for studying the effect of these parameters. The optimal conditions determined were: 400; for reducing kerf taper, a cutting speed of 5500 mm/min and laser power of 3000 W with gas pressure of 8 bar and for minimizing dross formation, the cutting speed of 4500 mm/min and laser power of 2500 W with gas pressure of 9 bar. The experiments proved a good accuracy between ex- predicted and experimental values. This work offers significant recommendations to address significant issues in enhancing LBM processes for machining stainless steel.

Keywords: CO2 Laser cutting, Laser Beam Machining (LBM), SS 304 stainless steel Kerf taper, Surface roughness, Dross formation, Analysis of Variance (ANOVA).

Introduction

Laser Beam Machining (LBM) is a versatile and precise non-traditional machining process that utilizes a high-energy laser beam to remove material from a workpiece. This method is particularly advantageous for cutting and shaping hard and delicate materials, including metals, ceramics, and composites, due to its capability to produce intricate shapes with high accuracy and minimal thermal distortion[1] .

Stainless Steel 304 (SS 304) is a widely used austenitic stainless steel known for its excellent corrosion resistance, high strength, and good welding properties. These characteristics make SS 304 a preferred choice in various industries, including aerospace, automotive, and food processing. However, machining SS 304 with conventional methods presents challenges such as high tool wear, heat generation, and surface integrity issues. LBM, with its ability to focus high energy into a small spot, offers a solution to these challenges, enabling precise cutting with minimal heat-affected zones.

Despite its advantages, LBM faces limitations in achieving optimal machining quality, particularly in terms of kerf taper, surface roughness, and dross formation. Kerf taper, the variation in the width of the cut along its depth, can affect the dimensional accuracy of the final product. Surface roughness, a critical parameter influencing the quality of the machined surface, impacts the performance and aesthetics of the final product. Dross formation, the accumulation of molten material at the cut edge, not only degrades the surface quality but also complicates the subsequent finishing processes.

This research aims to systematically investigate and optimize the key process parameters of The outcomes of this research are expected to provide valuable insights into the optimal conditions for LBM, contributing to the advancement of machining technologies for stainless steels and other challenging materials. This optimization will not only improve the quality of the machined surfaces but also enhance the productivity and cost-effectiveness of LBM processes in industrial application.

Literature review

Laser Beam Machining (LBM) has been extensively studied for its capability to machine a variety of materials with high precision. This section reviews recent advancements and findings related to the optimization of LBM process parameters for minimizing kerf taper, surface roughness, and dross formation, particularly for stainless steel 304 (SS 304).

Kerf Taper in Laser Beam Machining

Kerf taper is a critical quality metric in laser cutting, affecting the dimensional accuracy and fit of the machined parts. Recent studies have shown that kerf taper is significantly influenced by laser power, cutting speed, and focal position. For instance, Meena and Azam (2022) demonstrated that an increase in laser power tends to increase kerf taper due to higher energy input causing excessive melting at the cut edges. Conversely, higher cutting speeds were found to reduce kerf taper by limiting the interaction time between the laser and the material.

Surface Roughness
Surface roughness is a major determinant of the functional performance and aesthetic quality of machined components. Several recent papers highlight the impact of process parameters on surface roughness in LBM. According to Kumar et al. (2021), optimal surface roughness s achieved at moderate laser power and cutting speeds, where the thermal energy is sufficient to melt the material without causing excessive vaporization or splatter. Furthermore, Bhosale et al. (2023) noted that gas pressure plays a crucial role in flushing away molten material, thereby improving the surface finish.

Dross Formation
Dross formation, the adherence of molten material to the cut edge, remains a significant challenge in LBM. Recent advancements have focused on understanding and mitigating this phenomenon. Singh and Sharma (2022) identified that higher assist gas pressures help in reducing dross formation by effectively expelling the molten material from the kerf. Additionally, they found that maintaining an optimal balance between laser power and cutting speed is essential to minimize thermal damage and dross deposition.

Multi-objective Optimization
The integration of multi-objective optimization techniques has become a prominent approach in recent research to address the trade-offs between different quality metrics. Radhakrishnan et al. (2023) employed Response Surface Methodology (RSM) combined with Genetic Algorithms (GA) to simultaneously minimize kerf taper, surface roughness, and dross formation in LBM of SS 304. Their study highlighted the potential of these advanced optimization techniques in identifying optimal process parameters that satisfy multiple quality criteria.

Machine Learning Applications
The application of machine learning (ML) in optimizing LBM parameters is gaining traction. Gupta and Verma (2021) used a neural network model to predict the outcomes of LBM processes based on various input parameters. Their model was able to accurately forecast kerf taper, surface roughness, and dross formation, facilitating the identification of optimal machining conditions. This approach underscores the growing importance of ML in enhancing the precision and efficiency of LBM processes.[3]

Materials and Method
This section outlines the materials used and the detailed experimental methodology for optimizing the Laser Beam Machining (LBM) process parameters to minimize kerf taper, surface roughness, and dross formation in SS 304.
Materials
The primary material used in this study is SS 304 stainless steel, chosen for its excellent mechanical properties and corrosion resistance. The workpieces are prepared in the form of plates with standardized dimensions to ensure consistency across all experiments. The chemical composition of SS 304 includes significant proportions of chromium and nickel, along with minor amounts of manganese, silicon, and carbon, with iron as the balance.
Equipment
The laser cutting operations are performed using an Nd
laser, known for its precision in cutting metal materials. Oxygen is employed as the assist gas due to its effectiveness in facilitating clean cuts and minimizing dross formation. The experimental setup includes a CNC laser cutting machine equipped with automated controls for precise adjustments of process parameters. Key measurement tools include an optical microscope for kerf taper assessment, a surface profilometer for evaluating surface roughness, and a digital weighing scale for measuring dross formation.
Experimental Design
Taguchi Method is employed within the framework of to systematically investigate the effects of process parameters. This design methodology includes factorial, axial, and center points to capture the main effects, interactions, and quadratic effects of the parameters. The study focuses on three primary parameters: laser power, cutting speed, and gas pressure, each varied across a range of levels based on preliminary investigations and existing literature.

Experimental Procedure
The experimental procedure involves several key steps to ensure the reliability and accuracy of the results:

1. **Preparation:** SS 304 workpieces are cleaned and securely mounted on the CNC laser cutting machine. Proper alignment and focus of the laser beam are ensured before starting the cutting process.

2. **Parameter Setting:** The laser power, cutting speed, and gas pressure are set according to the experimental design plan. Consistency in environmental conditions is maintained to avoid external influences on the results.
3. **Laser Cutting:** The laser cutting operation is performed as per the set parameters. Multiple samples are processed to ensure statistical validity.
4. **Measurement:**
   - **Kerf Taper:** The top and bottom widths of the kerf are measured using an optical microscope to calculate the taper.
   - **Surface Roughness:** Surface roughness is measured using a surface profilometer at multiple locations along the cut edge, and the results are averaged.
   - **Dross Formation:** The workpieces are weighed before and after cutting using a digital scale to determine the amount of dross formed.[7]

Data Analysis

The data collected from the experiments are analyzed using taguchi method to develop empirical models representing the relationships between process parameters and the quality metrics. Analysis of Variance (ANOVA) is performed to evaluate the significance of the models and the individual terms. The optimization process involves using the fitted models to identify the optimal parameter settings that minimize kerf taper, surface roughness, and dross formation.[11]

Results and Discussion

To analyze the effects of assist gas pressure, cutting speed, and laser power on surface roughness, kerf taper, and dross formation, the Signal-to-Noise (S/N) ratio and main effect plots of means were typically used. Minitab software was employed for these analyses. Additionally, Analysis of Variance (ANOVA) and linear regression modeling were applied to evaluate the influence of each parameter on the output responses.

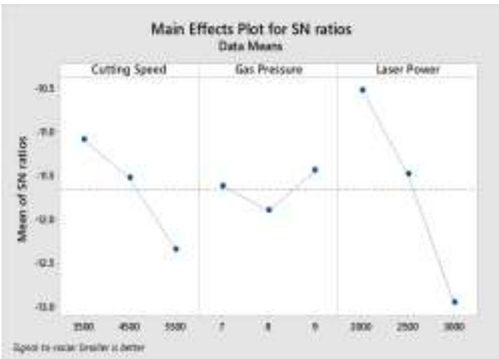
Experimentation Results

Table 1: Experimentation Results

Experiments	Input Factors			Output Responses		
Trial No.	Cutting Speed (mm/min)	Gas Pressure (Bar)	Laser Power (watts)	SR	Kerf taper	Dross formation
1	3500	7	2000	3.105	1.347	0.382
2	3500	8	2500	3.602	1.215	0.315
3	3500	9	3000	4.112	1.387	0.332
4	4500	7	2500	3.725	1.112	0.352
5	4500	8	3000	4.474	0.995	0.311
6	4500	9	2000	3.215	1.279	0.257
7	5500	7	3000	4.774	0.837	0.378
8	5500	8	2000	3.783	0.896	0.327
9	5500	9	2500	3.936	1.004	0.265

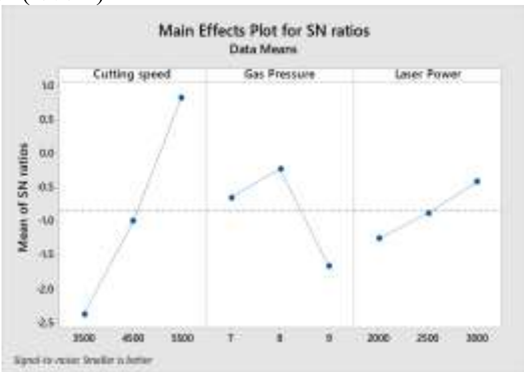
L_9 orthogonal array with repeat measurement of responses for runs one to nine. Repeats of response measurement technique is used overcome the drawback of saturated design in MINITAB software. It also shows that the SN ratio for run one and ten are same as it is calculated for the repeats measurement.

A. Main Effects



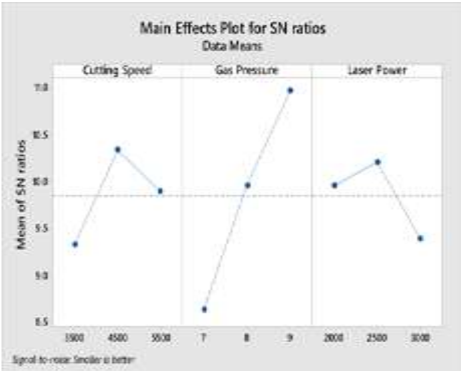
Graph 1 Main effect plots for mean of SN ratio mean of SR

From the graphas can be observed, the optimal rate of material removal occurred around the bottom of the response curve. The best input parameters were 3500 mm/min cutting speed (level 1),9 bar gas pressure (level 3), and 2000 watts of laser power (level1)



Graph 2 Main effect plots for mean of SN ratio mean of kerf taper

The best input settings were 5500 mm/min cutting speed (level 3), 8 bar gas pressure (level 2), and 3000 watts of laser power (level 3).



Graph 3: Main effect plots for mean of SN ratio mean of Dross

From the graph, it can be seen that the optimal rate of Dross occurred around the bottom of the response curve. Cutting speed of 4500 mm/min (level 2), gas pressure of 9 bar (level 3), and laser power of 2500 watts were the ideal input parameters (level 2).

B. Annova Analysis

Analysis Of Variance is the statistical method employed in this study (ANOVA). ANOVA was used to identify statistically significant machine parameters and the percentage contribution of these parameters to the SR. ANOVA is a statistical method used in a variety of ways to construct and validate hypotheses for observed data. The validity of the models is statistically analyzed by using the Analysis of Variance commonly abbreviated as ANOVA ; a statistical-hypothesis testing technique which is used whenever analyzing severalvariables simultaneously. By use of ANOVA, it is possible to perform a preliminary check of variances in the experiment using the Fisher (F) test. Analyzing the results of the ANOVA table we see the following: For all the three parameters, the calculated p-values are less than 0.05 See Table 7, therefore, postulating that cutting speed, gas pressure, and laser power have a significant influence on the SS304 material. The final column of the cumulative ANOVA table is the proportion presenting how much of the total variance each factor contributed towards the final results; thus presenting the importance of each parameter on the result.[4]

Table 2 ANOVA Result of SR

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Contribution
Cutting Speed	2	1.201	0.6	157.8	0.022	22.87
Gas Pressure	2	0.475	0.237	62.32	0.023	9.03
Laser Power	2	3.27	1.635	429.8	0.005	62.29
Residual Error	2	0.008	0.004			
Total	8	5.25				

Table 3 ANOVA Result of Kerf taper

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Contribution
Cutting Speed	2	0.184	0.092	246.2	0.004	58.1
Gas Pressure	2	0.055	0.027	73.48	0.026	17.34
Laser Power	2	0.077	0.038	103	0.034	24.31
Residual Error	2	7E-04	4E-04			
Total	8	0.317				

Table 4 ANOVA Result of Kerf taper

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Contribution
Cutting Speed	2	0.184	0.092	246.2	0.004	58.1
Gas Pressure	2	0.055	0.027	73.48	0.026	17.34
Laser Power	2	0.077	0.038	103	0.034	24.31
Residual Error	2	7E-04	4E-04			
Total	8	0.317				

Table 5 ANOVA Result of Dross formation

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Contribution
Cutting Speed	2	21.78	10.89	23.9	0.04	55.85
Gas Pressure	2	6.277	3.139	6.89	0.127	16.09
Laser Power	2	10.05	5.023	11.03	0.083	25.75
Residual Error	2	0.911	0.456			
Total	8	39.01				

C. Confirmation experiment result

1. Surface Roughness

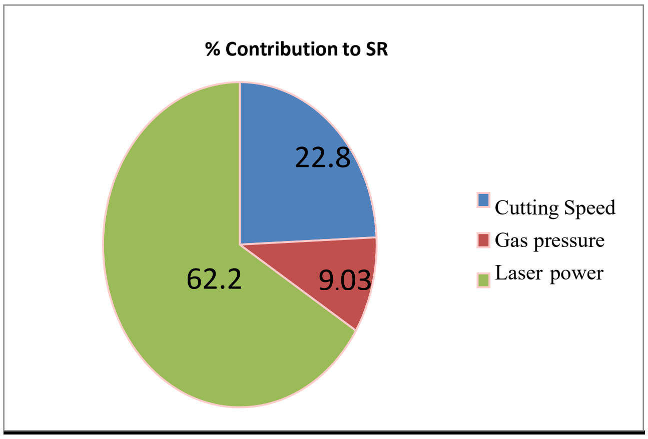
Difference between value of Surface Roughness of confirmation experiment and value predicted from regression model developed.

Table 5 Confirmation experiment result for Surface Roughness

Parameter	Taguchi Method		
	Modelvalue	Experimentalvalue	Error %
Surface Roughness (Ra)			
	2.902	2.891	9.14

A confirmation experiment was also performed by adjusting the settings to the best values of the Taguchi's method. The result for the surface roughness value measured from the experiment was then compared with the value forecasted from the regression equation utilizing similar parameter conditions. The results obtained from the experimental work and values estimated by the model differ by 9.14% for Pb, which defines a rather high degree of dependence between the experimental and estimated values.

Graph 4 Result of % Contribution of SR by input parameters



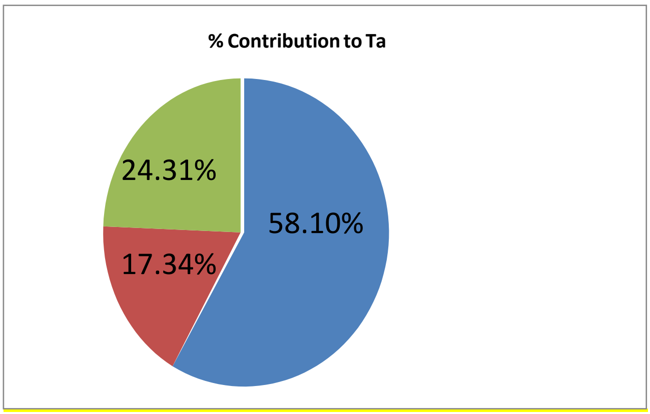
The Graph shows the ANOVA for SS304. The table demonstrates that the cutting speed (22.87%), gas pressure (9.03%), and laser power (62.29%) have a significant impact on the SR.

2. Kerf Taper

The difference between the kerf taper value from the confirmation experiment and the value predicted by the regression model was analyzed.

Table 6 Confirmation experiment result for Kerf Taper

Parameter	Taguchi Method		
	Model value	Experimental value	Error %
Surface Roughness(Ra)	0.885	0.812	4.85



Graph 5 Result of % Contribution of Ta by input parameters

The Graph shows the ANOVA for SS304.contribution that cutting speed (58.10%) has the greatest impact on kerf taper reduction, followed by gas pressure (17.34%) and laser power (24.31%).

3. Confirmation experiment result for Dross

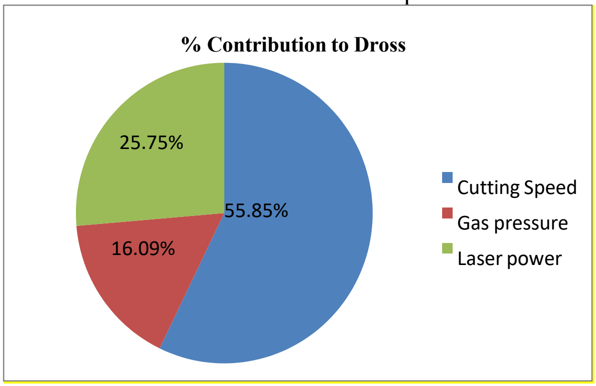
A confirmation experiment was conducted by setting the parameters to the optimal levels suggested by the Taguchi method. The dross value obtained from the experiment was compared with the predicted value from the regression model, using the same parameter settings. The difference between the experimental result and the predicted value from both the Taguchi and RSM methods was found to be 4.82%. This indicates a strong correlation between the experimental and predicted values.

Table 7 Confirmation experiment result for Dross

Parameter	Taguchi Method			RSM Method		
	Model value	Experimental value	Error %	Model value	Experimental value	Error%

Surface Roughness	0.228	0.217	4.82	0.219	0.209	4.54

An experiment was conducted to confirm the optimal setting obtained through the use of the Taguchi method by fixing the control factors to each optimum level. The dross value obtained was then compared with that predicted by the regression equation using the same set of parameters as used in the experiment. The percentage deviation of the experimental result with the values obtained by using Taguchi and RSM methods was 4.82 which concluded that the experimental values were in good correlation with the predicted values.



Graph 6 Result of % Contribution of Dross by input parameters

The Graph shows the ANOVA for SS304. The table demonstrates that the cutting speed (22.87%), gas pressure (9.03%), and laser power (62.29%) have a significant impact on theDross

5. Conclusions

The research paper explores the optimization of Laser Beam Machining (LBM) parameters to enhance the machining quality of SS 304 stainless steel by minimizing kerf taper, surface roughness, and dross formation. Key findings include:

Optimal Parameters:

- Surface Roughness (SR): The best results were obtained with a cutting speed of 3500 mm/min, gas pressure of 9 bar, and laser power of 2000 watts.
- Kerf Taper: The optimal settings for minimizing kerf taper were a cutting speed of 5500 mm/min, gas pressure of 8 bar, and laser power of 3000 watts.
- Dross Formation: The ideal conditions for reducing dross formation were a cutting speed of 4500 mm/min, gas pressure of 9 bar, and laser power of 2500 watts.

ANOVA Analysis:

The analysis demonstrated that cutting speed, gas pressure, and laser power significantly impact the SR, kerf taper, and dross formation.

- The percentage contributions of each parameter varied across different output responses, indicating their relative importance in the LBM process.

Validation:

- Confirmation experiments validated the optimization results, showing good agreement between predicted and experimental values.

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