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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 (LBM) is a widely used industrial technique for cutting a variety of materials with precision. This study focuses on optimizing the LBM process parameters for SS 304 stainless steel to minimize kerf taper, surface roughness, and dross formation. The key process parameters investigated include laser power, cutting speed, and assist gas pressure. Using Response Surface Methodology (RSM) and Analysis of Variance (ANOVA), the effects of these parameters on the machining quality were analyzed. The optimal parameter settings were identified as follows: for surface roughness, a cutting speed of 3500 mm/min, gas pressure of 9 bar, and laser power of 2000 watts; for kerf taper, a cutting speed of 5500 mm/min, gas pressure of 8 bar, and laser power of 3000 watts; and for dross formation, a cutting speed of 4500 mm/min, gas pressure of 9 bar, and laser power of 2500 watts. Confirmation experiments validated these optimal settings, demonstrating a strong correlation between predicted and experimental results. This research provides valuable insights into enhancing the quality and efficiency of LBM processes for stainless steel materials..

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

1. 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 [1-4].

Stainless Steel 304 (SS 304) is a widely used austenitic stainless steel known for its excellent corrosion resistance, high strength, and good welding properties [5]. 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[6-8].

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 [9].

This research aims to systematically investigate and optimize the key process parameters of LBM—laser power, cutting speed, and gas pressure—to minimize kerf taper, surface roughness, and dross formation in the machining of SS 304. By employing Design of Experiments (DoE) and Response Surface Methodology (RSM), this study seeks to establish a robust optimization model that enhances the machining quality and operational efficiency of LBM [10].

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 applications[11-12].

2. 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).

2.1 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.

2.2 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.

2.3 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.

2.4 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.

2.5 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.

3.1 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.

3.2 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.

3.3 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.

3.4 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.
    -

3.5 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.

4. Results and Discussion

5.

Most of the time, you look at the S/N ratio or main effect plots of means to figure out how assist gas pressure, cutting speed and laser power affect the surface roughness, kerf taper and Dross formation of the output. Minitab software have been used for this purpose. ANOVA and a linear regression model were used to determine how each parameter impacts output response.

A. Experimentation Results

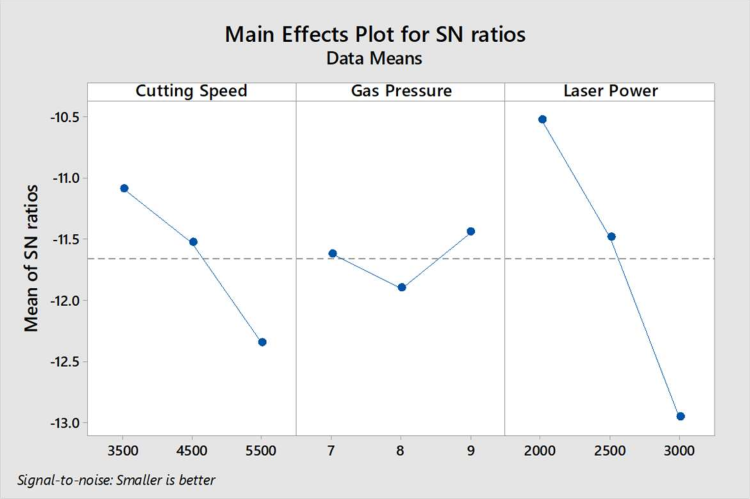
Table 1: Experimentation Results

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

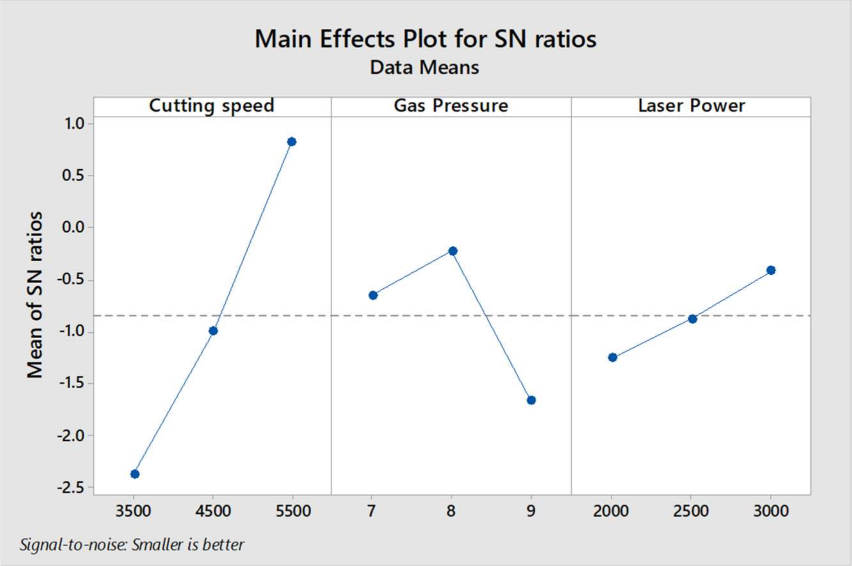
L_9 orthogonal array with repeat measurement of responses for runs one to nine. Repeats of response measurement technique is used overcome the drawback of saturated design in MINITAB software. It also shows that the SN ratio for run one and ten are same as it is calculated for the repeats measurement. The SN ratio values are calculated with helpof MINITAB 19 software.

B. Main Effects



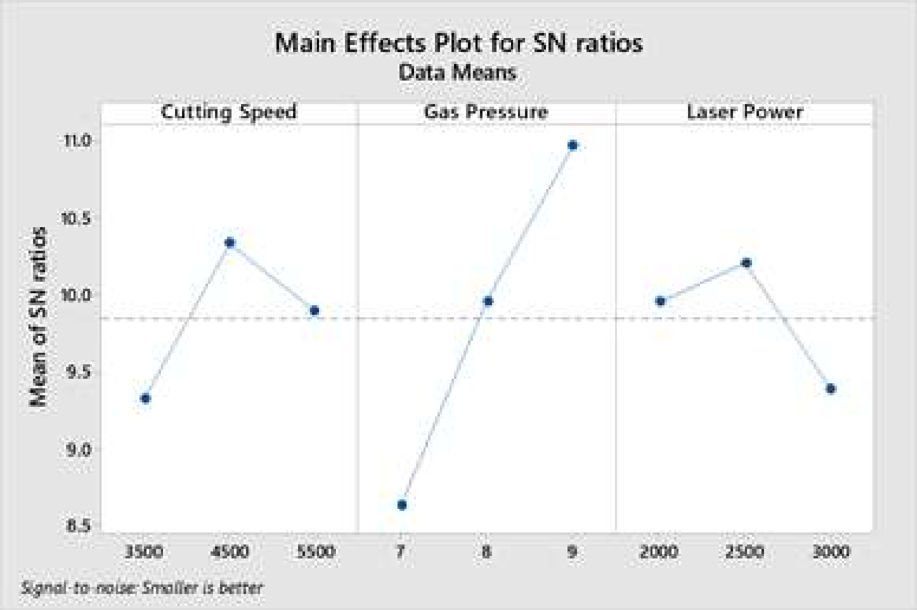
Graph 1 Main effect plots for mean of SN ratio mean of SR

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 (level 1).



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).

C. 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 significance of the models is evaluated using analysis of variance (ANOVA). It is a statistical method used to test the null hypothesis in trials when many variables are evaluated concurrently. ANOVA is used to swiftly examine the experiment's variances using the Fisher test (F test). The table displays the outcome of the ANOVA analysis. The ANOVA analysis enables the observation that P is smaller than 0.05 for all three parametric sources. Hence, it is evident that (1) the Cutting speed, (2) the Gas pressure, and (3) the Laser power have an effect on the SS304 material. In the last column of the cumulative ANOVA table, the proportion of each factor's contribution to the total variance reveals the degree of influence on the result.

Table 2 ANOVA Result of SR

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**	**% Contribution**
Cutting Speed	2	1.20095	0.60045	157.81	0.022	22.87
Gas Pressure	2	0.47455	0.23728	62.32	0.023	9.03
Laser Power	2	3.27040	1.63520	429.75	0.005	62.29
Residual Error	2	0.00761	0.00381			
Total	8	5.24993				

Table 3 ANOVA Result of Kerf taper

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**	**% Contribution**
Cutting Speed	2	0.183926	0.091963	246.21	0.004	58.10
Gas Pressure	2	0.054897	0.027448	73.48	0.026	17.34
Laser Power	2	0.076956	0.038478	103.02	0.034	24.31
Residual Error	2	0.000747	0.000373			
Total	8	0.316527				

Table 4 ANOVA Result of Kerf taper

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**	**% Contribution**
Cutting Speed	2	0.183926	0.091963	246.21	0.004	58.10
Gas Pressure	2	0.054897	0.027448	73.48	0.026	17.34
Laser Power	2	0.076956	0.038478	103.02	0.034	24.31
Residual Error	2	0.000747	0.000373			
Total	8	0.316527				

Table 5 ANOVA Result of Dross formation

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**	**% Contribution**
Cutting Speed	2	21.7763	10.8881	23.90	0.040	55.85
Gas Pressure	2	6.2771	3.1386	6.89	0.127	16.09
Laser Power	2	10.0468	5.0234	11.03	0.083	25.75
Residual Error	2	0.9112	0.4556			
Total	8	39.0114				

D. Confirmation experiment result

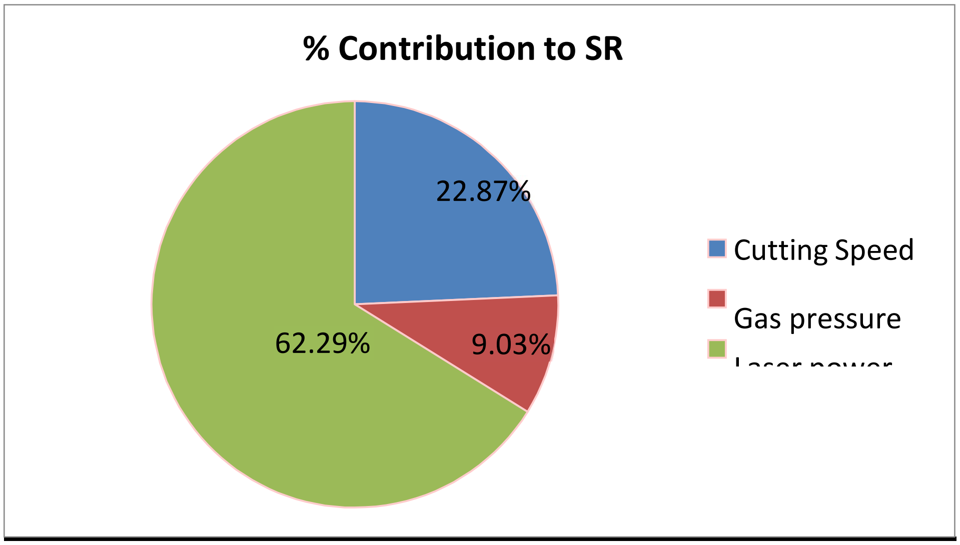
1. Surface Roughness

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

Table 5 Confirmation experiment result for Surface Roughness

Parameter	Taguchi Method		
	Model value	Experimental value	Error %
Surface Roughness(Ra)	2.902	2.891	9.14

Confirmation experiment is conducted by keeping parameters at optimum levels suggested by Taguchi method and the Surface Roughness value obtained has been compared with value predicted by the regression model keeping the parameters at same levels. It can be seen that the difference between experimental result and the predicted result of Taguchi are 9.14% This suggests that the experimental value correlates to the estimated value.



Graph 4 Result of % Contribution of SR by input parameters

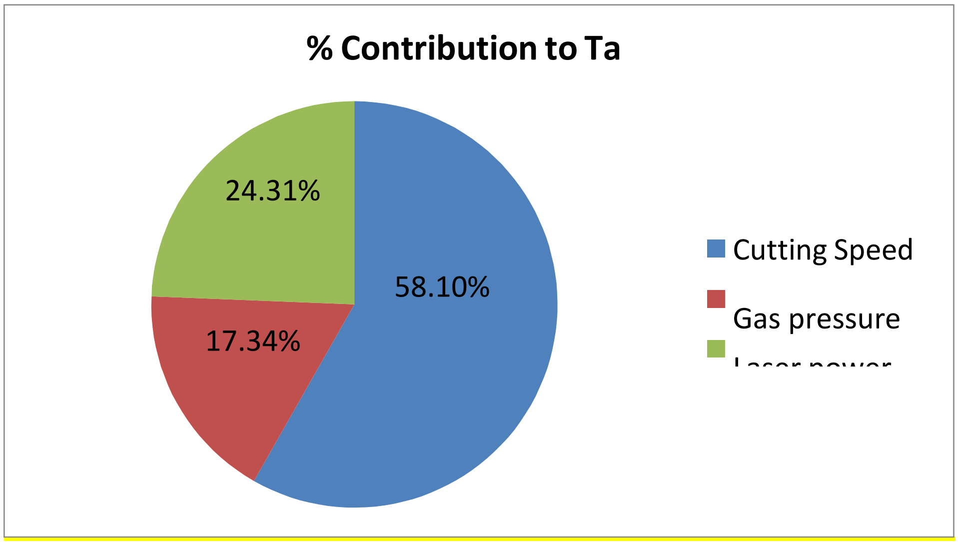
The Graph shows the ANOVA for SS304. The table demonstrates that the cutting speed (22.87%), gas pressure (9.03%), and laser power (62.29%) have a significant impact on the SR.

2. Kerf Taper

difference between value of Kerf taper of confirmation experiment and value predicted from regression model developed.

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 6 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%).

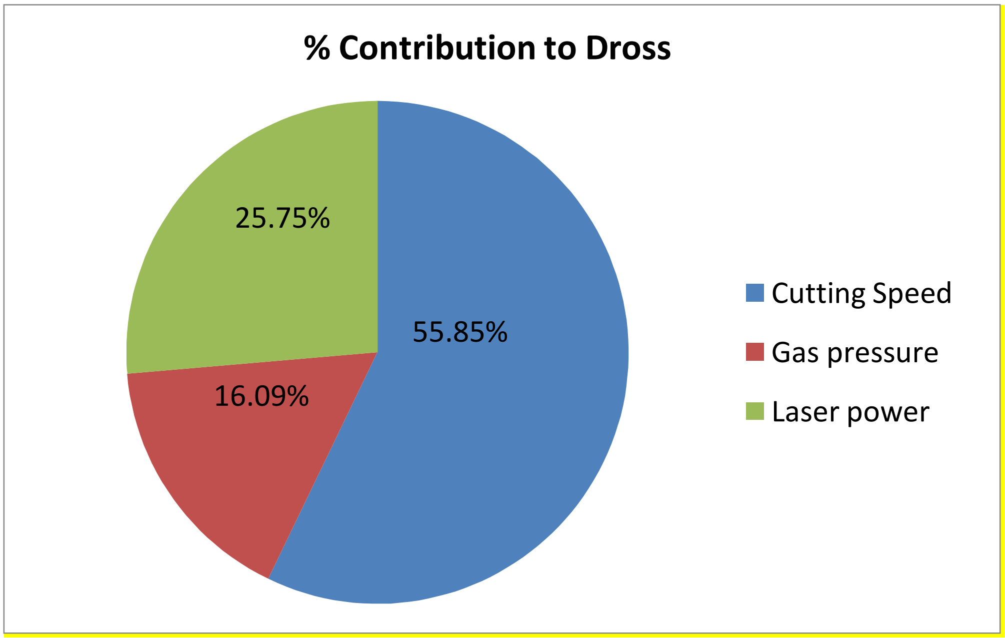
3. Confirmation experiment result for Dross

difference between value of Dross of confirmation experiment and value predicted from regression model developed.

Table 7 Confirmation experiment result for Dross

Parameter	Taguchi Method			RSM Method		
	Model value	Experimental value	Error %	Model value	Experimental value	Error %
Surface Roughness (Ra)	0.228	0.217	4.82	0.219	0.209	4.54

Confirmation experiment is conducted by keeping parameters at optimum levels suggested by Taguchi method and the dross value obtained has been compared with value predicted by the regression model keeping the parameters at same levels. It can be seen that the difference between experimental result and the predicted result of Taguchi and RSM method are 4.82 % This indicates that the experimental value correlates to the estimated value.



Graph 5.6 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): Best results were achieved with a cutting speed of 3500 mm/min, gas pressure of 9 bar, and laser power of 2000 watts.
- Kerf Taper: Optimal settings were a cutting speed of 5500 mm/min, gas pressure of 8 bar, and laser power of 3000 watts.
- Dross Formation: The ideal parameters 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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