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Investigation and Optimization of CO2 Laser Cutting Process on Stainless Steel using DOE technique to analyze the Influence of Process Parameters on the Dimensional Accuracy & Surface Roughness

Gautam Yeshwant Ingole[1], Ravindra Laxman Karwande[2],
Mohamad Javed Abdul Hameed[3],
[1]*(Department of Mechanical Engineering, MSS'S College of Engineering & Technology, Jalna, Maharashtra, India)*
[2,3]*(Department of Mechanical Engineering, MSS'S College of Engineering & Technology, Jalna, Maharashtra, India)*

Abstract:
Metal cutting industries face the challenge of enhancing productivity and sheet metal part quality, especially regarding dimensional accuracy and surface finish. Laser cutting, widely employed across various sectors, offers precision and flexibility but poses challenges like heat generation and oxidation. High pressure and variable cutting velocity result in heat buildup at the torch-sheet interface, causing issues such as burning, roughness, and burr formation, notably in thick stainless-steel sheets. Stainless steel, an essential engineering material, presents challenges for cutting using oxy-fuel methods due to its high melting point and the formation of tenacious oxides. However, laser cutting emerges as a viable solution for this task. This study focuses on analysing the impact of process parameters in a CO2 laser cutting system on the surface characteristics of 5mm Stainless Steel (SS) sheets (ASTM 304). The primary objective is to optimize laser power, cutting speed, and gas pressure to achieve the desired surface roughness. By employing Design of Experiments (DOE), Analysis of Variance (ANOVA), and Response Surface Methodology (RSM), this research scrutinizes the influence of laser cutting variables and identifies the optimal values for surface roughness. The findings underscore the significant impact of laser power on outcomes, compared to cutting speed and gas pressure.

Keywords - AISI SS304, ANOVA, Burr, Cutting Surface, DOE, Laser cutting, Process Optimization, RSM.

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I. Introduction

Laser-beam cutting machining is a thermally based material removal process that relies on highly coherent light as its energy source. When the intense energy of the laser beam interacts with the workpiece, it transfers thermal energy to the surface, causing material to melt and vaporize, facilitating precise removal. This unconventional manufacturing process enables the cutting of various materials with intricate shapes, offering a feasible, effective, and cost-efficient option for metal fabrication. It boasts advantages such as higher processing accuracy, superior cut quality with reduced surface roughness, narrower cut width for material saving, minimal heat-affected zone, and increased productivity. Moreover, laser cutting exhibits characteristics including high precision, low noise, no tool wear, and the absence of fixtures and replaceable tools, minimizing waste and eliminating the need for cutting lubricants. Beyond cutting, laser beams find extensive applications in wire stripping, cosmetic surgery, circuit skiving, drilling, marking, welding, sintering, and heat treatment across industries ranging from military and aerospace to medical and manufacturing. This versatile technology caters to materials ranging from stainless steel and aluminium alloy to wood, rubber, plastic, brass, and Hardox-400, showcasing its broad utility across diverse sectors.

In the ever-evolving landscape of modern manufacturing, the optimization of laser cutting processes stands as a pivotal focus, driven by the quest for enhanced productivity, precision, and quality across diverse industrial applications. Laser cutting, a cornerstone of advanced material processing, harnesses the power of highly coherent light to achieve precise material removal with minimal heat-affected zones. Over the past three decades, extensive research has delved into refining laser cutting techniques, exploring parameters such as laser power, cutting speed, and assist gas pressure to achieve optimal results. Studies have ranged from investigations into the cutting of specific materials like stainless steel and high-alloyed steels to the exploration of innovative cutting strategies such as preheating techniques and adjustments in cutting speed methodologies. Through methodologies like Design of Experiment (DOE), Analysis of Variance (ANOVA), and Response Surface Methodology (RSM), researchers have sought to fine-tune these parameters, aiming to minimize surface roughness, burr formation, and dimensional inaccuracies while maximizing cutting efficiency and quality. Moreover, advancements in laser technology have facilitated its application beyond cutting, encompassing a myriad of processes including welding, marking, sintering, and heat treatment, across industries ranging from aerospace and automotive to medical and manufacturing.

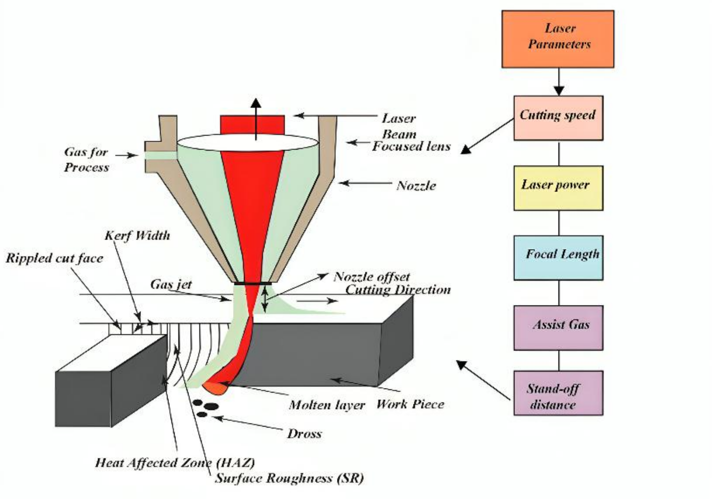


Fig. 1 Mechanism of Laser Cutting

II. Experimental Setup

Laser Beam Machining on SS-304 Stainless Steel material is carried out using a Bodor A3 laser cutting machine, with Oxygen as an assist gas for cutting, operating at a 100% working cycle. The photograph of the LASER cutting machine is given in Fig. 3.1. A 4 mm thickness SS-304 stainless steel was used as the workpiece material, with dimensions of 470 mm × 140 mm. Additionally, 60 mm × 40 mm slots with one edge as semi-circle were cut from the 4 mm thickness plate. The experiment is implemented based on two level full factorial by varying laser power (P), assist gas pressure (p) and Cutting Speed (V). Stainless steel-304, with a thickness of 5 mm, was selected as the workpiece

Fig. 2 Laser Cutting Machine

material. This choice was made due to its lower carbon content, which minimizes carbide precipitation. SS-304 is commonly used in high-temperature applications and is widely employed in sheet metal operations for various industrial and household purposes, such as screws, machinery parts, car headers, and electronics component fabrication. The chemical composition of SS-304 is detailed in Table 2. The study focused on analysing and optimizing cutting parameters, including laser power, cutting speed, and gas pressure, while considering the surface roughness and Dimensional Accuracy of the workpiece.

Table 1 Technical Specification of laser cutting machine

Model	Specification
Laser continuous rated output Maximum	1.5 Kw
cutting size	3048 × 1524 mm
Positioning accuracy	±0.05mm/m
Repositioning accuracy	±0.03mm
Max. linkage speed	100m/min
Max. acceleration	1.5G
Power Supply	Three- Phase 380V

Table 2 Chemical composition of the SS-304

C	Cr	Ni	Mn	Si	P	S	Fe
0.08	18-20	8-10.5	2.0	1.0	0.045	0.030	Balance

We utilized a Design of Experiment approach (DOE), Analysis of Variance (ANOVA), and Response Surface Methodology to examine the cutting parameters while taking into account the surface roughness and Average Dimensional Accuracy of the workpiece, aiming to pinpoint optimized parameter regions. Response Surface Methodology also allowed us to understand the relationship between the interaction of two cutting variables and surface roughness. The table provided (Table 3) showcases the values of the parameters that were adjusted during the execution of experiment.

Table 3 Laser cutting variables and their levels

Symbol	Cutting Parameters	Level 1	Level 2	Level 3
A	Laser power(kW)	1	1.25	1.5
B	Gas pressure(bar)	0.8	1.2	1.6
C	Cutting speed(m/min)	1	1.2	1.4

III. Analysis and discussion of experimental result

The optimization of process parameters in laser cutting was approached using a systematic experimental design. A Central Composite Design (CCD) was utilized to structure the experiments efficiently. The CCD method is well-suited for fitting a quadratic surface, allowing for an accurate

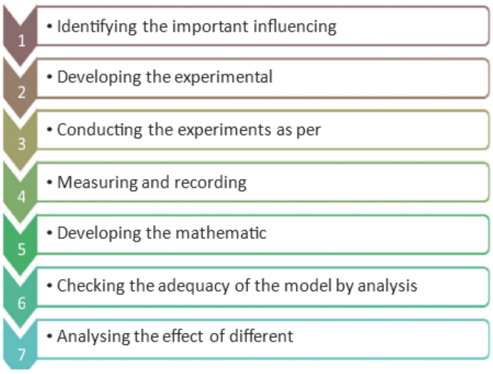


Fig. 3 Seven Steps of RSM

estimation of the response surface with a relatively small number of experiments. A total of 20 experiments were generated using CCD, which includes factorial points, axial points, and canter points. These points help to estimate the curvature of the response surface, assess reproducibility, and provide an estimate of the experimental error. Minitab software was employed to code the variables and establish the design matrix in Table 4, ensuring precision and ease of managing the experimental setup.

Each of the 20 experiments was performed systematically, altering one or more process parameters as per the CCD matrix. The process parameters investigated typically included laser power, cutting speed, and gas pressure. For each experiment, the responses such as surface roughness, and Average Dimensional Accuracy were meticulously measured. This systematic approach ensured a thorough investigation of the effects of the process parameters on the desired outcomes.

Table 4 Experimental Data

Std	Run	Block	Factor 1 A: laser Power kW	Factor 2 B: Gas Pressure Bar	Factor 3 A: Cutting Speed m/min	Response 1 Surface Roughness micron	Response 2 Average Dimensional Accuracy (mm)
1	19	1	1.25	1.2	1.2	2.76	40.2012
2	15	1	1.25	1.2	1.2	2.77	40.1982
3	17	1	1.25	1.2	1.2	2.78	40.1890
4	5	1	1.00	0.8	1.4	2.61	39.8751
5	20	1	1.25	1.2	1.2	2.79	40.2337
6	12	1	1.25	1.6	1.2	3.02	40.1902
7	11	1	1.25	0.8	1.2	2.50	39.9091
8	1	1	1.00	0.8	1.0	2.46	39.7855
9	4	1	1.50	1.6	1.0	3.15	40.0190
10	8	1	1.50	1.6	1.4	3.20	40.0187
11	6	1	1.50	0.8	1.4	2.75	39.8720
12	7	1	1.00	1.6	1.4	3.11	39.9741
13	13	1	1.25	1.2	1.0	2.69	40.1888
14	3	1	1.00	1.6	1.0	2.88	39.8748
15	14	1	1.25	1.2	1.4	2.83	40.2431
16	2	1	1.50	0.8	1.0	2.69	39.8122
17	9	1	1.00	1.2	1.2	2.60	40.0033
18	18	1	1.25	1.2	1.2	2.80	40.2513
19	10	1	1.50	1.2	1.2	2.96	40.2002
20	16	1	1.25	1.2	1.2	2.81	40.2298

In order to find the reasons for variation ANOVA was carried for Ra. This statistical method helps in understanding the significance of each factor and their interactions on the response variables. The key steps in ANOVA for this study included model fitting, significance testing, and interaction effects identification. A quadratic regression model was generated to describe the relationship between the process parameters and the response variables, which included terms for linear effects, quadratic effects, and interactions.

When conducting ANOVA, it is crucial to ensure that several key assumptions are met to validate the results. First, the independence of observations assumes that the data collected from different subjects or experimental units are independent, meaning that the measurement from one subject should not influence another. This is fundamental for the reliability of the ANOVA results. Second, the normality assumption requires that the response variable is approximately normally distributed within each group. This can be assessed using normal probability plots or statistical tests like the Shapiro-Wilk test. Third, the homogeneity of variances, or homoscedasticity, assumes that the variances within each group are equal. This ensures that the variability in each group is similar, which can be verified using tests such as Levene's test or Bartlett's test. Violations of these assumptions can lead to incorrect conclusions, so it's essential to check and address any deviations before relying on ANOVA results. Analysis of variance technique (ANOVA) is carried with Minitab. Value of P is used to determine whether a factor is significant; typically compare against an alpha value of 0.05. If the p-value is lower than 0.05, then the factor is significant. ANOVA table indicated that Laser Power has significant effect on Surface Roughness values followed by Gas Pressure and Cutting Speed.

Table 5 ANNOVA for Ra

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	0.911273	0.101253	67.92	0.000
Linear	3	0.866990	0.288997	193.87	0.000
Laser Power (LP)	1	0.161290	0.161290	108.20	0.000
Gas Pressure (GP)	1	0.640090	0.640090	429.39	0.000
Cutting Speed (Cs)	1	0.065610	0.065610	44.01	0.000
Square	3	0.012945	0.004315	2.89	0.088
LP*LP	1	0.002945	0.002945	1.98	0.190
GP*GP	1	0.000445	0.000445	0.30	0.597
Cs*Cs	1	0.000445	0.000445	0.30	0.597
2-Way Interaction	3	0.031337	0.010446	7.01	0.008
LP*GP	1	0.004512	0.004512	3.03	0.113
LP*Cs	1	0.025312	0.025312	16.98	0.002
GP*Cs	1	0.001512	0.001512	1.01	0.338
Error	10	0.014907	0.001491		
Lack-of-Fit	5	0.013157	0.002631	7.52	0.023
Pure Error	5	0.001750	0.000350		
Total	19	0.926180			

A Analysis of Surface Roughness (Ra)

Surface roughness was measured using the Taylor Hobson Surface Roughness Tester (Surtronic 3). Applying ANOVA on the experimental data, we obtained the influence of each parameter and the adequacy of the data. The summary of the analysis is shown in Table 5. A low P-value (≤0.05) indicates statistical significance for the source on the corresponding response (i.e., $\alpha = 0.05$, or 95% confidence level). This indicates that the obtained models are considered to be statistically significant, which is desirable, as it demonstrates that the terms in the model have a significant effect on the response.

The Model F-value of 67.92 implies the model is significant, indicating that the likelihood of such a large F-value occurring due to noise is very low. Values of "Prob > F" less than 0.0500 indicate model terms are significant, whereas values greater than 0.1000 indicate the model terms are not significant. The Lack of Fit F-value of 7.52 implies the Lack of Fit is significant, suggesting that there is only a 2.3% chance that such a large Lack of Fit F-value could occur due to noise.

The Pareto chart of the standardized effects, shown in Figure 4, highlights the influence of each factor on the response. The chart indicates that Gas Pressure (GP) has the most significant effect, followed by Laser Power (LP), Cutting Speed (Cs), and the interaction between Cutting Speed and Gas Pressure (AC).

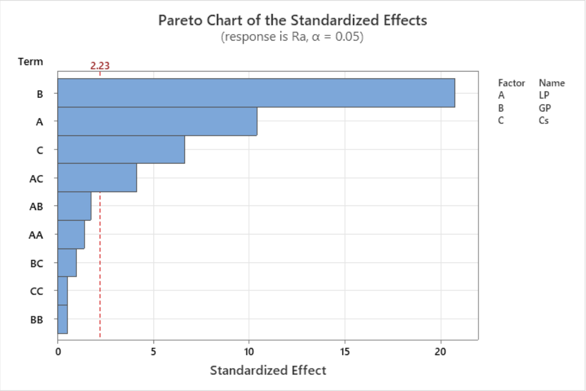


Fig. 3 Pareto Chart of Standardized Effects

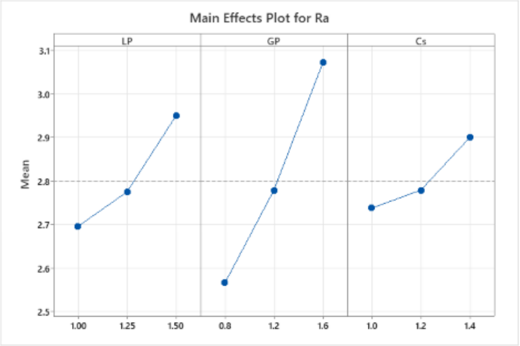


Fig. 5 Main effect Plot

The main effects plot for Ra, shown in Figure 5, illustrates the individual effects of Laser Power (LP), Gas Pressure (GP), and Cutting Speed (Cs) on the surface roughness. The plot shows that as LP, GP, and Cs increase, the mean surface roughness (Ra) also tends to increase, indicating a positive correlation between these factors and the response.

The surface plots for Ra (surface roughness) shown in Figure 6 illustrate the interaction effects between Laser Power (LP), Gas Pressure (GP), and Cutting Speed (Cs).

The plots indicate that increasing LP and GP together leads to higher surface roughness, as does increasing LP and Cs, and GP and Cs. These interactions highlight those higher levels of these factors, whether individually or in combination, result in increased surface roughness.

Regression Equation for the Surface Roughness:

$$Ra = -0.010 + 0.83\ LP + 0.945\ GP + 1.25\ Cs + 0.524\ LP*LP + 0.080\ GP*GP + 0.318\ Cs*Cs$$

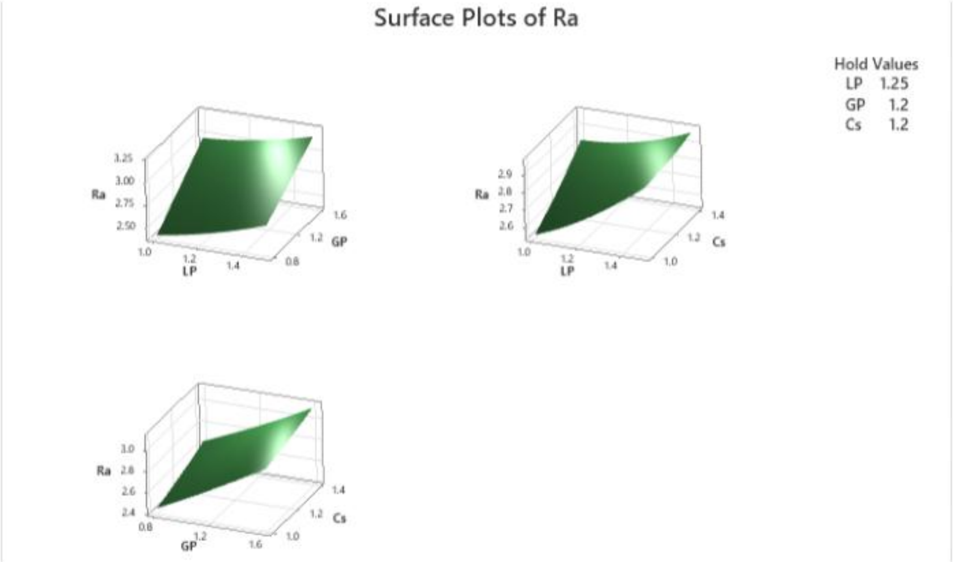


Fig. 6 Surface Plot of Ra

Table 6 ANNOVA for Da

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	0.494333	0.054926	26.45	0.000
Linear	3	0.093632	0.031211	15.03	0.000
Laser Power (LP)	1	0.016753	0.016753	8.07	0.018
Gas Pressure (GP)	1	0.067716	0.067716	32.61	0.000
Cutting Speed (Cs)	1	0.009163	0.009163	4.41	0.062
Square	3	0.394880	0.131627	63.39	0.000
LP*LP	1	0.043662	0.043662	21.03	0.001
GP*GP	1	0.087233	0.087233	42.01	0.000
Cs*Cs	1	0.000383	0.000383	0.18	0.677
2-Way Interaction	3	0.005822	0.001941	0.93	0.460
LP*GP	1	0.003411	0.003411	1.64	0.229
LP*Cs	1	0.002093	0.002093	1.01	0.339
GP*Cs	1	0.000318	0.000318	0.15	0.704
Error	10	0.020764	0.002076		
Lack-of-Fit	5	0.017758	0.003552	5.91	0.037
Pure Error	5	0.003006	0.000601		
Total	19	0.515097			

B Analysis of Average Dimensional Accuracy (Da):

Trimos Vertical 3 TVA-600 2D Height Gauge was used to measure the Average Dimensional Accuracy. The analysis is shown in Table 6. A low P-value (≤0.05) indicates statistical significance for the source on the corresponding response (i.e., $\alpha = 0.05$, or 95% confidence level). This means that the obtained models are considered statistically significant, which is desirable, as it demonstrates that the terms in the model have a significant effect on the response.

The Model F-value of 26.45 implies the model is significant, indicating that the likelihood of such a large F-value occurring due to noise is very low. Values of "Prob > F" less than 0.0500 indicate model terms are significant, whereas values greater than 0.1000 indicate the model terms are not significant. The Lack of Fit F-value of 5.91 implies the Lack of Fit is significant, suggesting that there is only a 3.7% chance that such a large Lack of Fit F-value could occur due to noise.

The Pareto chart of the standardized Effect shown in figure 7 indicates that the interaction term BB (related to Gas Pressure, GP) has the most significant effect, followed by the main effect of Gas Pressure (B), and then the interaction term AA (related to Laser Power, LP). Cutting Speed (Cs) and the interaction between Cutting Speed and Gas Pressure (AC) also contribute, but their effects are not statistically significant at the 0.05 level. This suggests that GP is the most influential factor, with LP and their interactions also playing crucial roles in affecting the response variable Da.

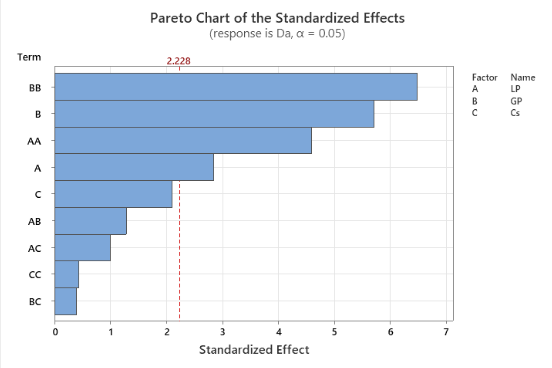


Fig. 7 Pareto Chart of the Standardized Effects

The Main Effect plot shown in figure 8 shows that as LP increases, the mean response Da also increases, reaching a peak, and then decreases as LP further increases. Similarly, as GP, and Cs increase, the mean response Da initially rises to a peak and then decreases. This indicates that the mean Da is optimized at intermediate levels of LP, GP, and Cs.

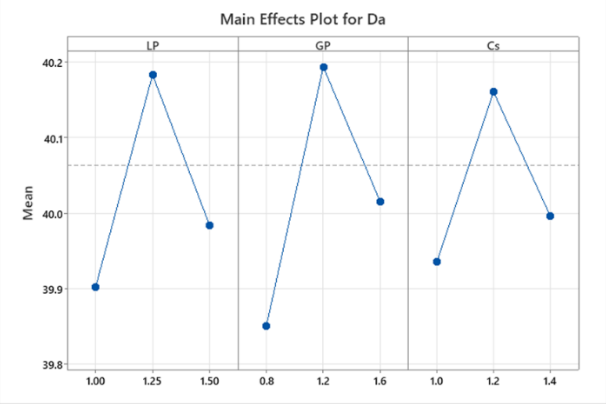
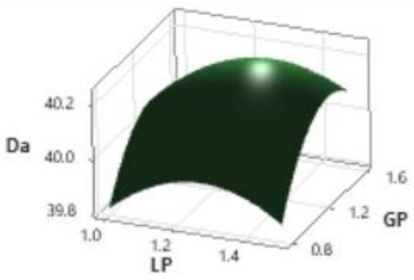


Fig. 8 Main Effect Plot for Da

The Surface plot graph shown in figure 9 and 10 highlights that the plot of LP and GP shows that Da increases with moderate levels of both factors, reaching a peak at intermediate values and declining at higher or lower levels. Similarly, the plot of LP and Cs indicates that dimensional accuracy is optimized at intermediate levels of both factors. The plot of GP and Cs also demonstrates that Da is maximized when both factors are at moderate levels. Overall, these surface plots emphasize that dimensional accuracy is optimized when LP, GP, and Cs are balanced at intermediate values, indicating a non-linear relationship where neither too high nor too low levels yield the best results.

Regression Equation for Average Dimensional Accuracy (Da):

$$Da = 34.12 + 5.34\,LP + 2.714\,GP + 1.36\,Cs - 2.016\,LP*LP - 1.113\,GP*GP - 0.295\,Cs*Cs + 0.207\,LP*GP - 0.323\,LP*Cs - 0.079\,GP*Cs$$



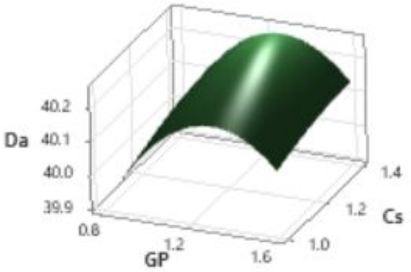


Fig.9 Surace Plot of Da

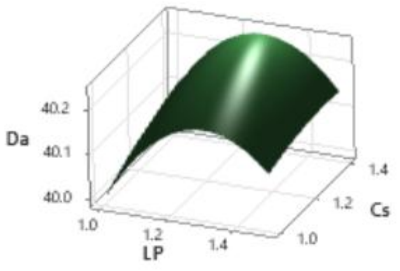


Fig. 10 Surface Plot of Da

IV. Conclusion

In this study, a comprehensive analysis of process parameters influencing laser cutting was conducted using a CNC laser cutting machine Bodor A3. Following Design of Experiments (DOE) analysis, 20 experimental runs were identified for Cutting operations on 4 mm thick SS 304 material. Achieving optimal surface roughness (Ra) and dimensional accuracy (Da) in laser cutting depends on managing laser power, gas pressure, and cutting speed effectively. Higher laser power initially reduces roughness by improving material removal efficiency, but excessive power can overheat the material, increasing roughness. Gas pressure is critical for ejecting molten material, which promotes smoother cuts and finer finishes. Cutting speed impacts both Ra and Da: moderate speeds minimize roughness by reducing heat input per unit length, whereas very high speeds can compromise cut quality and dimensional precision. Balancing medium to high laser power, optimal gas pressure, and adjusted cutting speed is essential for consistent quality across different materials and thicknesses.

Through regression analysis, the study determined that laser power holds the highest significance among cutting speed and gas pressure in influencing the laser cutting process. Additionally, the interaction between laser power and gas pressure was identified as the most significant. The optimized values derived from this analysis were determined to be Laser Power at 1 KW, Gas Pressure at 0.8 Bar, and Cutting Speed set to 1 m/min.

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