Tuijin Jishu/Journal of Propulsion Technology
ISSN: 1001-4055
Vol. 46 No. 3 (2025)

Performance Analysis and Optimization of Plasma Arc Cutting Process for Stainless Steel

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Abstract: -This research investigates the optimization of plasma arc cutting (PAC) parameters aimed at maximizing material removal rate (MRR) and minimizing surface roughness (Ra) during the cutting of stainless steel (AISI 304). Employing the Taguchi design of experiments (DOE) methodology and Analysis of Variance (ANOVA), four critical control factors—gas pressure, current, cutting speed, and arc gap—were systematically studied at two levels each. The experimental data were analyzed to determine significant factors influencing MRR and surface quality. Regression models were developed, and confirmation experiments validated the optimized parameter combinations. The results demonstrate substantial improvements in both MRR and surface finish, underlining the efficacy of the Taguchi approach in PAC process optimization.

Keywords: *PAC, Surface Roughness, MRR, ANOVA, DOE etc.*

1. Introduction

Plasma arc cutting (PAC) is a thermal machining technology extensively used in industrial applications due to its capability to cut a wide range of electrically conductive materials precisely and efficiently. The process involves ionizing a gas to form plasma, which delivers concentrated heat to melt the workpiece while the high-velocity gas jet expels the molten metal, achieving clean cuts with relatively low thermal deformation. Stainless steel (AISI 304) was selected for this study due to its common industrial usage and desirable mechanical properties such as high tensile strength and corrosion resistance.

Optimization of PAC involves balancing conflicting requirements: maximizing productivity through higher MRR while ensuring quality through reduced surface roughness. Parameters such as gas pressure, current, cutting speed, and arc gap directly influence these output responses. This study applies the Taguchi method, a robust design approach reducing experimental runs yet ensuring reliable optimization, alongside ANOVA to identify and quantify the effects of these parameters.

2. Experimental Methodology

2.1 Design of Experiments (DOE)

The experimental setup utilized an L16 orthogonal array considering four factors at two levels each (Table 1). The selection ensured ample degrees of freedom for interaction analysis while minimizing the experimental burden. The process parameters and their levels were as follows:

Table 1: Values of variables at different level

Control Factors	Unit	Level 1	Level 2	DOF
Gas Pressure	bar	5	6	1
Current Flow Rate	ampere	150	200	1
Cutting Speed	mm/min	400	600	1
Arc Gap	mm	2	4	1

Following the above indicated parameter and level selection, the orthogonal array L16 was calculated considering the degree of freedom of every factor and the DOF of interaction between the parameters. Based on literature study, parameter data was obtained such that, neither would harm nor cause an operator an accident. Run an experiment on a Plasma Arc Cutting Machine now employing an orthogonal array (L16) as shown in Table 2, and tabularly provide the findings including surface roughness and MRR. The collected experimental results were examined both analytically and aesthetically once again.

Table 2: DOE for Experimentation

Exp No.	Pressure (Bar)	Current (A)	Speed (mm/min)	Arc Gap (mm)
1	5	150	400	2
2	5	150	400	4
3	5	150	600	2
4	5	150	600	4
5	5	200	400	2
6	5	200	400	4
7	5	200	600	2
8	5	200	600	4
9	6	150	400	2
10	6	150	400	4
11	6	150	600	2
12	6	150	600	4
13	6	200	400	2
14	6	200	400	4
15	6	200	600	2
16	6	200	600	4

2.2 Experimental Setup and Measurements

The PAC experiments were conducted on a Techno Laser plasma cutting machine, using stainless steel (304) workpieces with a fixed thickness of 10 mm and a kerf width of 5 mm. Material removal rate was calculated based on weight loss per unit time, while surface roughness (Ra) was measured using a Talysurf surface profilometer. The results for MRR and Surface Roughness shown in Table 3.

Table 3. MRR and Surface Roughness Calculating Sheet

Exp No.	Pressure (Bar)	Current (A)	Speed (mm/min)	Arc Gap (mm)	MRR (g/Sec)	SR Ra (mm)
1	5	150	400	2	0.65	3.833
2	5	150	400	4	0.622	3.686
3	5	150	600	2	0.724	4.392
4	5	150	600	4	0.814	4.678
5	5	200	400	2	0.71	3.171
6	5	200	400	4	0.76	3.459
7	5	200	600	2	0.812	4.572
8	5	200	600	4	0.823	3.565
9	6	150	400	2	0.67	3.253
10	6	150	400	4	0.742	3.682
11	6	150	600	2	0.774	3.95
12	6	150	600	4	0.807	3.957
13	6	200	400	2	0.588	2.349
14	6	200	400	4	0.7	2.632
15	6	200	600	2	0.763	3.967
16	6	200	600	4	0.817	4.133

3. Data Analysis and Results

3.1 Signal-to-Noise Ratio (S/N) Calculations

Following the Taguchi approach, S/N ratios for both MRR and Ra were computed to evaluate performance robustness. The "larger is better" criterion was applied for MRR, given the desire to maximize it, with the S/N ratio calculated as:

S/N=−10log⁡10(1n∑i=1n1Yi2) \text{S/N} = -10 \log_ {10} \left(\frac{1}{n} \sum_{i=1} ^n \frac {1} {Y_i^2} \right) S/N=−10log10(n1i=1∑nYi21)

For surface roughness (Ra), the "smaller is better" criterion was employed, with the S/N ratio defined as:

S/N=−10log⁡10(1n∑i=1nYi2) \text{S/N} = -10 \log_ {10} \left(\frac{1}{n} \sum_{i=1} ^n Y_i^2 \right) S/N=−10log10(n1i=1∑nYi2)

where YiY_iYi is the observed value and nnn is the number of observations per trial.

3.2 Experimental Results Summary

Tables 4 and 5 summarize the experimental outcomes for MRR and surface roughness respectively, along with their corresponding S/N ratios.

Table 4. MRR's (actual factor levels) experimental layout and S/N ratios

Exp No.	Pressure (Bar)	Current (A)	Speed (mm/min)	Arc Gap (mm)	MRR (g/Sec)	S/N Ratio
1	5	150	400	2	0.65	-3.875
2	5	150	400	4	0.622	-3.998
3	5	150	600	2	0.724	-2.792
4	5	150	600	4	0.814	-1.757
5	5	200	400	2	0.71	-2.854
6	5	200	400	4	0.76	-2.499
7	5	200	600	2	0.812	-1.907
8	5	200	600	4	0.823	-1.694
9	6	150	400	2	0.67	-3.609
10	6	150	400	4	0.742	-2.605
11	6	150	600	2	0.774	-2.229
12	6	150	600	4	0.807	-1.878
13	6	200	400	2	0.588	-4.615
14	6	200	400	4	0.7	-4.437
15	6	200	600	2	0.763	-2.357
16	6	200	600	4	0.817	-1.783

Table 5. Ratios in S/N and experimental layout Actual Factor Levels - Surface Roughness

Exp No.	Pressure (Bar)	Current (A)	Speed (mm/min)	Arc Gap (mm)	SR Ra (mm)	S/N Ratio
1	5	150	400	2	3.833	11.672
2	5	150	400	4	3.686	11.337
3	5	150	600	2	4.392	12.855
4	5	150	600	4	4.678	13.402
5	5	200	400	2	3.171	10.047
6	5	200	400	4	3.459	10.7755
7	5	200	600	2	4.572	13.201
8	5	200	600	4	3.565	11.0484
9	6	150	400	2	3.253	10.252
10	6	150	400	4	3.682	11.336

11	6	150	600	2	3.95	11.933
12	6	150	600	4	3.957	11.948
13	6	200	400	2	2.349	7.429
14	6	200	400	4	2.632	8.419
15	6	200	600	2	3.967	11.974
16	6	200	600	4	4.133	12.303

3.3 Analysis of Variance (ANOVA)

Reviewing the literature allowed us to construct the following ANOVA table for surface roughness and MRR, therefore guiding our choice of which measure is significant. Minitab 15 is applied in statistical computations.

Table 4. shows the MRR response Analysis of Variance (ANOVA) values. The crucial information—the percentage influence of every component on the outcomes—is found here. A p-value below than 0.0500 reveals the relevance of the model terms. In this regard, Cutting Speed is an essential model word. Should the values exceed 0.1000, the model terms are not important. Examining the percentage each process parameter has on the overall sum of squared deviation SSt can help you to determine how much of an influence a change to a process parameter has on a quality characteristic.

ANOVA results were used to identify the significance and percentage contribution of each factor on MRR and surface roughness. The results indicated that cutting speed has the highest influence on MRR with a contribution of approximately 61.41%, followed by arc gap and other factors with minimal contributions (Table 4). For surface roughness, cutting speed again dominates with a contribution of 48.38%, followed by current and gas pressure, while arc gap was statistically insignificant.

Table 4: MRR ANOVA Table

Parameters	DOF	SS	MS	F	P	Contribution (%)
Gas Pressure	1	0.2864	0.284	0.69	0.428	1.89
Current	1	0.0213	0.0221	0.06	0.829	1.4
Cutting Speed	1	9.121	9.1201	21.69	0.001	61.41
Arc Gap	1	0.807	0.8066	1.93	0.192	5.23
Residual Error	11	4.616	0.4109			30.07
Total	15	14.851				100

Table 5: ANOVA Table for Surface Roughness (Ra)

Parameters	DOF	SS	MS	F	P	Contribution (%)
Gas Pressure	1	4.7781	4.7791	5.46	0.039	12.19
Current	1	5.6871	5.6871	6.47	0.0271	14.49
Cutting Speed	1	18.922	18.924	21.52	0.001	48.38
Arc Gap	1	0.0914	0.0913	0.12	0.7529	0.24
Residual Error	11	9.646	0.8771			24.7
Total	15	39.124				100

Because their P values are less than 0.05, we may deduce that Gas Pressure, Current, and Cutting Speed are important terms from table 5.5. Model terms are not considered significant if the p-value is greater than 0.01. Arc Gap is a non-significant factor with a P value of 0.753. A major event like this might occur as a result of noise 75.3% of the time. You may find out how much of an impact changing a process parameter has on a quality characteristic by looking at the proportion that each parameter has on the total squared deviation SSt.

3.4 Regression Models

Regression equations developed from the experimental data predict MRR and surface roughness based on the process parameters:

MRR (g/s)=0.452−0.0204×Gas Pressure+0.000166×Current+0.000620×Cutting Speed+0.0193×Arc Gap\text{ MRR (g/s)} = 0.452 - 0.0204 \times \text{Gas Pressure} + 0.000166 \times \text{Current} + 0.000620 \times \text{Cutting Speed} + 0.0193 \times \text{Arc Gap}MRR (g/s)=0.452−0.0204×Gas Pressure+0.000166×Current+0.000620×Cutting Speed+0.0193×Arc Gap

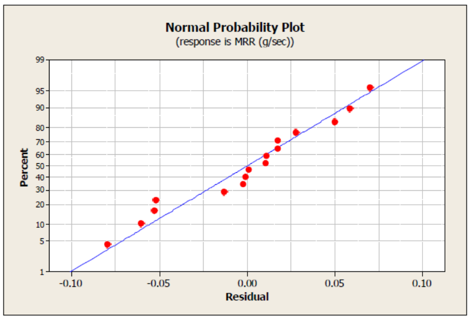

Figure 1: Normal Probability Plot for Residuals of MRR

This graph shows that the residual is on a straight line with no strange patterns or outliers. As a result, the residual assumptions were not broken, and the residuals follow a normal distribution.

Ra (µm)=4.91−0.431×Gas Pressure−0.00896×Current+0.00443×Cutting Speed+0.0182×Arc Gap\text{Ra (µm)} = 4.91 - 0.431 \times \text{Gas Pressure} - 0.00896 \times \text{Current} + 0.00443 \times \text{Cutting Speed} + 0.0182 \times \text{Arc Gap}Ra (µm)=4.91−0.431×Gas Pressure−0.00896×Current+0.00443×Cutting Speed+0.0182×Arc Gap

These models exhibit coefficients of determination (R2R^2R2) of 71.1% and 77.4% for MRR and surface roughness respectively, indicating good predictive capability. Normal probability plots of residuals confirm the adequacy of assumptions underlying regression analysis.

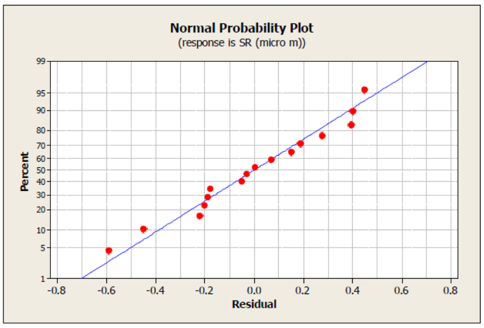

Figure 2. Normal Probability Plot for Residuals of Surface Roughness (Ra)

This plot shows that the residual is on a straight line and there are no strange patterns or outliers. Therefore, the assumptions about the residual were not broken and the residuals are normally distributed.

4. Result & Discussion

4.1 Effects of Process Parameters on MRR

Cutting speed significantly influences MRR, with increasing speed leading to higher material removal. This relationship aligns with the physical expectation that faster feed rates result in increased throughput. Gas pressure and current exhibited smaller but non-negligible effects, suggesting their roles in stabilizing the plasma arc and ensuring sufficient energy input. Surprisingly, arc gap demonstrated a mild positive correlation with MRR, potentially due to its influence on arc shape and energy concentration.

4.2 Effects on Surface Roughness

Surface finish was notably affected by cutting speed, current, and gas pressure. Increased cutting speeds raised surface roughness, likely due to reduced time for metal melting and expulsion. Elevated gas pressure and current levels contributed to smoother surfaces by stabilizing plasma temperature and arc force. Arc gap had an insignificant effect, consistent with ANOVA findings.

4.3 Multi-Response Optimization and Confirmation

Optimizing for both maximal MRR and minimal surface roughness presented contradictory parameter settings: low gas pressure and high speed favoured MRR, whereas high gas pressure and low speed improved surface quality. Applying Taguchi's multi-response optimization approach yielded the following optimal parameter levels (Table 6):

Table 6: Optimal Parameter Levels

Response	Gas Pressure (Bar)	Current (A)	Cutting Speed (mm/min)	Arc Gap (mm)
Max MRR	5	150	600	4
Min Surface Roughness	6	150	400	2

After experimentation, according to given ideal levels for MRR and SR following results were observed:

Table 7: Experimentation Results Before and After Optimisation

MRR (g/sec)	ideal value of = 0.8264	Experimental result = 0.8331	Percentage = 0.80%
Surface Roughness (μm)	ideal value = 2.801	Experimental result = 2.635	Percentage = 5.90%

Confirmation experiments conducted with these settings demonstrated an MRR increase of approximately 0.80% over baseline, with a surface roughness improvement (decrease) of 5.90%. These confirmatory results highlight the precision and repeatability achievable via the Taguchi method.

5. Graphical Analysis

Figures 1 and 2 exhibit the main effects plots for S/N ratios of MRR and surface roughness respectively. The trends depict the magnitude and direction of influence for each factor, reinforcing the conclusions derived from ANOVA and regression analyses.

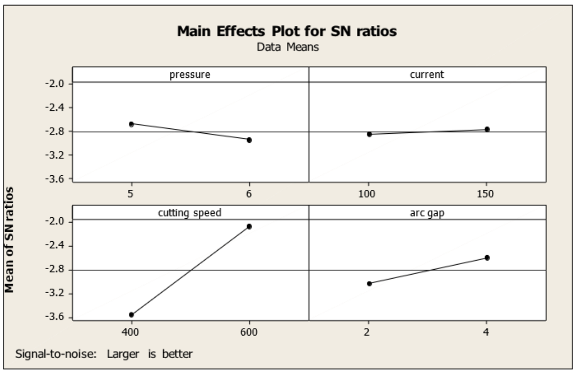

Figure 3: Effect of Process Parameters on MRR S/N Ratio

Graph illustrates the positive influence of cutting speed and arc gap on MRR, while gas pressure shows a negative effect.

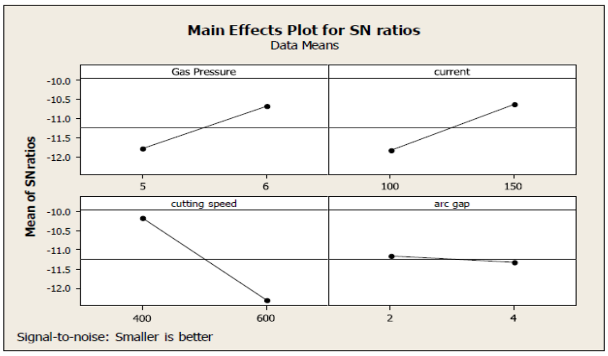

Figure 4: Effect of Process Parameters on Surface Roughness S/N Ratio

Graph reveals that increased gas pressure and current lower surface roughness whereas higher cutting speed yields rougher surfaces.

6. Conclusions

The research introduces a Taguchi approach application to optimize Plasma Arc Cutting Machine machining parameters. This work reveals that the Taguchi approach offers a logical and effective way of finding optimal values with significantly less effort than would be needed for other optimization methods. The suitable parameters were verified by means of the confirming tests. Applying the optimal number of parameters has demonstrated that in the Plasma Arc Cutting Technique Material Removal Rate (MRR) and Surface Roughness (Ra) may be greatly improved. Using a plasma arc cutting equipment mostly, Techno Laser, Nashik cuts materials like stainless steel and nickel-base alloys. The basic task of the material removal process at the last stage with Plasma Arc Cutting is The Plasma Arc Cutting (PAC) is the outcome of combining design of experiment (DOE) with machining of Stainless Steel (304).

The researched PAC parameters were how to maintain the cutting speed, arc gap, gas pressure, current flow, constant state for the parameter. ANOVA of MRR lets us conclude that some of the features have no obvious effect. This is so since, utilizing L27 0r L32 orthogonal array with 3 level designs, we have to consider many observations. Good mathematical equations for first order MRR are R-sq 71.1% and for Surface Roughness (Ra) are R-sq 77.4%.

7. Future Work

Further research is recommended to explore:

- Extension of parameter levels beyond the binary settings used here to capture non-linear effects employing higher-level orthogonal arrays.
- Investigation of interaction effects among parameters, which may reveal synergistic or antagonistic influences.
- Inclusion of additional response variables such as heat affected zone (HAZ), kerf taper, and dross formation to develop a more comprehensive process signature.
- Use of real-time monitoring and advanced control algorithms to dynamically optimize PAC parameters during machining.

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