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Experimental Investigations to Study the Impact of Machining Parameters on Mild Steel Using Plasma Arc Cutting

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ABSTRACT

Plasma arc cutting is extensively used to cut steels and aluminum. Plasma arc cutting was invented in 1950's and since then, it became commercial on its advent into the industry. The purpose of this research is to ascertain the influence of various parameters on plasma arc cutting process while machining mild steel. The experiments were conducted using Taguchi L16 orthogonal array with current, voltage, speed, plate thickness as the control parameters and surface roughness, kerf as the response variables. The optimal parameter setting for the machining process is determined by conducting a Grey-Taguchi method. Orthogonal array L16 (4 power 4) of Taguchi, Signal to Noise ratio, the Analysis of Variance(ANOVA) are employed to find the optimal levels and to analyze the optimum levels and to analyze the impact of current, voltage, speed, plate thickness on kerf and surface roughness.

Keywords – ANOVA, Grey Relational Grade, Grey Relational Method, Kerf, Optimal parameters, Orthogonal Array, Plasma Arc Cutting, Taguchi Method.

I. INTRODUCTION

The plasma arc cutting (PAC) is a widely used process to cut steel in various industries using a plasma torch. In this process, an electric arc is produced by blowing an inert gas (usually Argon) at high speed out of a nozzle [1]. The arc formed between the electrode and the workpiece is narrowed by a nozzle and hence, the temperature and velocity of plasma coming out of the nozzle increases. The temperature of the plasma reaches a peak value of 20000°C and the velocity approaches the speed of sound. In the present work, a CNC plasma arc cutting machine is used for conducting the experiments.

In a PAC process, the power source used has a drooping characteristic and a high voltage. The operating voltage range lies in between 50V to 60V and the arc initiated is up to 400V D.C. A dual gas system is used in order to provide a gas shield. The gas shield increases arc constriction and helps in blowing away the dross. Oxygen is used as a plasma forming gas and nitrogen is used as a shielding gas. Input parameters such as plate thickness, speed of the nozzle, current and voltage are used in the study.

The objective of this work is to optimize the multiple performance measures such as surface roughness and kerf. PAC is one of the most predominantly used processes for cutting mild steel in the industry and due to this reason mild steel has been chosen as a work material for the study [2].

Mild steel is also known as plain carbon steel and is now the most commonly used, providing many applications [3]. Mild steel con contains approximately 0.05%-0.19% carbon, a maximum of 0.40% silicon, 0.70%-0.90% manganese, 0.04% sulphur and 0.04% phosphorous. Mild steel has low tensile strength and being a softer material it is weldable.

In this work, Taguchi method is used to optimize the machining parameters as it has been a powerful tool for enhancing productivity and quality at low cost. Taguchi method of parameter design is exploited for optimizing the material characteristics like surface roughness and kerf. The orthogonal array L16 with grey relational analysis is used to investigate the performance characteristics in PAC process for machining mild steel.

The grey relational coefficients corresponding to each of the performance characteristics are computed. These grey relational coefficients are averaged to obtain the grey relational grade. The grey relational grade is used to assess the multiple performance characteristics. As a result, the complicated multiple performance characteristics are transformed into a simple optimization of single grey relational grade.

"[4], [5]"

Statistical analysis of variance (ANOVA) is performed to identify the statistically significant process parameter. The optimal combination of process parameters can be predicted with the aid of grey relational analysis and statistical analysis of variance. Ultimately the optimal process parameters obtained from process parameter design are verified by conducting a confirmation experiment.

II. EXPERIMENTAL PROCEDURE

2.1 Schematics of Machining

In plasma arc cutting process the material is removed by an electrical arc formed by the inert gas (ARGON) between the tip of the nozzle and surface of the work material. The electrical arc formed turns some part of the gas into plasma which removes the material in form of small kerfs by melting the work material. The material during the cutting process is facilitated with a water bed so as to cool it. The common machining parameters in the plasma arc cutting process are plate thickness, speed of the nozzle, current and voltage. "[6], [7]" The electrode is typically made of copper with an insert made of hafnium. A gap of 3.25mm is maintained between the torch tip and work piece. An inert gas (Argon) is blown at high speed out of a nozzle and at the same. The chemical composition of mild steel used as a work piece in the cutting process is given below.

TABLE 1 CHEMICAL COMPOSITION OF MILD STEEL

Carbon	Silicon	Manganese	Sulphur	Phosphorous
0.16-0.18%	0.40% Max	0.70-0.90%	0.040 % Max	0.040% Max

In the present study, the major performance characteristics considered are Kerf and Surface Roughness. After completion of the cutting process, the kerf width is calculated in millimeters by using vernier calipers. The surface roughness is values are measured by using surface roughness tester.

Fig. 1 CNC Plasma arc cutting machine

Fig. 2 Surface Roughness Tester

2.2 Process Parameters and Design

The input parameters in the present work are plate thickness, speed, current and voltage. Each factor is investigated at four levels to determine the optimal settings for plasma arc cutting process [8].

TABLE 2 CONTROL FACTORS AND THEIR LEVELS

Symbol	Control factors	Units	Level-1	Level-2	Level-3	Level-4
A	Plate Thickness	mm	8	10	14	16
B	Speed	mm /min	2500	3000	3500	4000
C	Current	A	222	228	235	253
D	Voltage	V	130	150	170	190

The experiment is based on Taguchi L16 orthogonal array design. This array can handle four level design parameters. Each of the machining parameters is assigned to the columns of the design matrix and there are sixteen such input parameter combinations available. Therefore, the entire parameter space can be studied by these sixteen experiments using the L16 orthogonal array [9].

TABLE 3 DESIGN MATRIX AND EXPERIMENTAL RESULTS

Expt. no	Control Factors				Kerf (mm)	Surface Roughness (μm)
	A	B	C	D		
1	1	1	1	1	3.38	2.33
2	1	2	2	2	3.32	2.45
3	1	3	3	3	3.26	2.38
4	1	4	4	4	3.24	2.84
5	2	1	2	3	3.42	2.78
6	2	2	1	4	3.46	2.61
7	2	3	4	1	3.30	2.66
8	2	4	3	2	3.34	2.71
9	3	1	3	4	3.58	3.20
10	3	2	4	3	3.52	3.15
11	3	3	1	2	3.66	3.52
12	3	4	2	1	3.60	3.44
13	4	1	4	2	3.72	3.95
14	4	2	3	1	3.78	3.54
15	4	3	2	4	3.82	3.86
16	4	4	1	3	3.88	3.71

1. j=1, 2...n; k=1,2…m, n is the number of experimental data items and m is the number of responses.
2. $y_o(k)$ is the reference sequence ($y_o(k)$=1, k=1,2…m); $y_j(k)$ is the specific comparison sequence.
3. Δ_{oj} = ‖ $y_o(k)$ - $y_j(k)$ ‖ = The absolute value of difference between $y_o(k)$ and $y_j(k)$.

III. GREY RELATIONAL ANALYSIS PROCEDURE

Step 1: The response characteristic $y_j(k)$ is normalized as $y_j^*(k)$ ($0 \le y_j^*(k) \le 1$) by the following formula to transform the random grey data into dimensionless parameters. This is known as data pre-processing. The quality characteristics of the original data are transformed into a set of comparable sequences by data pre-processing."[10], [11]"

The main categories for normalizing the original sequence depends on the quality characteristics are as follows:

'Larger the better':

$$y_j^*(k) = \frac{y_j(k) - \min(y_j(k))}{\max(y_j(k)) - \min(y_j(k))} \quad (1)$$

'Smaller the better':

$$y_j^*(k) = \frac{\max(y_j(k)) - y_j(k)}{\max(y_j(k)) - \min(y_j(k))} \quad (2)$$

Step 2: The grey relational grade for the normalized values is calculated by using a weighing method. The weighing method integrates the grey relational co-efficients of each experiment into the grey relational grade.

Calculate Grey relational Co-efficient for the normalized values.

$$\gamma(y_o(k), y_j(k)) = \frac{\Delta\min + \xi.\Delta\max}{\Delta_{oj}(k) + \xi.\Delta\max} \quad (3)$$

Where,

4. $\Delta\min = \min_{\forall j \in i} \min_{\forall k} \left| y_o(k) - y_j(k) \right|$ is the smallest value of $y_j(k)$

5. $\Delta\max = \max_{\forall j \in i} \max_{\forall k} \left| y_o(k) - y_j(k) \right|$ is the largest value of $y_j(k)$

6. ξ is the distinguishing co-efficient which is defined in the range $0 \le \xi \le 1$

Step 4: The grey relational grade aids in evaluating the multiple performance characteristics of the machining process. The grey relational grade is calculated as

$$\overline{\gamma_j} = \frac{1}{k} \sum_{j=1}^{m} \gamma_{oj} \quad (4)$$

Where γ_j the grey relational grade for the jth experiment and k is the number of performance characteristics.

Step 5: The optimal factor and the combination of levels are determined. The optimal parameters are determined from the maximum value of grey relational grade. Thus, the parameters affecting the process can be estimated.

Table 4 Grey Relational Generation And Δ_{oi} Of Each Of The Performance Characteristics

Trail no	Normalized		Deviation Sequence Δ_{oi}	
	Kerf	Ra	Kerf	Ra
1	0.78125	1.00000	0.21875	0.00000
2	0.8750	0.92592	0.12450	0.07408
3	0.96875	0.96913	0.03125	0.03087
4	1.00000	0.68518	0.00000	0.31482
5	0.71875	0.72222	0.28125	0.27778
6	0.65625	0.82716	0.34375	0.17284
7	0.90625	0.79629	0.09375	0.20371
8	0.84375	0.76543	0.15625	0.23457
9	0.46875	0.46296	0.53125	0.53704
10	0.56250	0.49382	0.43750	0.50618
11	0.34375	0.26543	0.65625	0.73457
12	0.43750	0.31481	0.56250	0.68519
13	0.25000	0.00000	0.75000	1.00000
14	0.15625	0.25309	0.84375	0.74691
15	0.09375	0.05555	0.90625	0.94445
16	0.00000	0.14815	1.00000	0.85185

Table 5 Grey Relational Coefficient And Grey Relational Grade Of Each Performance Characteristics (Distinguished Coefficient = 0.5)

Trail No	Kerf	Ra	Grey relational grade
1	0.390243902	0.333333333	0.361788618
2	0.363636364	0.350650808	0.357143586
3	0.340425532	0.340337479	0.340381505
4	0.333333333	0.421876846	0.377605090
5	0.410256410	0.409091653	0.409674032
6	0.432432432	0.376744326	0.404588379
7	0.355555556	0.385716159	0.370635857
8	0.372093023	0.395122607	0.383607815
9	0.516129032	0.519232367	0.517680700
10	0.470588235	0.503109215	0.486848725
11	0.592592593	0.653227598	0.622910095
12	0.533333333	0.613639990	0.573486662
13	0.666666667	1.000000000	0.833333333
14	0.761904762	0.663931270	0.712918016
15	0.842105263	0.900009000	0.871057132

16	1.000000000	0.771426367	0.885713184

Table 6 Control Factors And Grey Relational Grade

Expt. no	Control Factors A	B	C	D	Grey relational grade
1	1	1	1	1	0.361788618
2	1	2	2	2	0.357143586
3	1	3	3	3	0.340381505
4	1	4	4	4	0.377605090
5	2	1	2	3	0.409674032
6	2	2	1	4	0.404588379
7	2	3	4	1	0.370635857
8	2	4	3	2	0.383607815
9	3	1	3	4	0.517680700
10	3	2	4	3	0.486848725
11	3	3	1	2	0.622910095
12	3	4	2	1	0.573486662
13	4	1	4	2	0.833333333
14	4	2	3	1	0.712918016
15	4	3	2	4	0.871057132
16	4	4	1	3	0.885713184

The main effects of multiple performance characteristics on the plasma arc cutting process are ascertained from the grey relational grade in Table 6. Thus, it is observed that the optimization of a perplexed multiple performance characteristics is transformed into a naive optimization problem with grey relational grade as single response. The corresponding response table of means for overall grey relational grade is tabulated below."[12], [13]"

TABLE 7 RESPONSE TABLE (MEAN) OF GREY RELATIONAL GRADE FOR MILD STEEL

Level	A	B	C	D
1	0.3592	0.5306	0.5688	0.5027
2	0.3921	0.4904	0.5528	0.5392
3	0.5502	0.5512	0.4886	0.5407
4	0.8258	0.5551	0.5171	0.5327
Delta	0.4665	0.0647	0.0801	0.0379
Rank	1	3	2	4

The optimal plasma arc cutting process parameter obtained from the Taguchi orthogonal array from the experiment was A4B4C1D3 (16 mm, 4000 mm/min, 222 A, 170 V). This optimal parameter setting is utilized to predict the grey relation that represents the plasma arc cutting of mild steel.

The fig. 3 portrays the effect of cutting parameters on the multiple performance characteristics and it can be observed that the higher the values in the figure represent the desirable performance characteristics. The importance of each factor can be interpreted from the maximum and minimum values of grey relational grade. Therefore, the order of importance of cutting parameters in plasma arc cutting is plate thickness, current, speed and voltage [14].

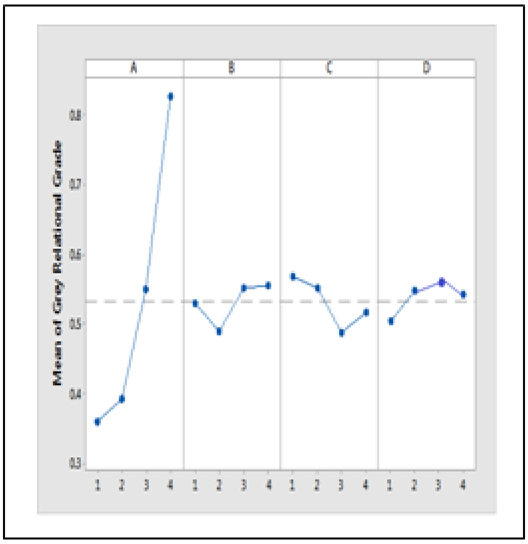

Fig. 3 Effect of control parameters on grey relational grade

IV. ANALYSIS OF VARIANCE

ANOVA is used to investigate the parameter which significantly affects the characteristics of other parameters. It is the statistical technique used to construe the experimental results. Hence it investigates the possible variations due to combination of such parameters [15]. The percentage contribution by each of the process parameter in the sum of squared deviations can be used to evaluate the importance of performance characteristics.

Thus

$$SS_T = SS_F + SS_E \quad (5)$$

Where $SS_T = \sum_{j=1}^{p}(\alpha_j - \alpha_m)^2$ – total sum of squared deviations about the mean

α_j = Mean response for jth experiment

α_m = Sum of squared deviations due to each factor

SS_F = Sum of squared deviations due to each factor

SS_E = Sum of squared deviations due to error

In ANOVA, the mean square deviation is calculated as:

MS = Sum of squared deviation/ Dof. (6)

F-value is defined as:

F = MS for a term/ MS for the error term (7)

The percentage contribution (p) of the design parameters is computed using the following:

$p = SS_j/SS_T$ (8)

Where, SS_j is the sum of squared deviations for each design parameter.

The results of ANOVA are tabulated below. It is observed that the most contributing process parameter is plate thickness (94.6%) and the least significant parameter is voltage (0.81%). The other two process parameters speed and current conduce about 2.71% and 1.83%. Therefore, it can be observed that the results of ANOVA and the rank of the grey relational grade are kindred.

TABLE 8 RESULTS OF ANOVA ON GREY GRADE

Symbol	DOF	Sum of Squares	Mean Squares	F calculated	Contribution (%)
A	3	0.544155	0.1814	1801.51	94.60
B	3	0.010555	0.0035	34.94	1.83
C	3	0.015544	0.0052	51.46	2.71
D	3	0.004637	0.0015	15.35	0.81
Error	3	0.000302	0.0001		0.05
Total	15	0.575193			100

V. CONFORMATION TESTS

The predicted optimum is calculated by conducting a confirmation test. The optimal level of the design parameters are used to calculate the estimated grey relational grade η_{opt} as follows.

$$\eta_{opt} = \bar{\eta} + \sum_{j=1}^{o} (\eta_j - \bar{\eta}) \quad (9)$$

Where, $\bar{\eta}$ is the total mean of the grey relational grade, η_j is the grey relational grade at the optimal level and 'o' is the number of significant design parameters that affect the multiple response characteristics.

TABLE 9 RESULTS OF ANOVA ON GREY GRADE

	Initial machining parameters	Optimal parameters predicted	Optimal parameters experimental
Levels	A1B1C1D1	A4B4C1D3	A4B4C1D3
Kerf, mm	3.38		3.88
Ra, µm	2.33		3.71
Grey relational grade	0.36178862	0.87131000	0.88571318

Finally, the confirmation experiment is conducted at the levels A4B4C1D3. The kerf and surface roughness are obtained as 3.71 µm and 3.88 mm respectively. The grey relational grade computed in this experiment is found to be 0.855713184. As observed in table 8, there is a significant improvement in grey relational grade [16]. The value of kerf is increased from 3.38 mm to 3.88 mm whereas the surface roughness skyrocketed from 2.33 µm to 3.71 µm. The overall improvement in grey relational grade is 0.52392456.

VI. CONCLUSION

The plasma arc cutting experiments were conducted based on Taguchi L16 orthogonal array using a CNC plasma arc cutting machine to study the impact of various process parameters on the process. The surface roughness is measured using a profilometer in µm and kerf is measured with the aid of vernier calipers in mm. The major factors considered are plate thickness, speed, current and voltage. A grey relational analysis is performed to investigate the multiple performance characteristics of the plasma arc cutting process. The conclusions of the experimental work can be summarized as follows.

Grey relational analysis is an efficient and powerful tool for optimizing the multiple response characteristics. ANOVA is performed on the grey relational grade to ascertain the most significant parameter affecting the process. From the analysis, it is found that the most significant parameters that affect the plasma arc cutting process are plate thickness followed by current. The optimal parameter setting is found to be A4B4C1D3. The efficiency of machining process can be improved by machining under optimal parameter settings. It is observed that the grey relational grade is improved by 59.15% from the confirmation tests.

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