Multi objective optimization of process parameters in plasma arc cutting of SS 420 using Grey-Taguchi analysis

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Abstract— *In current scenario, with the increase of demand in market for obtain high surface finish and machining of complex shape geometries, conventional machining process are replaced with Non-Conventional machining process. Plasma arc cutting (PAC) is one of the Non-Conventional machining process. This paper explores the effects and multi objective optimization of process variables in PAC, the process parameters considered for optimization are cutting current, cutting speed and Torch height. In this study, martensitic stainless steel (SS) 420 of 10 mm thickness has been used as work piece material. The experimental runs are carried out based on L9 orthogonal array (OA). Surface roughness (Ra) and Material removal rate (MRR) are taken as process responses. The objective of optimization is to achieve minimum surface roughness and high material removal rate simultaneously, for obtaining minimum surface roughness and maximum material removal rate process parameters are optimized based on Grey-Taguchi technique. Analysis of variance (ANOVA) has been carried out to get the contribution of each process parameters on the process responses and finally effects of process variables on Ra and MRR are plotted and studied by using response surface methodology (RSM).*

Keywords — *Plasma arc cutting, Ra, MRR, Grey relational analysis, Analysis of variance, RSM.*

I. INTRODUCTION

1.1 Plasma arc Machining (PAM):

Modern industries depend on the processing of many heavy metals and alloys. Now a days, various thermal machining processes for machining of newer materials, one among them is Plasma arc Cutting process which is used for machining materials in different fields, they are railway wagon manufacturing, boiler manufacturers and food processing machinery. Generally there are four forms of physical matter, they are solid state, liquid state, gaseous state and another one is plasma state. After gaseous state if temperature is raised above $3,000^0$ c the atoms gets ionized this state of gas is called plasma state.

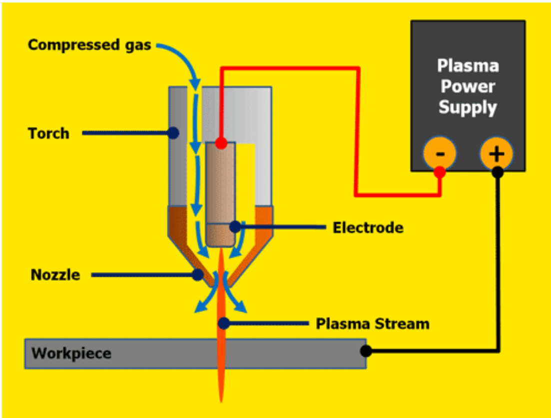

Fig.1: Schematic Diagram of PAC Process

With the help of this high temperature gas, we can melt and separate the material. The source of energy in plasma arc cutting (PAC) is in the form of heat, which is concentrated on a work piece and reacts with it. Thus the work material melts out or even vaporizes and finally cut into pieces [10].The materials like aluminium, titanium alloys, magnesium and its alloys, stainless steel, copper alloys which have large heat capacity, high thermal conductivity and good oxidation resistance can't be cut by tradition machining process like oxy-fuel cutting. So, plasma arc cutting is more advantages than tradition machining process.

Previously, some of researchers have been tried to optimize process parameters in plasma arc cutting. Milan Kumar Das et. Al. investigates the effects of process parameters such as arc current, Torch height and gas pressure for Plasma arc cutting of EN31 steel and also optimized process variables with considerations of process responses such MRR and Ra by using grey relational analysis [1]. K.P. Maity and Dilip Kumar bagal have investigated the effect of plasma arc cutting process variables such as current, torch height, feed rate and voltage on the process responses such as MRR, chamfer, Dross and mean surface roughness of AISI 316 stainless steel and also optimized the process variables for multi objective responses by using grey relational analysis and principal component analysis [3]. Subbarao chamarthi et. Al. have been investigated process parameters in plasma arc cutting such as plasma gas pressure, arc voltage, cutting speed and also optimized process variables for obtain best surface finish for Hardox-400 plate [4]. K. Salonitis and S. Vatousianos have investigated plasma arc cutting process experimentally for identifying process variables that influence the most on cut quality. The process variables were examined, namely Torch height, gas pressure, cutting current, cutting speed and also, optimized the process variables for achieving minimum surface roughness and minimum Heat affected Zone (HAZ) [5]. Kulvinder Rana et. Al. has optimized process variables in plasma arc cutting for minimizing HAZ for Mild steel thin plates. The process variables which are optimized namely, current, cutting speed, air pressure and stand-off distance [6]. R. Bhuvnesh et. Al. have investigated the process variables namely cutting speed, air pressure, arc gap, cutting current and also optimized process variables for multiple responses surface roughness and material removal rate by using Taguchi techniques for AISI 1017 Steel [7].

The main objective of this present study is the investigation of process parameter effects on responses and optimization of process parameters Viz. cutting current, cutting speed and Torch height for Ra and MRR in plasma arc cutting of stainless steel 420 using grey Taguchi analysis. ANOVA is also performed to get percentage of contribution of each process parameter on the process responses.

II. EXPERIMENTAL PROCEDURE

2.1 Experimental setup:

All experimental runs was done on the CNC Plasma arc cutting (MESSER) with a double stream torch. PAC has been performed on SS420 plates of 10 mm thickness with the utilization of Argon and Hydrogen as plasma gas and Nitrogen as shielding gas. The plasma arc cutting system which is used for this research had a nozzle with an outlet diameter of 2.0 mm and it is made up of Brass, the arc voltage setting of 120 volts, primary and secondary gas pressure at 9.1 bar was used.

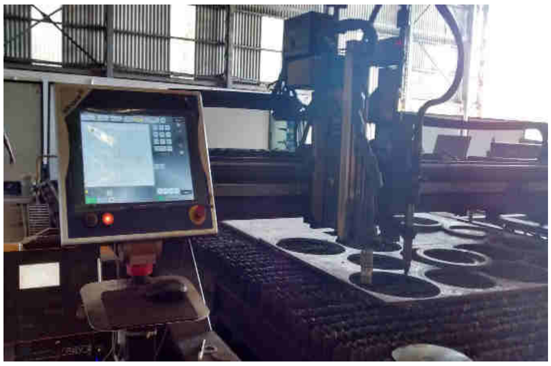

Fig.2: Plasma arc cutting Equipment

In this research, the experimental design has three process parameters namely, cutting current, cutting speed and torch height. The process responses considered in the present study are: Surface roughness (Ra) and material removal rate (MRR). MRR is calculated as weight difference of work piece material before and after machining process to the machining time and Surface roughness (Ra) measurement is done by using a Talysurf (Mitutoyo). In the machining process parameter design, 3 levels with equal space of process parameters are selected as shown in Table1.

Table 1: Process parameters and their levels

Process parameters	Units	Notation	Levels		
			1	2	3
Cutting Current	Amp	A	100	130	160
Cutting Speed	mm/min	B	1000	1300	1600
Torch height	mm	C	4.0	5.0	6.0

Fig. 3: Talysurf (Mitutoyo) equipment

2.2 Work Piece Material

In this experiment, Rectangular block of 170 mm X 170 mm X 10 mm thickness of martensitic stainless steel was used as work piece material. SS 420 is a high-carbon steel with a minimum chromium content of 12%. Stainless steel 420 with high carbon content and high hardness, good corrosion resistance and good oxidation resistance. The major applications of SS420 include threaded pipe for oil well, surgical equipment, shear blades, and pump shafts. The chemical composition and mechanical properties of SS 420 are shown in Table 2 and Table 3 respectively.

Table 2. Chemical composition (wt. %) of SS 420

C	Cr	Mn	Si	P	S	Fe
0.15 (min)	12.0-14.0	1.00	1.00	0.04	0.03	Balance

Table 3: Mechanical properties of SS 420

Density (kg/m^3)	Poisson's ratio	Elastic modulus (GPa)	Tensile strength (MPa)
7800	0.27- 0.30	200	800

2.3 Design of experiments (DOE):

Design of experiment technique which is used for obtaining maximum output values from minimum number of experimental run, time, and money. By using this technique we can reduce time, number of experiments for investigating the experiments, In Taguchi technique, an orthogonal array (OA) is used to reduce the number of experimental runs for identifying the optimal machining process parameters. To determine the main effects, an OA requires minimal number of experimental runs. In this study, there are three process parameters and three levels each so, the DOF for this experimental is 6 [3 X (3 – 1)]. By using Taguchi technique L_9 OA has been used for this experiment. The condition for using L_9 OA is the total Degree of freedom (DOF) of selected OA must be greater than the total DOF required for the experiment.

III. RESULT AND DISCUSSIONS

The experimental results for Ra and MRR are included in table 4. The main objective of this investigation is optimization of process variables for multiple responses in PAC. Taguchi method is suitable for single response optimization only, but optimization of multiple responses is completely different from single response optimization. So, for optimizing multi response characteristics, grey-taguchi analysis is employed in this paper.

Table 4: Design of experiment and experimental results

Exp No.	Cutting Current (Amp)	Cutting speed (mm/min)	Torch height (mm)	Ra (µm)	MRR (gm/sec)
1	100	1000	4	0.907	1.635
2	100	1300	5	0.844	1.588
3	100	1600	6	0.886	3.269
4	130	1000	5	1.105	2.171
5	130	1300	6	1.002	2.325
6	130	1600	4	0.923	3.53
7	160	1000	6	1.231	2.476
8	160	1300	4	1.092	2.71
9	160	1600	5	1.214	3.982

3.1 Grey analysis

The experimental results obtained from surface roughness and material removal rate are presented in table 4. Grey relational grade is the final response for optimizing process parameters with Taguchi analysis, which is attained from the following set of calculations.

3.1.1 Grey relational generation

Grey relational generation is the first step in grey relational analysis in which experimental results should be normalized in the range of 0 to 1. For normalizing surface roughness (Ra) data, lower-the-better (LB) criterion used (equ. 1) and for normalizing material removal rate data, higher-the-better (HB) criterion is used (equ. 2).

$$X_i(k) = \frac{\max y_i(k) - y_i(k)}{\max y_i(k) - \min y_i(k)} \qquad (1)$$

$$X_i(k) = \frac{y_i(k) - \min y_i(k)}{\max y_i(k) - \min y_i(k)} \qquad (2)$$

Where, $X_i(k)$ is the grey relational generation value, max. $y_i(k)$ is the greatest value of $y_i(k)$ for k^{th} response. Min $y_i(k)$ is the smallest value associated with $y_i(k)$ for k^{th} response. The normalized data after grey relational generation is given in table 5. Best value in normalized result is the better performance which should be equal to 1.

3.1.2 Grey relational coefficient

After normalizing Ra and MRR response data, Grey relational coefficients are calculated to exhibit relationship between the best and actual normalized experimental results. The grey relational coefficient $\varepsilon_i(k)$ can be expressed as:

$$\varepsilon_i(k) = \frac{\Delta_{min} + \varphi\,\Delta_{max}}{\Delta_{oi}(k) + \varphi\,\Delta_{max}} \qquad (3)$$

Where, $\Delta_{oi} = X_{oi}(k) - X_i(k)$, Δ_{oi} is the difference of absolute value between $X_0(k)$ and $X_i(k)$. Δ Minis the minimum value of Δ_{oi} and Δ minis the maximum value of Δ oi. φ is the identification coefficient, the value of φ in the range of $0 \le \varphi \le 1$, the recommended value of the distinguishing coefficient, φ is

0.5, due to moderate distinguishing effects and good stability of outcomes [1]. In this study, φvalue is taken as 0.5 for further analysis. The grey relational coefficient values for Ra and MRR are shown in table 6.

Table 5: Normalized of experimental data

Exp. No.	Surface roughness	Material removal rate
1	0.837	0.020
2	1	0
3	0.891	0.702
4	0.326	0.244
5	0.592	0.308
6	0.796	0.811
7	0	0.371
8	0.359	0.469
9	0.044	1

Table 6: Grey relational coefficient for Ra and MRR

Exp. No.	Surface roughness	Material removal rate
1	0.754	0.338
2	1	0.333
3	0.821	0.627
4	0.426	0.398
5	0.551	0.419
6	0.710	0.726
7	0.333	0.443
8	0.438	0.485
9	0.343	1

3.1.3 Grey relational grade and grey relational ordering:

Grey relational grade is taken as overall process response instead of multiple process responses such as Ra and MRR. Grey relational grade is calculated by averaging the grey relational coefficient values of multi responses as follows and it is indicated by γi.

Table 7: Grey relational grade and order

Exp No.	Grade	Order
1	0.546	5
2	0.667	4
3	0.724	1
4	0.412	8
5	0.485	6
6	0.718	2
7	0.388	9
8	0.462	7
9	0.672	3

3.2 Factor effects on Grey relational grade

The main effect plot for grey relational grade is shown in fig 4. In the main effect plot, a parameter for which the line has the highest inclination will have more significant effect and the line which is near to horizontal line has no significant effect. From the main effect plot it is clear that cutting speed (B) has more significant effect and cutting Torch (c) has less significant effect. Since, higher grey relational grade signifies that system is likely optimally, the optimal condition for each parameter is considered at those points where the mean grey relational grade is found to be maximum. Hence, the optimal process parameter combination for minimum surface roughness and maximum material removal rate of plasma arc cutting of Stainless steel (SS) 420 is given as A1 B3 C2.

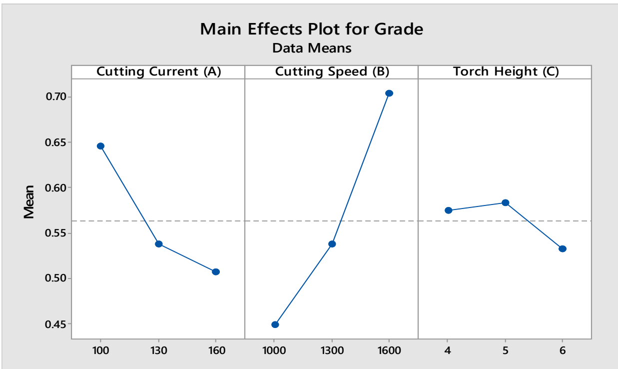

Fig.4: Main effects plot for mean of grey relational grade

3.3 Analysis of variance

The purpose of ANOVA is to investigate which process parameters have significantly effect on the process responses. In ANOVA values of P less than 0.050 indicates parameter has significant effect and values more than 0.100 indicates the parameters are not significant. The percentage contribution can be calculated as:

$$P = \frac{SS_d}{SS_T} \quad (5)$$

Where, SS $_d$ is the sum of squared deviation for each parameter and SS T is the total sum of squares.

In this study, Analysis of variance (ANOVA) has been carried out by using Minitab 17 Software. Table 8 shows the Analysis of variance result for overall grey relational grade of surface roughness and material removal rate. From table 8, it is very much clear that, parameter B (cutting speed) has P value less than 0.05 i.e. 0.049 so that, cutting speed is more significant effect on surface

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roughness and material removal rate, which is about 71.015% contribution and Torch height (C) has no significant effect compare to cutting current, which is about 3.193% contribution.

Table 8: ANOVA table for grey relational grade

Source	DOF	Sum of squares	Mean squares	P-value	F-value	% Contribution
A	2	0.03162	0.01581	6.11	0.141	22.167
B	2	0.1013	0.0506	19.58	0.049	71.015
C	2	0.04554		0.88	0.532	3.193
Error	2	0.05172	0.00258			3.626
Total	8	0.14264				

3.4 Effects of Process parameters on Ra and MRR

To study the effects of process parameters on Surface roughness (Ra) and MRR, Response surface methodology (RSM) is applied by using Design expert 8.0.7.1 Software to experimental results where the experiments were conducted as per DOE.

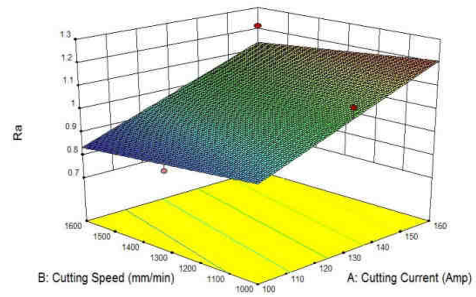
3.4.1 Response surface Methodology (RSM):

RSM was developed by Box and Co-laborators in 1950s. It is used to develop empirical model of complex process. RSM consists of statistical as well as mathematical techniques, which are used to develop the model and done analysis for different problems in which a response of interest is influenced by various process parameters (process variables) and the objective is to optimize the process responses. The procedure of RSM involves the following steps:

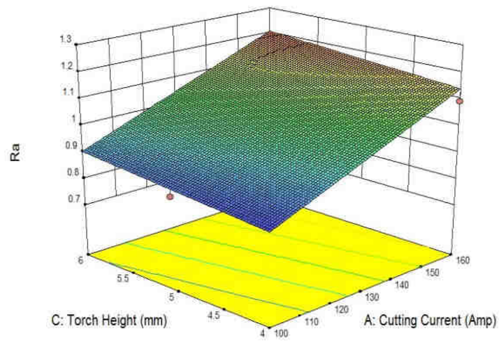
- Selection of process variables through screening studies and limitation of experimental region
- The choice of experimental design and experimental run according to selected orthogonal array
- Find the optimal conditions for experimental process parameters that produce minimum or maximum value of response.
- Represent the direct and interactive effects of process parameters on responses through 2D and 3D plots.

Fig 5 shows the 3D Surface plots for Surface roughness (Ra). Fig 5(a , b, c) shows Ra increases with increase of cutting current and Torch height and Ra decreases with increase of cutting speed.

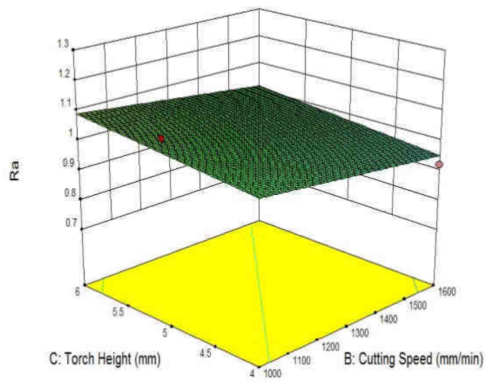
Fig 6 shows the 3-Dimensional Surface plots for MRR. Fig 6 (a, b, c) shows that Material removal rate increases rapidly with increase of cutting current, cutting speed and MRR increases slightly with increase of torch height.



5(a)

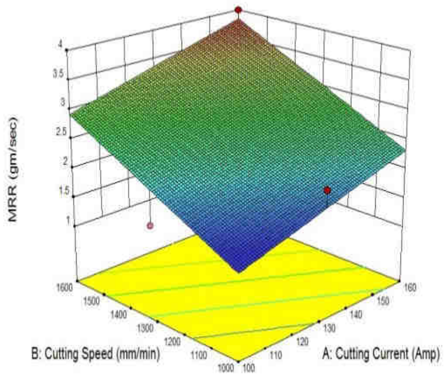


5(b)

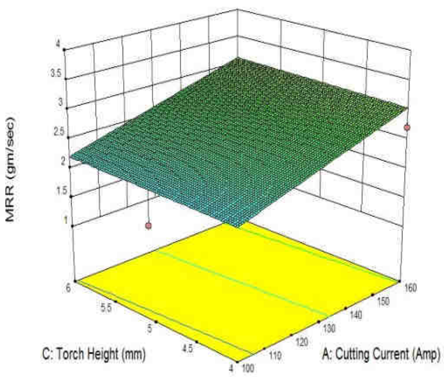


5(c)

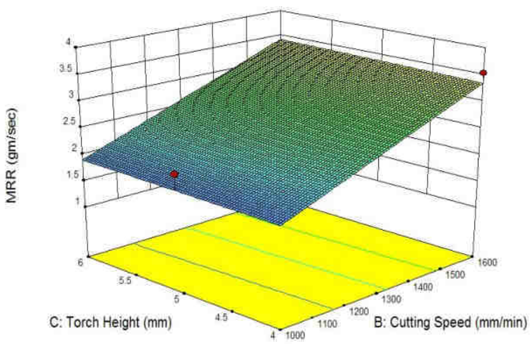
Fig.5: 3D Surface plots for
a) Ra with Cutting current and cutting speed
b) Ra with Cutting current and torch height
C) Ra with Cutting speed and torch height



6(a)



6(b)



6(c)

Fig.6: 3D Surface plots for
a) MRR with Cutting current and cutting speed
b) MRR with Cutting current and torch height
c) MRR with Cutting speed and Torch height

IV. CONCLUSION

The scope of present paper was the experimental investigation and optimization of process parameters in plasma arc cutting of stainless steel 420 using grey relational analysis. The process parameters examined in this investigation are cutting current, cutting speed and torch height. The following conclusions are made.

- From the effects of process parameters on responses, it is clear that Ra increases while increasing cutting current, Ra decreases while increasing cutting speed and torch height.
- With increase of cutting current, cutting speed and torch height, MRR also increases.
- Based on grey analysis, the optimal setting for obtaining minimum surface roughness and maximum material removal rate are A1 B3 C2 i.e. 100 Amp cutting current, 1600 mm/min cutting speed and 5 mm torch height.
- ANOVA resulted that the cutting speed has been more influence parameter on Surface roughness and MRR.

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