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Modeling of Machining Parameters of Structural Steel using Plasma ARC Cutting: A Response Surface Approach

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***Abstract*— This paper represents the experimental investigation on the plasma arc cutting of structural steel (IS 2062 E250 BR). The relevance of this study is that it establishes empirical relations, as a function of machining variables, relevant to analyze the machinability of structural steel material. The response parameters considered are material removal rate (MRR), top and bottom kerf widths and bevel angle: while machining variables are current, standoff distance(SOD), pressure and speed. Experiments are performed using response surface methodology (RSM). The mathematical modeling is done using regression analysis and linear regression equations for all the responses are obtained and process performance data for various parameters is analyzed using ANOVA.**

Keywords— Plasma Arc Cutting, Structural Steel, Process Parameters, MRR, DOE, RSM, Mathematical Modeling, Regression Analysis, ANOVA

I. INTRODUCTION

Structural steel: IS 2062 E250 BR is suitable for welded, bolted and reveted structures and for general engineering purpose. Plasma cutting was developed at the end of the 1950s for cutting high-alloy steels and aluminium. It was designed to be used on all metals which, due to their chemical composition, could not be subjected to oxy-fuel cutting owing to its extremely high cutting speeds especially with thin materials and narrow heat-affected zone. The technique is also used today for cutting non-alloy steels and low-alloy steels. Plasma arc cutting is used for cutting normal structural steel upto about 40 mm in thickness and results in very little distortion, perticularly in case of thin work pieces. The high cutting speeds are especially important in the priliminary fabricating process. In comparision with oxyfuel cutting, cutting speeds of 5 to 6 times greater can be achieved by plasma arc cutting [11].

Many researchers have done work on plasma arc cutting of different materials like EN 31 steel, AISI 31 stainless steel, St 37 mild steel, hardox-400, S235 mild steel, EN 10025 low alloy steel and AISI 304 stainless steel [1-10]. But detailed mathematical models representing the influence of predominant machining variables on machinability parameters are yet to be established. This paper attempts to develop empirical models, using response surface methodology(RSM) [12], as functions of current, standoff distance(SOD), pressure and speed; for the response parameters material removal rate(MRR), top and bottom kerf widths and bevel angle.

II. MATERIAL SELECTION

Experiments are conducted on Structural Steel: IS 2062 E250 BR material (density 7.9 g/cm^3) which is suitable for welded, bolted and riveted structures and for general engineering purposes. The work piece size is 100 mm x 50 mm x 5 mm.

Table 1: Chemical composition of IS 2062 E250 BR

Element	C	Mn	S	P	Si
% Contribution	0.22	1.50	0.045	0.045	0.40

Table 2: Mechanical Properties of IS 2062 E250 BR

Tensile Strength (MPa)	Yield Stress (MPa)			% Elongation
	< 20 mm	20-40 mm	>40 mm	
410	250	240	230	23

III. DESIGN OF EXPERIMENT: RESPONSE SURFACE METHODOLOGY

Response surface methodology (RSM) box-bhenken design is selected. The Box-Behnken Design is quadratic and does not contain embedded factorial or fractional factorial design. As a result, Box-Behnken Design has a limited capability of orthogonal blocking, compared to Central Composite Design. The main difference of Box-Behnken Design from Central Composite Design is that Box-Behnken is a three level quadratic design, in which the explored space of factors is represented by [1,0,+ 1]. The "true" physical lower and upper limits corresponding to [1,+ 1]. In this design, however, the sample combinations are treated such that they are located at midpoints of edges formed by any two factors.

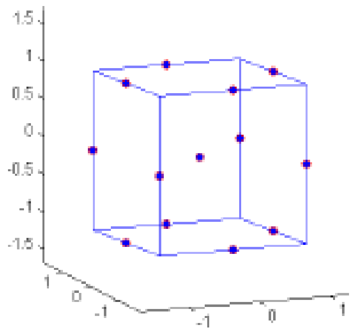

Figure 1: Box Behnken Design

IV. EXPERIMENTATION

The experiments are conducted using a Quality CUT 40 Air Plasma Cutting Machine. In this cutting machine manual plasma arc cutting torch as well as trolley mounted automatic plasma arc cutting torch are provided. For experimentation, trolley based plasma arc cutting torch is used for maintaining stand-off distance and cutting speed during actual cutting.

It is observed from exploratory experiments that uniform levels of cutting speed cannot be selected for all current levels. Whereas, same levels for pressure and stand-off distance can be adopted. The levels of factors selected for the final experiment runs by response surface methodology as shown in table 3 and 4 and final experiments are conducted and the results are shown in table 5.

Table 3: Levels of Current, SOD and Pressure

Level	Current	SOD	Pressure
	A	mm	Bar
-1	30	1.5	4
0	35	2	4.5
1	40	2.5	5

Table 4: Levels of Speed for different currents

Level	Speed (m/min)		
	Current 30A	Current 35A	Current 40A
-1	0.24	0.15	0.38
0	0.3	0.3	0.43
1	0.38	0.43	0.5

Table 5: Experimental runs

Runs	Input Parameters				Response Parameters			
	Current	SOD	Pressure	Speed	MRR	TKW	BKW	BA
					mm^3/min	mm	mm	Degree
1	-1	-1	0	0	1783.90	2.24	1.66	9.13
2	1	-1	0	0	1852.22	2.06	1.65	5.37
3	-1	1	0	0	1257.01	2.32	1.76	6.56
4	1	1	0	0	1854.39	2.20	1.94	4.21
5	0	0	-1	-1	897.10	2.27	2.21	9.22
6	0	0	1	-1	778.91	2.30	2.24	7.75
7	0	0	-1	1	1982.60	2.10	1.42	7.93
8	0	0	1	1	2685.80	2.03	1.47	8.77
9	-1	0	-1	0	1804.81	2.20	1.48	10.92
10	1	0	-1	0	1944.89	2.06	1.82	4.21
11	-1	0	1	0	1241.80	2.17	1.42	11.25
12	1	0	1	0	2364.58	2.03	1.69	5.65
13	0	-1	0	-1	862.87	2.25	2.06	7.57
14	0	1	0	-1	1011.73	2.40	2.36	7.24
15	0	-1	0	1	2553.43	2.06	1.33	7.60
16	0	1	0	1	1973.82	2.07	1.66	4.24
17	-1	0	0	-1	1278.17	2.30	1.92	9.48
18	1	0	0	-1	1833.25	2.34	2.17	4.94
19	-1	0	0	1	2553.60	2.22	1.15	8.48
20	1	0	0	1	3188.66	2.03	1.37	3.66
21	0	-1	-1	0	1419.64	2.06	1.49	6.58
22	0	1	-1	0	1447.53	2.31	2.05	5.83
23	0	-1	1	0	1367.31	2.20	1.78	8.98
24	0	1	1	0	1471.40	2.12	1.65	6.33
25	0	0	0	0	2101.64	2.10	1.62	7.16
26	0	0	0	0	1789.94	2.05	1.59	8.46
27	0	0	0	0	1700.17	2.06	1.57	6.76

V. MATHEMATICAL MODELING

In many problems two or more variables are related, and it is of interest to model and explore this relationship. In general, suppose that there is a single dependent variable or response y that depends on k independent or regressor variables, for example, x_1, x_2, . . . , x_k. The relationship between these variables is characterized by a mathematical model called a regression model.

Here, Linear Regression Model is used for modeling machinability parameters of structural steel using plasma arc cutting and the first order linear equations for each parameter are obtained as follow:

MRR (mm^3/min) = 568 - 17.5 (Current) - 137 (SOD) + 69 (Pressure) + 5346 (Speed)

Top Kerf Width (mm) = 2.56 - 0.00686 (Current) + 0.0917 (SOD) - 0.0250 (Pressure) - 0.690 (Speed)

Bottom Kerf Width (mm) = 0.499 + 0.0509 (Current) + 0.242 (SOD) - 0.0367 (Pressure) - 2.71 (Speed)

Bevel Angle (degree) = 23.5 - 0.413 (Current) - 1.80 (SOD) + 0.673 (Pressure) - 3.85 (Speed)

A. Graphical Analysis of Residuals Using Normal Probability plots

Graphical methods have an advantage over numerical methods for model validation because they readily illustrate a broad range of complex aspects of the relationship between the model and the data.

Figure 2 to 5 shows the normal probability plots for residuals of all four responses. It is observed that the residual follows a straight line and there are no unusual patterns or outliers. As a result, the assumptions regarding the residual were not violated and the residuals are normally distributed. Also the pattern in all the graphs suggests that the results obtained are unbiased, therefore, indicates that the model and results are valid.

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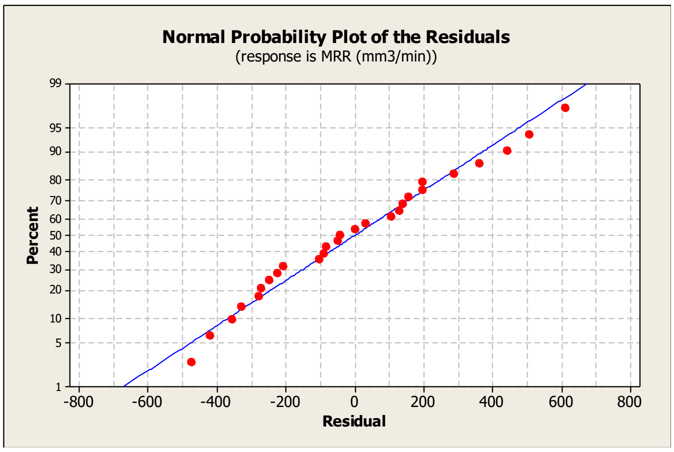

Figure 2: Normal Probability Plot for Residuals of MRR

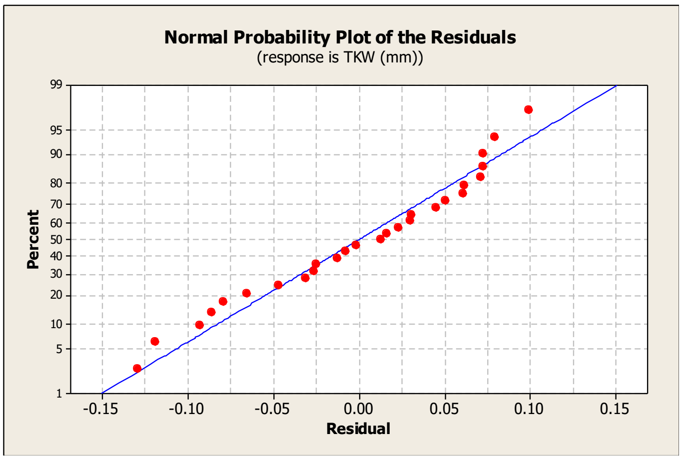

Figure 3: Normal Probability Plot for Residuals of Top Kerf Width

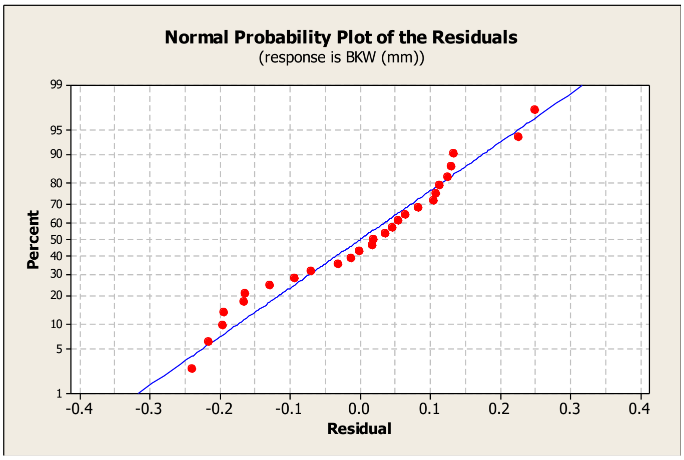

Figure 4: Normal Probability Plot for Residuals of Bottom Kerf Width

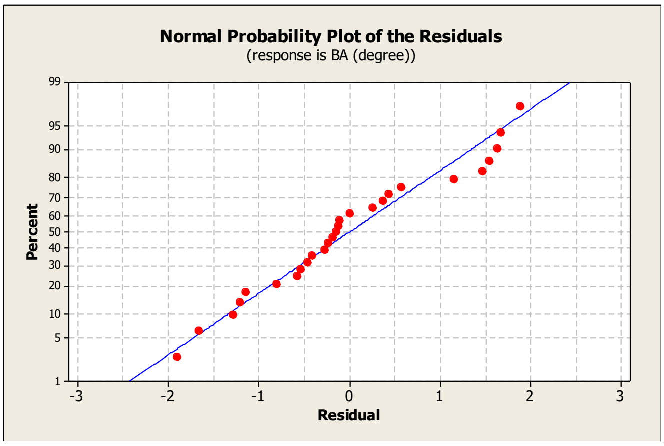

Figure 5: Normal Probability Plot for Residuals of Bevel Angle

VI. RESULTS AND DISCUSSION

A. Main Effect Plots

1) Main Effects Plot for MRR

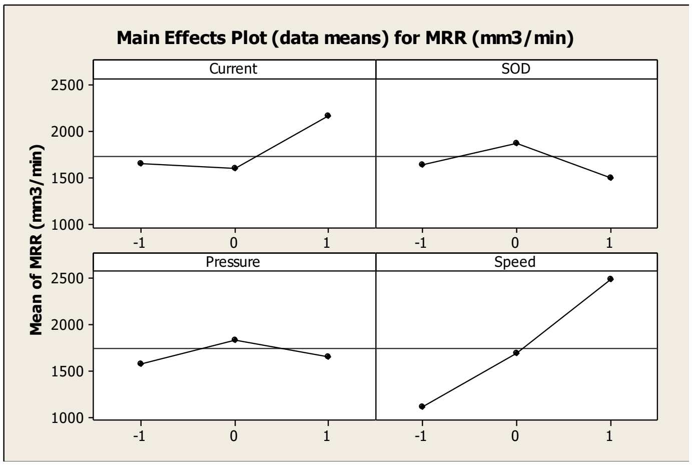

Figure 6: Main effects plot for MRR

From figure 6, it is observed that the speed and then the current are having the most significant effect on material removal rate followed by stand-off distance and pressure. At the highest level of speed and current, cutting energy is transferred in greater volume of material and thus material is removed in lesser time causing MRR to increase.

With increase in pressure MRR increases up to intermediate level and then reduces showing that excessive pressure gives cooling effect rather than blowing the molten material from the heated zone. For stand-off distance MRR at intermediate level is better than that at extreme levels.

2) Main Effects Plot for Top Kerf Width (TKW)

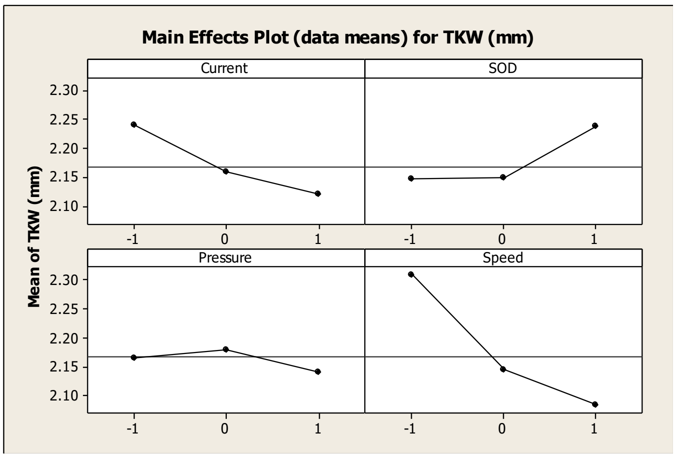

Figure 7: Main effects plot for Top Kerf Width

It is observed that the speed shows the most significant effect with decrease in top kerf width increase in cutting speed indicating that smaller time being available for heat energy transfer at a specific point with increase in speed. Following to speed, current is the second most significant parameter affection the top kerf width. It is observed that by increasing current, top kerf width decreases.

The second most effective parameter is stand-off distance and it is observed that there is increase in top kerf width with increase in stand-off distance due to larger concentration of heat at top surface and high temperature of plasma arc coming in more contact with top.

3) Main Effects Plot for Bottom Kerf Width (BKW)

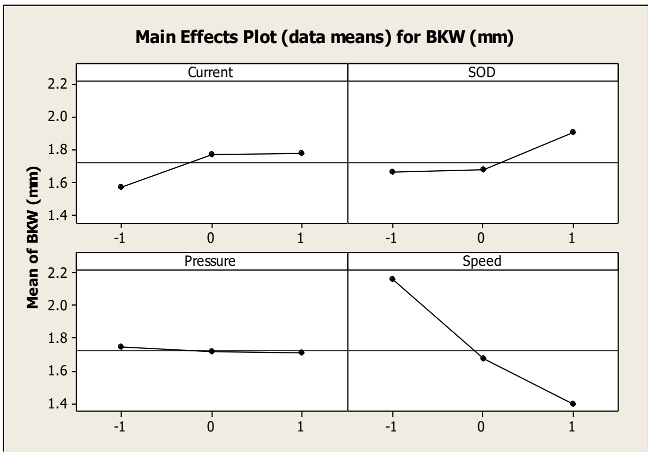

Figure 8: Main effects plot for Bottom Kerf Width

From the plot shown in figure 8, it is observed that speed is the major parameter affecting bottom kerf width due to the fact that by increasing speed, less time for plasma arc contact with material is available so that the cutting energy is less at the bottom surface of the material.

Stand-off distance shows the second most significant effect which increases in bottom kerf width at the higher level and almost same at lower and intermediate level. Variations in temperature zone of the plasma arc cutting into contact with the work at different stand-off distance causes this trend. With increase in current, the energy in the plasma arc increases which is proportionally propagated to the bottom causing increase in bottom kerf width to the intermediate level and then there is slight decrease.

4) Main Effects Plot for Bevel Angle (BA)

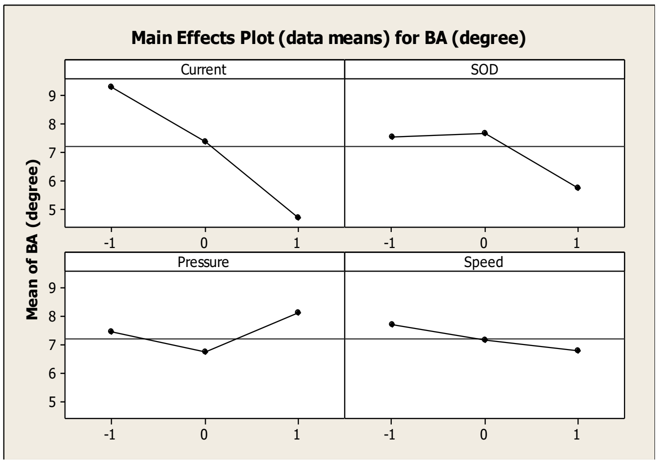

Figure 9: Main effects plot for Bevel Angle

From the main effect plot shown in figure 9, it is noticed that current is the most significant factor. With increase in current, bevel angle decreases because required amount of cutting energy is transferred in material thickness.

For lower and intermediate level of stand-off distance, there is small variation in bevel angle. But from intermediate to higher level, the bevel angle reduces with increase in stand-off distance as the plasma zone with uniform temperature comes in contact with the cross section being cut. The speed affects the bevel angle the least.

B. Analysis of Variance

1) Analysis of Variance for MRR

Table 6: ANOVA Table for MRR

Source	DF	Seq SS	Adj SS	Adj MS	F	P	% Contribution
Current	2	1451938	1050925	525463	8.98	0.002	16.01
SOD	2	466870	537935	268968	4.60	0.024	5.15
Pressure	2	376643	300190	150095	2.57	0.105	4.16
Speed	2	5717213	5717213	2858607	28.87	0.000	63.07
Error	18	1052950	1052950	58497			11.61
Total	26	9065613					100.00
S = 241.862		R-Sq = 88.39%				R-Sq(adj) = 83.22%	

The important information that can be obtained from the table is the percentage influence of all factors over responses. P value less than 0.0500 indicate model terms are significant. In this case speed, current and stand-off distance is significant model terms. Values greater than 0.1000 indicate the model terms are not significant. The percentage contribution by each of the process parameter in the total sum of squared deviation can be used to evaluate the importance of the process parameter change on the quality characteristic. Here, the contribution of speed for MRR is highest: 63.07%.

2) Analysis of Variance for Top Kerf Width

Table 7: ANOVA Table for Top Kerf Width

Source	DF	Seq SS	Adj SS	Adj MS	F	P	% Contribution
Current	2	0.047684	0.060787	0.030394	8.49	0.003	14.00
SOD	2	0.039022	0.051654	0.025827	7.22	0.005	11.52
Pressure	2	0.002653	0.003143	0.001571	0.44	0.651	0.77
Speed	2	0.186365	0.186365	0.093182	26.04	0.000	54.78
Error	18	0.064417	0.064417	0.003579			18.93
Total	26	0.340141					100.00
S = 0.0598223		R-Sq = 81.06%				R-Sq(adj) = 72.64%	

From ANOVA table 7, it is observed that for top kerf width; speed, current and stand-off distance is the significant factor as P value for these factors is less than 0.05. The percentage contribution of significant factors speed, current and stand-off distance are 54.78%, 14.00% and 11.52% respectively.

3) Analysis of Variance for Bottom Kerf Width

Table 8: ANOVA Table for Bottom Kerf Width

Source	DF	Seq SS	Adj SS	Adj MS	F	P	% Contribution
Current	2	0.19358	0.13584	0.06792	5.66	0.012	7.84
SOD	2	0.22777	0.27604	0.13802	11.50	0.001	9.22
Pressure	2	0.00454	0.01944	0.00972	0.81	0.461	0.18
Speed	2	1.82821	1.82821	0.91410	76.14	0.000	74.01
Error	18	0.21610	0.21610	0.01201			8.75
Total	26	2.47020					100.00
S = 0.109570			R-Sq = 91.25%			R-Sq(adj) = 87.36%	

ANOVA table for bottom kerf width shows that speed, stand-off distance and current are the significant factors affecting bottom kerf width with the P-values of 0.000, 0.001 and 0.012 respectively. The factor with highest contribution of 74.01% is speed for bottom kerf width.

4) Analysis of Variance for Bevel Angle

Table 9: ANOVA Table for Bevel Angle

Source	DF	Seq SS	Adj SS	Adj MS	F	P	% Contribution
Current	2	65.238	65.207	32.604	36.49	0.000	61.03
SOD	2	17.865	14.444	7.222	8.08	0.003	16.71
Pressure	2	5.160	4.647	2.323	2.60	0.102	4.83
Speed	2	2.545	2.545	1.272	1.42	0.267	2.38
Error	18	16.084	16.084	0.894			15.05
Total	26	106.893					100.00
S = 0.945290			R-Sq = 84.95%			R-Sq(adj) = 78.27%	

From table 9 it is observed that current is the most significant factor affecting bevel angle and stand-off distance is also having significant effect on bevel angle as its p value is less than 0.05. Speed and pressure have no significant effect on bevel angle as their p values are greater than 0.05. The % contribution of current and stand-off distance are 61.03% and 16.71% respectively.

VII. CONCLUSION

The effect of selected input parameters on the output responses like MRR, top kerf width, bottom kerf width and bevel angle are studied by experimentation performed using Response Surface Methodology.

First Order Linear Model is obtained for all the parameters using Linear Regression Model which helps to predict the values of response parameters for any combination of selected input parameters.

The pattern of residuals observed in normality plots indicates that the results are unbiased as the residuals nearly follow a straight line and thus it shows that the model and results are valid.

From the analysis of variance, it can be concluded that the most significant plasma arc cutting process variable influencing material removal rate, top kerf width and bottom kerf width of structural steel material is speed whereas for bevel angle, it is current. These models can be effectively utilized by the process planners to select the level of parameters to meet any specific plasma arc cutting requirements of structural steel within the range of experimentation.

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