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Optimizing Plasma Arc Cutting Parameters for Structural Steel using Grey Relational Analysis

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***Abstract*— This paper represents the experimental investigation on the plasma arc cutting of structural steel (IS 2062 E250 BR). 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). Further grey relational analysis is used to optimize the parameters. For material removal rate, higher the better output performance characteristic is considered whereas lower the better characteristic is considered for top kerf width, bottom kerf width and bevel angle. Optimization can be used for selecting the values of process variables to get the desired values of response parameters.**

Keywords*— *Plasma Arc Cutting, Structural Steel, Process Parameters, MRR, DOE, RSM, Optimization, Grey Relational Analysis (GRA).

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, particularly in case of thin work pieces. The high cutting speeds are especially important in the preliminary fabricating process. In comparision with oxyfuel cutting, cutting speeds of 5 to 6 times greater can be achieved by plasma arc cutting [1].

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 [2-11]. But the optimization of parameters using GRA is yet to be done. This paper attempts to perform GRA of plasma arc cutting process for the cutting of structural steel to get the optimum combination of process parameters for desired results.

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-Behnken 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 are corresponding to [-1, 0, +1]. In this design, however, the sample combinations are treated such that they are located at midpoints of edges formed by any two factors [17].

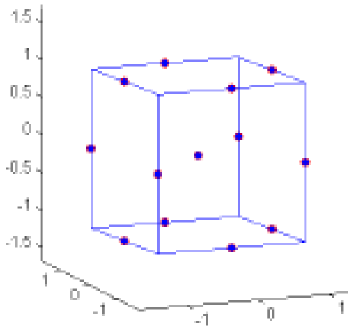

Figure 1: Box Behnken Design [17]

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.

The levels of factors selected for the final experiment runs by response surface methodology are 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. GREY RELATIONAL ANAYSIS

A. Grey theory steps

The information that is either incomplete or undetermined is called Grey. The Grey system provides multidisciplinary approaches for analysis and abstract modeling of systems for which the information is limited, incomplete and characterized by random uncertainty [14].

The three terms that are typical symbols and features for Grey System are:

a) The Grey number in Grey system is a number with incomplete information.
b) The Grey element represents an element with incomplete information.
c) The Grey relation is the relation with incomplete information.

B. Grey relational analysis

The generation of Grey relation for experimental runs is shown in Figure 2. The process is elaborated here.

Let the number of the experimental runs be *m*, and the number of the response parameters be *n*. Then a *m* x *n* value matrix (called eigen value matrix) is set up.

$$X = \begin{bmatrix} x_1(1), x_1(2), \ldots. x_1(n) \\ x_2(1), x_2(2), \ldots x_2(n) \\ \ldots. \\ \ldots. \\ x_m(1), x_m(2), \ldots x_m(n) \end{bmatrix} \quad (1),$$

Where, $x_i(k)$ is the value of the number *i* experiment run and the number *k* response factors.

Usually, three kinds of influence factors are included, they are:

1. Benefit – type factor (the bigger the better),
2. Defect – type (the smaller the better)
3. Medium – type, or nominal-the-best (the nearer to a certain standard value the better).

1. Setting up eigenvalue matrix, input original data
2. Standardized data transformation, formulas:
   I) the bigger the better (2),
   II) the smaller the better (3), or
   III) nominal-the best (4)
3. Calculation of Grey relational degree:
   - getting absolute difference of compared series and referential series using formula (5)
   - find out minimum and maximum
   - choose the constant *p* (set to 0.5)
   - calculation of relational coeficient and relational degree
4. Set up the ranking of software projects based on influence factors

Figure 2: The generation of Grey relation degree

It is difficult to compare between the different kinds of factors because they exert a different influence. Therefore, the standardized transformation of these factors must be done. Three formulas can be used for this purpose.

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$$x_i(k) = \frac{x_i(k) - \min x_i(k)}{\max x_i(k) - \min x_i(k)} \quad (2)$$

The first standardized formula is suitable for the benefit – type factor.

$$x_i(k) = \frac{\max x_i(k) - x_i(k)}{\max x_i(k) - \min x_i(k)} \quad (3)$$

The second standardized formula is suitable for defect – type factor.

$$x_i(k) = \frac{|x_i(k) - x_0(k)|}{\max x_i(k) - x_0(k)} \quad (4)$$

The third standardized formula is suitable for the medium – type factor.

The grey relation degree can be calculated by steps as follows:

a) The absolute difference of the compared series and the referential series should be obtained by using the following formula:

$$\Delta x_i(k) = |x_0(k) - x_i(k)| \quad (5)$$

and the maximum and the minimum difference should be found.

b) The distinguishing coefficient p is between 0 and 1. Generally, the distinguishing coefficient p is set to 0.5.

c) Calculation of the relational coefficient and relational degree by (6) as follows.

In Grey relational analysis, Grey relational coefficient ξ can be expressed as follows:

$$\xi_i(k) = \frac{\Delta \min + p\Delta \max}{\Delta x_i(k) + p\Delta \max} \quad (6)$$

and then the relational degree follows as:

$$r_i = \sum [w(k)\xi(k)] \quad (7)$$

In equation (7), ξ is the Grey relational coefficient, *w (k)* is the proportion of the number *k* influence factor to the total influence indicators. The sum of *w (k)* is 100%. The result obtained when using (6) can be applied to measure the effectiveness of the experimental run.

C. Grey Relational Optimization for Plasma Arc Cutting process

Based on the theory and procedure of grey analysis discussed above the grey relational analysis for plasma arc cutting of Structural Steel (IS 2062 E250 Br) is carried out. The result of data Grey Relational generating is shown in table 6.

The determination of grey relational co-efficient is carried out for each quality parameters considering value of distinguishing coefficient as 0.5. The Grey Relational grade is calculated and rank is given as shown in table 7.

Plasma arc cutting is used as a primary cutting process to obtain rough dimension size for components. The component edges should not be very highly taper giving larger requirement of post processing. The MRR should be relatively high for primary cutting process. At the same time the kerf width should be as small as possible to reduce metal loss. To apply grey analysis similar weight is given to MRR, reduction of kerf width and obtaining straight parallel cut edges. This work is mainly concerned with studying the effect of process parameters on MRR of Structural Steel using Plasma Arc Cutting. MRR is given more weight of 70%. Top kerf width, bottom kerf width and bevel angle is given the weight of 10% each. These weights are used to calculate grey relational grade and its order in optimization process as shown in Table 8.

Table 6: Grey Relational Generating

Ex. No.	**MRR**	**TKW**	**BKW**	**BA**
Ideal	**1.0000**	**1.0000**	**1.0000**	**1.0000**
1	0.4171	0.4324	0.5785	0.2793
2	0.4454	0.9189	0.5868	0.7747
3	0.1984	0.2162	0.4959	0.6179
4	0.4463	0.5405	0.3471	0.9275
5	0.0490	0.3514	0.1240	0.2675
6	0.0000	0.2703	0.0992	0.4611
7	0.4995	0.8108	0.7769	0.4374
8	0.7913	1.0000	0.7355	0.3267
9	0.4257	0.5405	0.7273	0.0435
10	0.4839	0.9189	0.4463	0.9275
11	0.1921	0.6216	0.7769	0.0000
12	0.6580	1.0000	0.5537	0.7378
13	0.0348	0.4054	0.2479	0.4848
14	0.0966	0.0000	0.0000	0.5283
15	0.7364	0.9189	0.8512	0.4809
16	0.4959	0.8919	0.5785	0.9236
17	0.2072	0.2703	0.3636	0.2332
18	0.4375	0.1622	0.1570	0.8314
19	0.7365	0.4865	1.0000	0.3650
20	1.0000	1.0000	0.8182	1.0000
21	0.2659	0.9189	0.7190	0.6153
22	0.2775	0.2432	0.2562	0.7141
23	0.2442	0.5405	0.4793	0.2991
24	0.2874	0.7568	0.5868	0.6482
25	0.5489	0.8108	0.6116	0.5389
26	0.4196	0.9459	0.6364	0.3676
27	0.3823	0.9189	0.6529	0.5916

Table 7: Gray relational coefficients of the individual quality characteristics, Grey Relational Grade and its Order

Ex. No.	MRR	TKW	BKW	BA	Grade	Rank
Weight	0.7000	0.1000	0.1000	0.1000		
1	0.4617	0.4684	0.5426	0.4096	0.4652	18
2	0.4741	0.8605	0.5475	0.6894	0.5416	9
3	0.3841	0.3895	0.4979	0.5668	0.4143	22
4	0.4745	0.5211	0.4337	0.8734	0.5150	12
5	0.3446	0.4353	0.3634	0.4057	0.3617	26
6	0.3333	0.4066	0.3569	0.4813	0.3578	27
7	0.4998	0.7255	0.6914	0.4706	0.5386	10
8	0.7055	1.0000	0.6541	0.4262	0.7019	2
9	0.4654	0.5211	0.6471	0.3433	0.4769	16
10	0.4921	0.8605	0.4745	0.8734	0.5653	7
11	0.3823	0.5692	0.6914	0.3333	0.4270	20
12	0.5938	1.0000	0.5284	0.6560	0.6341	5
13	0.3413	0.4568	0.3993	0.4925	0.3737	24
14	0.3563	0.3333	0.3333	0.5146	0.3675	25
15	0.6548	0.8605	0.7707	0.4906	0.6705	3
16	0.4979	0.8222	0.5426	0.8674	0.5718	6
17	0.3868	0.4066	0.4400	0.3947	0.3949	23
18	0.4706	0.3737	0.3723	0.7478	0.4788	15
19	0.6548	0.4933	1.0000	0.4405	0.6518	4
20	1.0000	1.0000	0.7333	1.0000	0.9733	1
21	0.4052	0.8605	0.6402	0.5652	0.4902	14
22	0.4090	0.3978	0.4020	0.6362	0.4299	19
23	0.3981	0.5211	0.4899	0.4163	0.4214	21
24	0.4123	0.6727	0.5475	0.5870	0.4694	17
25	0.5257	0.7255	0.5628	0.5202	0.5488	8
26	0.4628	0.9024	0.5789	0.4415	0.5162	11
27	0.4473	0.8605	0.5902	0.5504	0.5133	13

After calculating grey relational grade and its order in optimization process the effect of each level of each parameter is calculated and the results are listed in Table 8 and shown in Figure 3.

Table 8: Response table for grey relational grade

Factor	Grey Relational Grade			Max-Min
	Level 1	Level 2	Level 3	
Current	0.4717	0.4888	0.6180	0.1463
SOD	0.4938	0.5427	0.4613	0.0814
Pressure	0.4771	0.5331	0.5019	0.0560
Speed	0.3891	0.4952	0.6846	0.2955

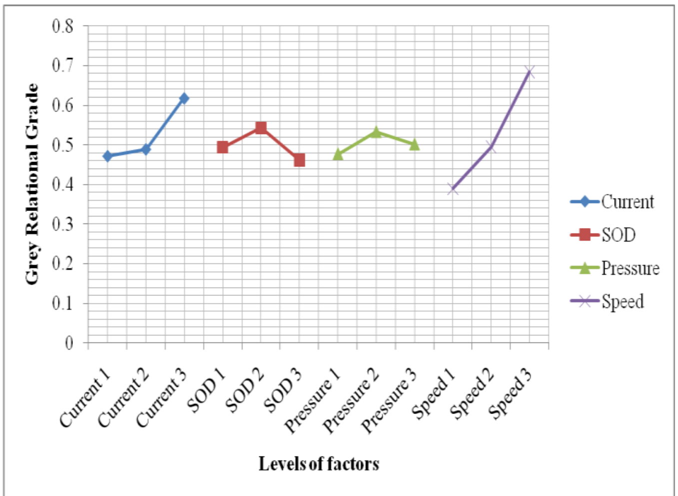

Figure 3: Effect of plasma arc cutting process parameters on multi-performance characteristics

VI. 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.

Grey relational analysis helps to grade the experimental levels for each of the individual variables and to find the most suitable levels for weighted combination of response variables. Here, for the selected weighted combination of responses, higher levels of speed and current; and medium levels of stand-off distance and pressure are observed to be the optimum levels.

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