

Optimization of bead geometry parameters of bead-on-plate weldments prepared by submerged arc welding using Taguchi Technique

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Abstract—A multi-response optimization problem was developed in search of an optimal parametric combination to yield favorable bead geometry of bead-on-plate weldments produced by submerged arc welding. Taguchi's L25 orthogonal array design was employed to optimize the results within experimental limits. The objective functions were selected in terms of responses of bead geometry, viz. height of reinforcement, depth of penetration, bead width and distance; as influenced by the process parameters such as welding current, arc voltage, welding speed and nozzle-to-plate distance. On the other hand, the type, width and height of flux, welding wire material and plate thickness were kept constant. Analysis of variance was used to study the significance of the input parameters on the selected responses and the results were confirmed through additional experimentation.

Keywords—Orthogonal array; signal-to-noise ratio; Taguchi approach; ANOVA

I. INTRODUCTION

The mechanical properties of a weldment depend largely on bead geometry parameters such as depth of penetration, reinforcement and bead width. Submerged arc welding (SAW) is a multi-objective, multi-factor metal fabrication technique [1,3]. Several process parameters interact in a complex manner resulting in direct or indirect influence on bead geometry and hence on the mechanical behavior of the welds prepared by this process. Hence, it is necessary to find an optimal process condition in terms of welding parameters such as, current, voltage, welding speed and nozzle-to-plate distance to obtain the optimum bead geometry. Detailed analysis using statistical methods like factorial techniques have been employed by researchers to correlate these parameters with weld bead geometry, weld quality, etc [4-7].

Purohit [8] has determined bead geometry parameters for metal inert gas (MIG) underwater welded bead-on-plates using 2-level factorial design of experiments. Gunaraj and Murugan [9] have used 5-level factorial experiments to determine the main and interaction effects of process control variables on important bead geometry parameters including bead volume quantitatively and optimal bead volume with maximum penetration, minimum reinforcement and bead width have been obtained successfully.

Of late, Taguchi techniques are used extensively for solving optimization problems in the field of production engineering [10]. This method utilizes a well balanced experimental design consisting of a limited number of experimental runs, called orthogonal array (OA) and signal-to-noise ratio (S/N) which serve the objective function to be optimized within experimental limits. Further, to determine the significance of factors on the responses analysis of variance (ANOVA) is used.

This paper presents the details of an experimental work on surfacing of mild steel by chromium and manganese alloy steel by SAW process to yield desired quality of surfacing, in terms of bead geometry, as influenced by voltage (V), wire feed rate (Wf), electrode traverse speed (Tr) and nozzle-to-plate distance (NPD) which are varied at five different levels. Grey-based Taguchi approach has been carried out to solve this multi-response optimization problem [11].

II. EXPERIMENTAL PROGRAM

Hardfacing was done by laying beads-on-plate with SAW machine (Colton Autoweld). Copper coated electrode wire of diameter 3.14mm (AWS A/S 5.17:EH14) and flux (AWS A5.17/SFA5.17) with grain size of 2 to 3mm diameter and basicity index 1.6 ($Al_2O_3+MnO_2+CaO$). Specimens were extracted from the middle portions of the weldments and were polished using standard metallurgical procedure. Parameters associated with bead geometry namely, depth of penetration, height of reinforcement, bead width and width of HAZ were recorded using an optical triangular metallurgical microscope and also by the X-ray radiographic technique. Table 1 shows the levels of process parameters which were used to lay the beads-on-plates.

Experimental data were normalized for each of parameters (grey relational generation). For depth of penetration and heat affected zone (HAZ) the lower-the-better (LB) criterion was followed and for height of reinforcement and bead width the higher-the-better (HB) criterion was selected. The grey relational coefficients for each performance characteristics have been calculated using equation (1).

$$\hat{\xi}_i(k) = [\Delta_{min} + \phi \Delta_{max} / \Delta_{oi}(k) + \phi \Delta_{max}] \quad (1)$$

Table 1: Process Parameters and Their Levels

Parameter	Level 1	Level 2	Level 3	Level 4	Level 5
V (Volts)	28	30	32	34	36
W _f (Cm/s)	2.0	2.4	2.6	2.8	3.0
T _r (Cm/s)	1.0	1.2	1.3	1.4	1.5
NPD (Cm)	1.5	2.0	2.5	3.0	3.5

Table 2 presents the various combination of L25 orthogonal array for experimentation. It is noted that all the process parameters are maintained at all possible combinations of the 5 levels of parameters, thus simulating the actual experimental condition.

In all, 25 weldments were prepared using the above combinations. For each case, using standard metallographic practices of polishing, etching, etc, the different response parameters (out puts), namely, height of reinforcement (R), depth of penetration (P), bead width (W), percentage dilution (%D) and HAZ size were determined and the same are tabulated in Table 3. This was followed by determination of the grey relational coefficients for each response, which were added to the grey relational grade to yield the overall representative of all the features of the surfacing quality. If the value of a grey relational grade for any factor/combination is higher, it is said to be close to optimal. Table 4 shows grey relations generations. The coefficients are presented in Table 5 and the mean responses for the overall grey relational grade are as shown in Table 6.

III. CONFIRMATORY TESTS

After evaluating the optimal parameter settings, the next step is to predict and verify the enhancement of quality characteristics using the optimal parameter combination. The estimated grey relational grade using the optimal level design parameters are shown in Table 7 along with the actual values.

The signal-to-noise (S/N) ratio for overall grey relational grade was obtained using the criterion.

$$S/N \text{ (larger-the-better)} = -10 \log [1/n \sum 1/Y_i^2] \quad (2)$$

Where, n = number of measurements
 Y_i = measured characteristic value

Table 8 presents the values of the same.

For the orthogonal experimental design, it is possible to separate out the effect of each surfacing parameter at different levels. For example the mean grey relational grade for the voltage at levels 1,2,3,4 and 5 can be calculated by averaging the grey relational grades for the experiments 1-5, 6-10, 11-15, 16-20, and 21-25 respectively. And for the wire feed rate 1-4, 5-10, 11-14, 15-20, 21-25 and for the electrode traverse speed 1-3,4-10, 11-13,14-21,22-25 and for nozzle-to-plate distance 1-2, 3-10, 11-12, 13-20, 21-25, respectively.

Table 2: Design matrix showing levels of factors

SI No	V	W _f	T _r	NPD
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	1	4	4	4
5	1	5	5	5
6	2	1	2	3
7	2	2	3	4
8	2	3	4	5
9	2	4	5	1
10	2	5	1	2
11	3	1	3	5
12	3	2	4	1
13	3	3	5	2
14	3	4	1	3
15	3	5	2	4
16	4	1	4	2
17	4	2	5	3

18	4	3	1	4
19	4	4	2	5
20	4	5	3	1
21	5	1	5	4
22	5	2	1	5
23	5	3	2	1
24	5	4	3	2
25	5	5	4	3

Table 3: Experimental data

Sample	Bead width (mm)	Reinforcement (mm)	Penetration (mm)	HAZ size (mm)	% Dilution
1	50	4.0	3.0	1.5	42.0
2	50	4.2	3.1	1.6	42.4
3	48	4.4	3.3	1.5	42.8
4	49	3.9	2.9	1.4	42.6
5	49	4.6	3.2	1.7	41.0
6	51	4.6	3.3	1.5	41.7
7	49	4.4	3.4	1.4	43.5
8	48	4.3	3.6	1.5	45.5
9	48	4.4	3.4	1.8	43.5
10	49	4.8	3.6	1.8	42.8
11	51	4.3	2.9	1.3	47.5
12	49	4.4	3.2	1.4	42.1
13	48	4.3	3.1	1.3	42.0
14	50	4.0	2.9	1.2	42.2
15	48	4.1	2.9	1.3	41.4
16	49	4.2	3.4	1.7	44.7
17	48	4.3	2.9	1.4	40.2
18	48	4.3	2.9	1.3	40.2
19	50	4.4	3.2	1.7	42.1
20	51	4.4	3.1	1.5	41.3
21	50	4.8	3.6	1.2	42.8
22	49	4.9	3.2	1.2	40.0
23	49	4.3	3.1	1.2	42.0
24	49	3.5	2.6	1.0	42.6
25	50	4.2	3.1	1.5	42.4

Table 4: Grey relational generation

Sample	Bead width (mm)	Reinforcement (mm)	Penetration (mm)	HAZ size (mm)
1	0.3333	0.6428	0.40	0.3750
2	0.3333	0.5000	0.50	0.2500
3	1.0000	0.3571	0.70	0.3750
4	0.6666	0.7142	0.30	0.5000
5	0.6666	0.2142	0.60	0.1250
6	0.0001	0.2142	0.70	0.3750
7	0.6666	0.3571	0.80	0.5000
8	1.0000	0.4285	1.00	0.3750
9	1.0000	0.3571	0.80	0.0001
10	0.6666	0.7142	1.00	0.0001
11	0.0001	0.4285	0.30	0.6250
12	0.6666	0.3571	0.60	0.5000
13	1.0000	0.4285	0.50	0.6250
14	0.3333	0.6428	0.30	0.7500
15	1.0000	0.5714	0.30	0.6250
16	0.6666	0.5000	0.80	0.1250
17	1.0000	0.4285	0.30	0.5000
18	1.0000	0.4285	0.30	0.6250
19	0.3333	0.3571	0.60	0.1250
20	0.0001	0.3571	0.50	0.3750
21	0.3333	0.7142	1.00	0.7500
22	0.6666	0.0001	0.60	0.7500
23	0.6666	0.4285	0.50	0.7500
24	0.6666	0.0001	0.01	1.0000
25	0.3333	0.5000	0.50	0.3750

Table 5: Grey relational co-efficient of characteristics (si = 0.5)

Exp no	Bead width	Reinforcement	Penetration	HAZ
1	0.6761	0.9048	0.4736	0.7263
2	0.6765	0.9043	0.5294	0.6493
3	0.6763	0.6551	0.6923	0.7262
4	0.9998	0.9998	0.4285	0.7260
5	0.9988	0.5757	0.6000	0.5878
6	0.9992	0.5758	0.6923	0.7260
7	0.9989	0.9327	0.8181	0.7878

8	0.9987	0.6519	0.6923	0.7260
9	0.9998	0.6488	0.8181	0.7012
10	0.6421	0.6093	0.9998	0.7012
11	0.9998	0.6417	0.4285	0.9993
12	0.9982	0.9326	0.6000	0.9992
13	0.9975	0.9329	0.5294	0.9990
14	0.6757	0.6402	0.4285	0.6984
15	0.6756	0.6396	0.4285	0.6985
16	0.9989	0.9333	0.8181	0.9998
17	0.9992	0.8071	0.4285	0.9949
18	0.9989	0.8080	0.4285	0.9948
19	0.6759	0.6402	0.6000	0.7710
20	0.6753	0.6402	0.5294	0.6979
21	0.6753	0.6403	0.9998	0.6984
22	0.6745	0.9333	0.6000	0.9998
23	0.9998	0.9335	0.5294	0.9993
24	0.9988	0.9327	0.9998	0.9994
25	0.6753	0.6401	0.5294	0.7405

Table 6: Mean responses for overall grey relational grade

Grey relational grade						
Factor	Level 1	Level 2	Level 3	Level 4	Level 5	Delta
V	0.7079	0.7968	0.7469	0.7769	0.8087	0.0871
Wf	0.7152	0.7791	0.7813	0.7492	0.8087	0.0935
Tr	0.6908	0.7804	0.7813	0.7498	0.8225	0.1321
NPD	0.6925	0.7688	0.8249	0.7463	0.8087	0.1324

Delta = range (maximum – minimum)

Total mean grey relational grade = 0.706

Table 7: Results of Confirmatory Experiment

Initial factor setting		Optimal process condition	
Level of factors	V1Wf1	Predicted	Experiment
	Tr1NPD1 (mm)	V4Wf2 Tr2NPD3 (mm)	V4Wf2 Tr2NPD3 (mm)
W	50	49	49
R	4	3.2	3.5
P	3	2.8	2.6
HAZ	1.5	1.5	1

S/N (Overall)	-1.0800	0.7960	0.8000
Overall grey relational grade	0.6952	0.9826	0.7483
Improvement	0.0531	---	---

The best optimum sequence of parameters is **V4Wf2Tr2NPD3**

Table 8: Grey relational grade along with S/N ratio

Expt No	Grey Relational Grade	S/N Ratio
1	0.6952	-1.08
2	0.6898	-1.12
3	0.6874	-1.13
4	0.7885	-0.45
5	0.6905	-1.11
6	0.7483	-0.73
7	0.8847	0.21
8	0.7673	-0.60
9	0.7919	-0.43
0	0.7919	-0.43
11	0.7673	-0.60
12	0.8825	0.198
13	0.8647	0.070
14	0.6107	-1.662
15	0.6105	-1.603
16	0.9375	-0.570
17	0.8074	-0.322
18	0.8075	-0.323
19	0.6717	-1.240
20	0.6607	-1.309
21	0.7534	-0.697
22	0.8019	-0.362
23	0.8655	0.080
24	0.9826	0.883
25	0.6403	-1.433

IV. ANALYSIS OF VARIANCE

ANOVA is a statistical tool used to reveal the level of significance of individual factors as well as that of interaction of factors on a particular response. It separates the total variability of the response. ANOVA for overall grey relational grade was performed and the details are shown in Table 9.

Table 9: Analysis of variance (ANOVA)

Source	DF	SeqSS ×10 ⁻³	AdjSS ×10 ⁻³	Adj MS ×10 ⁻³	F	P
V	4	0.2692	0.2692	0.0592	0.70	0.60
Wf	4	0.8769	0.8769	0.2250	2.67	0.03
Tr	4	0.2859	0.2859	0.8190	9.72	0.42
NPD	4	0.4532	0.4532	0.1420	1.68	0.22
Error	4	0.2350	0.2350	0.0842	---	---
Total	20	---	---	---	---	---

V. CONCLUSION

In the present study, Taguchi optimization technique coupled with Grey relational analysis has been adopted for evaluating parametric combination to achieve acceptable depth of penetration, height of reinforcement, bead width and HAZ of the hardfaced weldments obtained by using submerged arc welding. The criteria selected for a weldment are to provide lower penetration and increased height of reinforcement, bead width and lower HAZ. To avoid drastic micro-structural changes between the weld metal and HAZ, it was concluded to minimize the HAZ (minimum width and depth of HAZ).

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