Effect of Process Parameters on Bead Geometry, Quality and Performance of Submerged Arc Weldment – Experimental and Statistical Analyses

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ABSTRACT

Submerged arc welding (SAW) is one of the chief metal fabrication processes in industry. It works with high current density and can affect high metal deposition rate. The present work emphasizes the influence of process parameters on quality and performance of submerged arc weldment by incorporating one of the traditional methods of statistical data analysis i.e. ANOVA. This approach aims to reveal the main and interactive effects of process parameters on different response variables associated with the weldment. Based on factorial design without replication, experiments were conducted with three different levels of process parameters like voltage, welding current and electrode stick out to obtain butt joints from mild steel plates. Experimental results were examined by exploring Analysis of Variance Method, using statistical software package MINITAB. Based on ANOVA, several graphical plots are shown- histogram of residuals, normal plot of residuals, residual verses order and residual verses specified variables etc. ANOVA delivers feasible data to justify the significance of process parameters on different response variables of submerged arc weldment in terms of their main effects and interactive effects. The effects due to variation of process parameters on (i) bead geometry in terms of bead width, depth of penetration, reinforcement, and (ii) bead quality as well as performance of the welded joint in terms of hardness, impact value and tensile strength are represented graphically. Graphical representations of the experimental data are supposed to contribute

valuable information for quality control of submerged arc welding process, which would help to obtain superior quality weld and also to achieve high productivity.

Key words: Submerged arc welding, (SAW), bead width, penetration, reinforcement, ANOVA, factorial design

INTRODUCTION

Submerged arc welding is one of the major metal fabrication techniques in industry due to its high quality and reliability. The ability to join thick plates with high metal deposition rate has made this process useful in large structural applications. Indeed various research works have been explored on various aspects of submerged arc welding but still investigations are being carried on to study the phenomenon that occurs during operation of submerged arc welding and many other related matters so that the process becomes controllable more precisely, and can be monitored well both manually as well as automatically.

B.G. Renwick & B.M. Patchett /1/ studied the characteristics of the weld bead, penetration, and melting rate under variable operating current conditions and found that those increased with the increase in current. C.E. Jackson /2/ established that penetration decreased with the increase in electrode diameter at constant current because of reduced current density. S.R. Gupta & N. Arora /3/ studied the effect of welding parameters on weld bead geometry and HAZ. V. Malin /4/ established relationships between shape of the root weld and variations in joint geometry. The work revealed the effects of joint geometry in terms of root opening, included angle, root face and plate misalignment on root welds including the root bead (deposit inside the groove) and root reinforcement (deposit outside the groove). V. Gunaraj & N. Murugan /5, 6/ determined the main and interaction effects of process control variables on important bead geometry parameters quantitatively and represented the results graphically. I.S. Kim *et al.* /8/ developed an intelligent system of Artificial Neural Network in gas metal arc welding process that was capable of receiving the desired weld dimensions as input and delivering the optimal welding parameters as output to achieve the desired weld quality. Y.S. Tarnag *et al.* /9/ applied Grey-based Taguchi methods for the optimization of the submerged arc welding process parameters in hard facing. They considered multiple weld qualities and determined optimal process parameters based on Grey relational grade from grey relational analysis proposed by Taguchi method. In the context of the present work useful information, knowledge and guidance have been obtained from some more publications and books as well /10-15/. The literature depicts that a huge amount of investigations have been performed so far in the area of submerged arc welding in which emphasis has been placed on studying the effect of process parameters on bead geometry only, with comparatively less work on quality and performance aspects of submerged arc weldment. On bead geometry more work is being reported, which indicates that there is need of more understanding in this respect. In the present work an

attempt has been made to evaluate the effects of process parameters on bead geometry, quality and at the same time on mechanical properties of the weldment.

2. DESIGN OF EXPERIMENT

The independent controllable process parameters affecting bead geometry, bead quality and performance of the welded joint are voltage, current, stick out, wire feed rate, welding speed or travel speed, stand off distance etc. In the present study three independent process parameters – voltage, welding current and electrode stick out – have been considered. Other parameters were assumed to be constant over the experimental domain. Trial runs have been carried out by varying one of the process parameters while keeping the rest at constant values. The process variables with their units, notations and values on different levels are furnished in Table 1. The working ranges for the process parameters were selected from the ASW handbook. Based on 3^3 factorial designs, the selected design matrix is a three level, three factors full factorial design consisting of 27 sets of coded conditions. The main and interaction effects of process parameters along with their degrees of freedom are shown in Table 2.

Table 1
Process Control Parameters and their Limits

Parameters	Unit	Notation	-1	0	1
For Backing Pass					
Current	Ampere	C1	450	465	470
Electrode Stick out	mm.	C2	22	24	26
Voltage	Volt	C3	30	32	34
For Secondary Pass					
Current	Ampere	C1	470	485	500
Electrode Stick out	mm.	C2	22	24	26
Voltage	Volt	C3	32	34	36

3. EXPERIMENTAL DATA COLLECTION

In the present work, experiments were performed to obtain butt joints from mild steel plates (100x40x12mm), by applying various levels of process parameters like voltage, welding current and electrode stick out. Parameters associated with bead geometry like bead width, penetration, reinforcement

etc. have been measured and weld quality was evaluated by hardness measurement and performance tests (like tensile test, impact test etc.) The toughness of weldment was measured in FIE Impact Testing Machine. Hardness test was carried out in Vickers Hardness Tester. Universal Testing Machine was employed to determine tensile strength of the joint. In order to illustrate the method for analyzing the effects of process parameters the entries of Table-4-13 will be treated for the purpose.

Table 2
Main effects & interactions of process parameters

	Main Effects & Interactions	Degrees of Freedom
Current	C1	2
Stick out	C2	2
	C1 x C2	4
Voltage	C3	2
	C1 x C3	4
	C2 x C3	4
	C1 x C2 x C3	8
	Total	26

Table 4
Width of weld bead (Data obtained from experiment) for backing pass

Levels of factor C1	Levels of factor C3								
	-1			0			1		
	Levels of factor C2			Levels of factor C2			Levels of factor C2		
	-1	0	1	-1	0	1	-1	0	1
-1	15.28	16.02	16.2	16.4	16.72	17.04	17.57	17.78	18.05
0	15.62	16.08	16.24	16.48	16.82	17.24	17.66	17.8	18.2
1	16.08	16.2	16.3	16.62	16.88	17.44	17.75	18.02	18.34

Table 5
Reinforcement (Data obtained from experiment) for backing pass

Levels of factor C1	Levels of factor C3								
	-1			0			1		
	Levels of factor C2			Levels of factor C2			Levels of factor C2		
	-1	0	1	-1	0	1	-1	0	1
-1	2.42	2.58	2.7	2.73	2.6	3.08	3.22	3.32	3.48
0	2.46	2.6	2.72	2.88	2.9	3.08	3.24	3.34	3.52
1	2.52	2.68	2.72	2.87	3.02	3.16	3.28	3.42	3.58

Table 6
Bead penetration (Data obtained from experiment) for backing pass

Levels of factor C1	Levels of factor C3								
	-1			0			1		
	Levels of factor C2			Levels of factor C2			Levels of factor C2		
	-1	0	1	-1	0	1	-1	0	1
-1	5.04	5.14	5.44	5.6	5.66	5.68	5.8	6	6.16
0	5.1	5.2	5.46	5.64	5.68	5.7	5.86	6	6.2
1	5.14	5.4	5.58	5.64	5.7	5.74	5.88	6.06	6.3

Table-7
Width of weld bead data obtained from experiment) for secondary pass

Levels of factor C1	Levels of factor C3								
	-1			0			1		
	Levels of factor C2			Levels of factor C2			Levels of factor C2		
	-1	0	1	-1	0	1	-1	0	1
-1	15.82	16.12	16.38	16.62	17.32	17.48	17.68	18.12	18.56
0	15.88	16.24	16.42	16.7	17.32	17.52	17.8	18.3	18.6
1	16.02	16.32	16.48	16.78	17.38	17.62	17.96	18.34	18.64

Table 8

Reinforcement (Data obtained from experiment) for secondary pass

Levels of factor C1	Levels of factor C3								
	-1			0			1		
	Levels of factor C2			Levels of factor C2			Levels of factor C2		
	-1	0	1	-1	0	1	-1	0	1
-1	2.4	2.52	2.86	3.08	3.12	3.26	3.32	3.48	3.56
0	2.42	2.72	2.86	3.06	3.24	3.26	3.38	3.48	3.6
1	2.48	2.84	2.98	3.08	3.26	3.28	3.42	3.52	3.64

Table 9

Bead penetration (Data obtained from experiment) for secondary pass

Levels of factor C1	Levels of factor C3								
	-1			0			1		
	Levels of factor C2			Levels of factor C2			Levels of factor C2		
	-1	0	1	-1	0	1	-1	0	1
-1	6.2	6.48	6.78	6.86	6.9	7.04	7.14	7.24	7.34
0	6.24	6.64	6.8	6.84	6.94	7.06	7.16	7.26	7.48
1	6.34	6.74	6.8	6.86	6.96	7.1	7.16	7.3	7.54

Table 10

Hardness (Data obtained from experiment)

Levels of factor C1	Levels of factor C3								
	-1			0			1		
	Levels of factor C2			Levels of factor C2			Levels of factor C2		
	-1	0	1	-1	0	1	-1	0	1
-1	340.496	344.661	353.224	373.696	390.875	393.426	406.561	409.267	409.267
0	328.444	342.569	355.414	359.857	362.109	380.917	406.561	398.603	417.549
1	320.761	322.656	336.406	346.772	348.903	359.857	378.487	373.696	380.917

Table 11
Impact Value (Data obtained from experiment)

Levels of factor C1	Levels of factor C3								
	-1			0			1		
	Levels of factor C2			Levels of factor C2			Levels of factor C2		
	-1	0	1	-1	0	1	-1	0	1
-1	16	15.8	15.4	14.8	14.6	14.4	13.8	13.8	13
0	16.4	16.2	15.8	15.6	15.2	14.8	14.2	14	13.6
1	16.4	16.2	16.2	15.6	15.6	15	14.6	14	14

Table-12
Yield Strength (Data obtained from experiment)

Levels of factor C1	Levels of factor C3								
	-1			0			1		
	Levels of factor C2			Levels of factor C2			Levels of factor C2		
	-1	0	1	-1	0	1	-1	0	1
-1	248.26	235.2	228.66	283.86	278.10	274.4	225.13	273.33	249.93
0	349.04	370.81	361.74	385.46	361.05	398.75	398.53	287.46	350.94
1	357.56	407.78	446.66	443.64	469.29	386.66	432.55	410.54	384.05

Table-13
Ultimate Strength (Data obtained from experiment)

Levels of factor C1	Levels of factor C3								
	-1			0			1		
	Levels of factor C2			Levels of factor C2			Levels of factor C2		
	-1	0	1	-1	0	1	-1	0	1
-1	339.73	235.2	346.26	425.79	410.54	446.26	231.75	280.00	256.51
0	456.43	476.75	453.82	496.53	477.10	500.13	509.6	365.86	490.00
1	476.75	539.32	473.33	496.62	545.21	480.00	513.65	490.00	516.48

4. STATISTICAL ANALYSIS

Balanced ANOVA can be effectively explored to examine the effects of multiple factors on a continuous response. This procedure requires that the number of observations of each combination of the factor level must be the same (balanced).

Hypothesis Testing

One of the most commonly used methods in statistical decision-making is hypothesis testing. In general, a hypothesis test is a process in which an initial claim is assumed to be true and this claim is then tested using sample data. Ordinarily, the initial claim refers to a population parameter of interest such as the population mean (μ). Hypothesis tests include two hypotheses the null hypothesis (denoted by H_0) and alternative hypothesis (denoted by H_1). The null hypothesis is the initial claim and is often specified using previous research or common knowledge. The alternative hypothesis is that one may believe to be true or hope to be true. The alternative hypothesis is sometimes referred to as the research hypothesis. The decision making process for a hypothesis test can be based on the probability value (p-value) for the given test.

- * If the p-value is less than or equal to a predetermined level of significance (α -level), null hypothesis is to be rejected support should be claimed for the alternative hypothesis.
- * If the p-value is greater than (α -level), one fails to reject the null hypothesis and cannot claim support for the alternative hypothesis.

When a hypothesis test is performed, there are four possible outcomes. The outcomes depend on whether the null hypothesis is true or false and whether one rejects or fails to reject the null hypothesis. These outcomes are summarized in the following table:

Table 3
Testing of Null Hypothesis

Null Hypothesis		
Decision	True	False
Fail to reject H_0	Correct decision $P=1-\alpha$	Type II Error $P=\beta$
Reject H_0	Type I Error $P=\alpha$	Correct decision $P=1-\beta$

When the null hypothesis is true and one rejects it, he makes a type I error. The probability of making a type I error is called alpha (α) and is sometimes referred to as the level of significance.

When the null hypothesis is false and one fails to reject it, he makes a type II error. The probability of making a type II error is called beta (β). The probability of rejecting the null hypothesis when it is false is equal to $1 - \beta$. This value is also referred to as the power of the test.

Analysis of Variance

The most important statistic in the analysis of variance table is the p-value (P). There is a p-value for each term in the model (except for the error term). The p-value for a term tells whether the effect for that term is significant. If P is less than or equal to the α -level that one has selected, then the effect for the term is significant. If P is larger than the selected α -level, the effect is not significant. If the effect of an interaction term is significant, then the effects of each factor are different at different levels of the other factor(s). For this reason, it does not make sense to try and interpret the individual effects of terms, which are involved in significant higher-order interactions. ANOVA results for different response variables are shown in Tables 14-23. The graphical representations showing the main effects and interactive effects of various process parameters on selected response variables are given in Figures 1-46.

Table 14
ANOVA for bead width (For Backing Pass)

Source	DF	SS	MS	F	P
C1	2	0.3701	0.1850	10.78	0.005*
C2	2	1.7363	0.8682	50.59	0.000*
C3	2	16.4077	8.2038	478.10	0.000*
C1*C2	4	0.0345	0.0086	0.50	0.735
C1*C3	4	0.0140	0.0035	0.20	0.929
C2*C3	4	0.0920	0.0230	1.34	0.335
Error	8	0.1373	0.0172		
Total	26	18.7919			

*Significant at 95% confidence level.

Table 15
ANOVA for reinforcement (For Backing Pass)

Source	DF	SS	MS	F	P
C1	2	0.06987	0.03494	10.72	0.005*
C2	2	0.33550	0.16775	51.47	0.000*
C3	2	2.74714	1.37357	421.44	0.000*
C1*C2	4	0.01721	0.00430	1.32	0.341
C1*C3	4	0.02224	0.00556	1.71	0.241
C2*C3	4	0.02628	0.00657	2.02	0.185
Error	8	0.02607	0.00326		
Total	26	3.24432			

*Significant at 95% confidence level.

Table 16
ANOVA for bead penetration (For Backing Pass)

Source	DF	SS	MS	F	P
C1	2	0.04847	0.02424	25.87	0.000*
C2	2	0.36554	0.18277	195.05	0.000*
C3	2	2.54065	1.27033	1355.68	0.000*
C1*C2	4	0.00504	0.00126	1.34	0.334
C1*C3	4	0.01259	0.00315	3.36	0.068
C2*C3	4	0.09819	0.02455	26.20	0.000*
Error	8	0.00750	0.00094		
Total	26	3.07799			

*Significant at 95% confidence level.

Table-17
ANOVA for bead width (For Secondary Pass)

Source	DF	SS	MS	F	P
C1	2	0.1153	0.0577	42.42	0.000*
C2	2	2.3752	1.1876	873.72	0.000*
C3	2	18.6464	9.3232	6859.04	0.000*
C1*C2	4	0.0104	0.0026	1.91	0.203
C1*C3	4	0.0056	0.0014	1.02	0.450
C2*C3	4	0.1254	0.0313	23.06	0.000*
Error	8	0.0109	0.0014		
Total	26	21.2892			

*Significant at 95% confidence level.

Table 18
ANOVA for reinforcement (For Secondary Pass)

Source	DF	SS	MS	F	P
C1	2	0.04507	0.02253	11.02	0.005*
C2	2	0.39636	0.19818	96.93	0.000*
C3	2	3.03680	1.51840	742.70	0.000*
C1*C2	4	0.01244	0.00311	1.52	0.284
C1*C3	4	0.01280	0.00320	1.57	0.273
C2*C3	4	0.06764	0.1691	8.27	0.006*
Error	8	0.01636	0.00204		
Total	26	3.58747			

*Significant at 95% confidence level.

Table 19
ANOVA for bead penetration (For Secondary Pass)

Source	DF	SS	MS	F	P
C1	2	0.03742	0.01871	6.79	0.019*
C2	2	0.54836	0.27418	99.50	0.000*
C3	2	2.42427	1.21213	439.89	0.000*
C1*C2	4	0.00489	0.00122	0.44	0.775
C1*C3	4	0.00791	0.00198	0.72	0.603
C2*C3	4	0.10311	0.02578	9.35	0.004*
Error	8	0.02204	0.00276		
Total	26	3.14800			

*Significant at 95% confidence level.

Table 20
ANOVA for hardness

Source	DF	SS	MS	F	P
C1	2	3797.7	1898.9	149.16	0.000*
C2	2	943.8	471.9	37.07	0.000*
C3	2	15978.4	7989.2	627.57	0.000*
C1*C2	4	172.1	43.0	3.38	0.067
C1*C3	4	426.9	106.7	8.38	0.006*
C2*C3	4	185.4	46.4	3.64	0.057
Error	8	101.8	12.7		
Total	26	21606.2			

*Significant at 95% confidence level.

Table 21

ANOVA for impact value

Source	DF	SS	MS	F	P
C1	2	2.1067	1.0533	32.69	0.000*
C2	2	1.5289	0.7644	23.72	0.000*
C3	2	20.9689	10.4844	325.38	0.000*
C1*C2	4	0.0711	0.0178	0.55	0.704
C1*C3	4	0.0711	0.0178	0.55	0.704
C2*C3	4	0.0356	0.0089	0.28	0.886
Error	8	0.2578	0.0322		
Total	26	25.0400			

*Significant at 95% confidence level.

Table 22

ANOVA for yield strength

Source	DF	SS	MS	F	P
C1	2	119980	59990	44.75	0.000*
C2	2	106	53	0.04	0.962
C3	2	5488	2744	2.05	0.191
C1*C2	4	3450	862	0.64	0.647
C1*C3	4	670	168	0.13	0.969
C2*C3	4	3056	764	0.57	0.692
Error	8	10724	1341		
Total	26	143473			

*Significant at 95% confidence level.

Table 23

ANOVA for ultimate tensile strength

Source	DF	SS	MS	F	P
C1	2	152178	76089	35.86	0.000*
C2	2	1338	669	0.32	0.738
C3	2	23593	11796	5.56	0.031*
C1*C2	4	7264	1816	0.86	0.0529
C1*C3	4	24936	6234	2.94	0.091
C2*C3	4	2182	545	0.26	0.897
Error	8	16973	2122		
Total	26	228464			

*Significant at 95% confidence level.

5. GRAPHICAL REPRESENTATIONS

Balanced ANOVA was used to analyze the experimental data statistically. A complete statistical software package, MINITAB-13.1, was used in the present context. The plots obtained from statistical analysis are shown in Figures 1-46. The significance of the plots is discussed in the next section.

Fig. 1: Histogram of Residuals of Bead Width

Fig. 2: Normal Probability Plot of The Residuals of Bead Width

Fig. 3: Residual versus Order of Data **Fig. 4:** Residuals of Bead Width versus Current (C1)

Fig. 5: Residuals of Bead Width versus Stick Out (C2)

Fig. 6: Residuals of Bead Width versus Voltage (C3)

Fig. 7: Main Effects Plot for Bead Width (Response C4)

Fig. 8: Interactive Effect of Current (C1) & Stick Out (C2) on Bead Width (C4)

Fig. 9: Interactive Effect of Current (C1) & Voltage (C3) on Bead Width (C4)

Fig. 10: Interactive Effect of Stick Out (C2) & Voltage (C3) on Bead Width (C4)

Fig. 11: Histogram of Residuals of Bead Reinforcement

Fig. 12: Normal Probability Plot of The Residuals of Bead Reinforcement

Fig. 13: Main Effects Plot for Bead Reinforcement (Response C5)

Fig. 14: Interactive Effect of Current (C1) & Stick Out (C2) on Reinforcement (C5)

Fig. 15: Interactive Effect of Current (C1) & Voltage (C3) on Reinforcement (C5)

Fig. 16: Interactive Effect of Stick Out (C2) & Voltage (C3) on Reinforcement (C5)

Fig. 17: Histogram of Residuals of Bead Penetration

Fig. 18: Normal Probability Plot of the Residuals of Bead Penetration

Fig. 19: Main Effects Plot for Bead Penetration (Response C6)

Fig. 20: Interactive Effect of Current (C1) & Stick Out (C2) on Bead Penetration (C6)

Fig. 21: Interactive Effect of Current (C1) & Voltage (C3) on Bead Penetration (C6)

Fig. 22: Interactive Effect of Stick Out (C2) & Voltage (C3) on Bead Penetration (C6)

Fig. 23: Histogram of Residuals of Hardness of Weldment

Fig. 24: Normal Probability Plot of the Residuals of Hardness of Weldment

Fig. 25: Main Effects Plot for Hardness of Weldment (Response C7)

Fig. 26: Interactive Effect of Current (C1) & Stick Out (C2) on Weld Hardness (C7)

Fig. 27: Interactive Effect of Current (C1) & Voltage (C3) on Weld Hardness (C7)

Fig. 28: Interactive Effect of Stick Out (C2) & Voltage (C3) on Weld Hardness (C7)

Fig. 29: Histogram of Residuals of Impact Value

Fig. 30: Normal Probability Plot of the Residuals of Impact Value

Fig. 31: Main Effects Plot for Impact Value (Response C8)

Fig. 32: Interactive Effect of Current (C1) & Stick Out (C2) on Impact Value of the Weld (C8)

Fig. 33: Interactive Effect of Current (C1) & Voltage (C3) on Impact Value of the Weld (C8)

Fig. 34: Interactive Effect of Stick Out (C2) & Voltage (C3) on Impact Value of the Weld (C8)

Fig. 35: Histogram of the Residuals of Yield Strength

Fig. 36: Normal Probability Plot of the Residuals of Yield Strength

Fig. 37: Main Effects Plot for Yield Strength of the Joint (Response C9)

Fig. 38: Interactive Effect of Current (C1) & Stick Out (C2) on Yield Strength of the Joint (C9)

Fig. 39: Interactive Effect of Current (C1) & Voltage (C3) on Yield Strength of the Joint (C9)

Fig. 40: Interactive Effect of Stick Out (C2) & Voltage (C3) on Yield Strength of the Joint (C9)

Fig. 41: Histogram of Residuals of Ultimate Tensile Strength

Fig. 42: Normal Probability Plot of the Residuals of Ultimate Tensile Strength

Fig. 43: Main Effects Plot for Ultimate Tensile Strength (Response C10)

Fig. 44: Interactive Effect of Current (C1) & Stick Out (C2) on Ultimate Tensile Strength of the Joint (C10)

Fig. 45: Interactive Effect of Current (C1) & Voltage (C3) on Ultimate Tensile Strength of the Joint (C10)

Fig. 46: Interactive Effect of Stick Out (C2) & Voltage (C3) on Ultimate Tensile Strength of the Joint (C10)

6. RESULTS AND DISCUSSIONS

On ANOVA:

ANOVA for bead width (Tables 14 and 17) depicts that P-value for current (C1), electrode stick out (C2) and welding voltage (C3) are less than the presumed α -level, i.e. 0.05. Therefore it can be easily concluded that the said process variables have a significant effect on width of the weld bead. It is evident from the table that the interactive effects of current-stick out, current-voltage, and voltage-stick out are all insignificant without imposing any effect on bead width, because all have P-value which is greater than α -level. However data obtained for bead width during secondary pass (Table 17) reveals that the interactive effect of stick out and voltage have a significant effect on bead width with zero p-value which is lower than α value, i.e. 0.05.

ANOVA table for reinforcement (Table 15) shows the significant effects of current, stick out and voltage on bead reinforcement. Because P-value for C1=0.005, for C2=0.000 and for C3=0.000, all are less than 0.05, the α -value. The interactive effects of the process parameters on reinforcement are insignificant here. ANOVA for bead reinforcement during secondary pass (Table 18) supports the above result, except that there is some interactive effect between C2 and C3.

ANOVA for bead penetration (Table 16) reveals the significance of the main effects of process parameters on bead penetration. Here it is interesting to note that the interactive effects of voltage and electrode stick out are significant. Same result was obtained from ANOVA of bead penetration (Table 19) for the secondary pass.

Table 20 and Table 21 show that all the process parameters have a significant effect (main effect) on hardness and impact value of the weldment respectively. The interactions of two factors are insignificant here, except the interaction between current and stick out ($P = 0.006$).

Table 22 provides important information. Welding current is the only factor that has a significant effect on yield strength of the joint. Other main effects and interactive effects of the factors are very much insignificant.

ANOVA for ultimate tensile strength of the joint (Table 23) reveals that the effect of welding current and voltage is significant on ultimate tensile strength of the joint. The main effect of electrode stick out and interactive effects of the process parameters are insignificant here.

On the graphs:

A histogram of the residuals shows the distribution of the residuals for all levels of the factors combined. Here are some specific things to look for.

- * Unusual observations: If the histogram contains a bar that is far away from the other bars, this may indicate unusual observations (outliers).
- * Several peaks: If the histogram contains two or more peaks, there may be other important variables, in addition to the factor of interest, influencing the response.

- * Normality: If the residuals are approximately normally distributed, then the histogram should be approximately bell shaped. Generally a moderate amount of data (about 50 observations) is needed to see the pattern in a histogram.
- * Skewed data: If the histogram is highly skewed, the residuals are probably not normally distributed.

For Bead Width:

The distribution of residuals for bead width (Response C4) appears to be symmetric about zero (Figure 1), with a single peak at the mean and there do not appear to be any outliers. This indicates that the residuals for bead width are distributed fairly normally.

Normal probability plots are useful for evaluating the normality of a data set, even if there are a fairly small number of observations. As a condition for using the test, the residuals from a one-way ANOVA should be normally distributed. If the points come close to form a straight line, this indicates that the residuals are approximately normally distributed. If the points do not come close to form a straight line, this indicates that the residuals are not normally distributed.

The normal probability plot for bead width (Figure 2) seems to indicate that the residuals are distributed fairly normally.

The graph (residuals versus order) shows the residuals plotted in order of the corresponding observations (Figure 3) in the work sheet of MINITAB. Thus, if the observations in the work sheet are organized accordingly to the time they were collected, one can use this plot to look for any systematic effects of time or collection order on the response variable.

The data for bead width were arranged in the order of data collection (Table 3). There does not appear to be a systematic effect of order on the data.

The plots of each residual versus specified variable can help one to determine if a variable is influencing the data in a systematic way. If the variable does not affect the response, the points at each level of the factor should be scattered evenly around zero. The plots of the bead width residuals against current, stick out and voltage are not scattered evenly around zero (Figures 4, 5 and 6), suggesting that the aforesaid process variables affect significantly on bead width.

Use of a Main Effects Plot in conjunction with an analysis of variance is very important. A main effect occurs when the mean response changes across the levels of a factor. This plot is used

- * To examine the level means for each factor
- * To compare the level means for several factors
- * To compare the relative strength of the effects across factors

The Main Effects Plot is most useful when one is dealing with several factors. The changes in the level means can be compared to see which factors influence the response the most. A main effect is present when different levels of a factor affect the response differently. For a factor with two levels, it can be found that one level increases the mean compared to the other level. This difference is a main effect.

MINITAB creates the Main Effects Plot by plotting the response mean for each factor level. A line connects the points for each factor. MINITAB also draws a reference line at the overall mean. To determine whether or not a main effect is present for a factor the line should be checked so that

- * When the line is horizontal (parallel to the x-axis), then there is no main effect present. Each level of the factor affects the response in the same way, and the response mean is the same across all factor levels.
- * When the line is not horizontal (parallel to the x-axis), then there is a presence of main effect. Different levels of the factor affect the response differently. The greater is the difference in the vertical position of the plotted points (the more the line is not parallel to the X-axis), the greater the magnitude of the main effect.

By comparing the slopes of the lines, the relative magnitude of the factor effects can be compared.

Main effects plot for bead width (Figure 7) reveals that current has a direct effect on bead width. As the levels of current increases an increased trend of the bead width can be noticed. A similar relation exists for electrode stick out and voltage on bead width. With increase in stick out and voltage, bead width increases gradually. It is also clear from the main effect plot that bead width increases slowly with increase in welding current. Bead width increases with increase in electrode stick out in a moderate way, while steep increment of bead width can be visualized with increase in welding voltage. Figure 8 reveals the interactive effect of current and electrode stick out. At constant current, increase in electrode stick out results increased bead width. Interaction plots for current and voltage (Figure 9) show that, as voltage is increased, that would cause increment in bead width, provided welding current is kept at a constant level. It is evident from Figure 10 that, at constant electrode stick out, increasing welding voltage would result increase in bead width.

For Reinforcement:

Figure 11 shows the histogram of residuals for reinforcement (Response C5). It is observed that the histogram is not symmetric and bell shaped, with a single peak at the mean. Moreover the histogram appears to be highly skewed. It is evident that the residuals are not probably normally distributed. The aforesaid conclusion is supported by the normal probability plot of residuals (Figure 12). The points on the plot do not come close to form a straight line. This indicates that the residuals are not normally distributed.

Figure 13 depicts direct or main effects of process variables on bead reinforcement. The plot shows that with increase in current, electrode stick out and voltage, reinforcement increases. Figure 14 establishes the two-way interactive effects of current and electrode stick out on bead reinforcement. From the constant current curves, a rough estimation on the dependence of stick out on bead reinforcement can be made, i.e. with increase in electrode stick out, reinforcement increases, while current is kept constant. But the rate of increase of bead reinforcement with increase in stick out varies while constant current level is varied. It is clear from Figure 15 that bead reinforcement increases with increase in welding voltage, provided welding current is kept constant. Similarly with increase in welding voltage, bead reinforcement gradually increases

for constant levels of welding current. Figure 16 shows the interactive effects of electrode stick out and voltage on reinforcement. At constant level of electrode stick out, increasing welding voltage, reinforcement increases gradually.

For Penetration:

Histogram for bead penetration (Response C6) shows that residuals for bead penetration are not symmetric about mean (Figure 17) which supports the fact that residuals are not evenly distributed. This conclusion supports Figure 18, i.e. normal probability plot of the residuals. Deviations of the points on the plot from a nearly closed fitted line show that the residuals do not obey normal distribution.

Main effects of the selected process variables such as current, electrode stick out and voltage on bead penetration are shown in Figure 22. Figure 19 reveals that with increase in welding current, electrode stick out and voltage, penetration increases. Figure 20 establishes the interactive effects of current and electrode stick out on bead penetration. At constant current level increase in electrode stick out results increase in bead penetration. Effects of interaction between welding current and voltage on bead penetration are shown in Figure 21. Bead penetration increases with increase in welding voltage provided current kept constant. In a similar way it can be concluded from Figure 22 that, at constant electrode stick out, increase in welding voltage results increase in bead penetration.

For Weld Hardness:

The histogram of residuals for hardness of weld bead (Response C7) is shown in Figure 23. The residuals are not symmetrical about the mean, which indicates that the residuals are not normally distributed. The histogram contains two peaks, so a conclusion can easily be made that there may be other important variables, in addition to the factors of interest, influencing the response.

Normal probability plot of the residuals for bead hardness (Figure 24) depicts that the points on the plot deviate from a close fit straight line, supporting the fact that the residuals do not fairly follow normal distribution.

Figure 25 reveals the main effects of welding current, electrode stick out and voltage on hardness of weld bead. It is evident from the figure that with increase in welding current, hardness of the weld bead decreases. At the same time the figure shows that as electrode stick out and voltage increase, hardness of weld bead also increases. Figure 26 shows the interactive effects of welding current and electrode stick out on hardness of the weldment. With constant current level, increase in electrode stick out results increase in hardness of the weldment. But the rate of increase of hardness value with increasing stick out is different for different current levels. Figure 27 depicts that at constant current level, increase in welding voltage cause increase in bead hardness. But this increment does not follow any specific pattern. Interaction between stick out and voltage is shown in Figure 28. The figure reveals that with increase in welding voltage, hardness of weld bead increases at fixed electrode stick out.

For Impact Strength:

Figure 29 shows the histogram of residuals for the data of impact value of the weldment (Response C8). At a glance it can be easily concluded that the residuals are deviated far away from the theoretical normal distribution of statistics. The presence of two outliers in the histogram supports that there are some unidentified factors affecting the response, i.e. impact value of the weld.

Normal probability plot of the residuals for impact value of the weld (Figure 30) shows that the points on the plot do not come closer to form a straight line. This supports that the residuals do not obey normal distribution.

In relation to Figure 31, direct effects of current, stick out and voltage can easily be identified. It is evident from the plots that, with increase in welding, current impact value increases but with increase in electrode stick out and voltage, impact value decreases.

Figure 32 depicts the interactions of current and electrode stick out on impact value of the weldment. From the figure it can be concluded that with constant levels of current, as electrode stick out increases, impact value decreases. But with the domain of the experimental data of the present work, one cannot predict the trend of decrement of impact value with increase in stick out very precisely, when current is held constant.

Figures 33-34 exhibit the interactive effects of current-voltage and voltage-stick out respectively, on impact value of the weld. With current at constant level, increase in voltage results decrease in impact value and increase in welding voltage causes decrease in impact value, keeping stick out at constant level.

For Yield Strength:

The histogram of residuals for yield strength of the joint is shown in Figure 35. It is evident from the figure that the residuals do not follow normal distribution. The normal probability plot of residuals (Figure 36) due to their deviation to form a straight line supports this statement.

Figure 37 shows direct or main effects of the factors on yield strength of the joint. It is clear that with increase in current, yield strength of the joint gradually increases. It is interesting to note that yield strength of the joint remains more or less constant (with a slight decreasing trend) with increasing electrode stick out. Within the domain of the experiment, it is very difficult to refer any specific relation between voltage and yield strength. It is shown in the figure that, with increase in voltage, yield strength of the joint first increases then decreases. The same conclusion can be drawn from Figure 38 i.e. interaction effects of current and stick out on yield strength of the joint. While current is kept constant at 450 A, as stick out increases yield strength first increases then decreases. The same trend is obtained at constant current at 470 A. When current is kept constant at 465 A, yield strength first decreases then increases with the increase in electrode stick out. Figure-39 is very important in this context. It indicates interactive effects of current and voltage. With the increase in voltage, yield strength of the joint first increases gradually and then decreases, while current is held constant. Figure 40 shows the interactive effects of voltage and electrode stick out on yield strength of the joint. With constant level of electrode stick out, as welding voltage increases yield strength of

the joint first increases then decreases.

For Ultimate Tensile Strength:

Figure 41 shows the histogram of residuals for the data of ultimate tensile strength of the joint (Response C10). It is shown that the residuals in the histogram are symmetric about its mean, which concludes that the residuals for the ultimate tensile strength of the weldment follow normal distribution. This claim is obviously true because the normal probability plot of residuals (Figure 42) approaches to form a straight line in the plot.

Figure 43 depicts the main effects of process parameters on ultimate tensile strength of the joint. It is clear from the figure that, with increase in welding current ultimate tensile strength of the weld increases. The main effect plot of electrode stick out on ultimate tensile strength of the joint shows an interesting pattern. It first decreases then increases with increase in electrode stick out. For better prediction more data would have been required. More extensive experiments are, therefore, required and can be planned as a continuation of the present work. This conclusion can also be applied after observing the main effect plot of voltage on ultimate tensile strength of the joint. It is seen that with increase in welding voltage, ultimate tensile strength of the joint first increases then decreases. Figure 44 reveals the interactive effect of current and electrode stick out on ultimate tensile strength of the joint. It is clear that at constant current (450 A), with increase in electrode stick out ultimate tensile strength first decreases and then increases. The same nature can be obtained at a current (465 A). But a different behavior can be observed from the constant current curve at 470 A. With increase in electrode stick out, ultimate tensile strength first increases and then decreases. Figure 45 exhibits the interaction between current and voltage on ultimate tensile strength of the joint. At constant current of 450 A and 465 A, with increase in welding voltage ultimate tensile strength first increases and then decreases. However, the curve at constant current of 475 A shows that, with increase in welding voltage, ultimate tensile strength remains more or less constant. So more detailed experimentation would have to be explored in this context. The interactive effect of voltage and stick out on ultimate tensile strength of the joint is shown in Figure 46. The figure shows that with increase in voltage, ultimate tensile strength of the weldment first increases then decreases, provided stick out is kept at constant value.

7. CONCLUSIONS

Based on experimental observations in submerged arc welding of mild steel plates, the following conclusions can be drawn from the statistical analysis of the observed data. Current is found to be the most important parameter that influences the bead geometry as well as the performance of the weld metal /the welded joint.

Electrode stick out also seems to be an important process variable with its direct significant effects on bead width, reinforcement and penetration. On some of the quality parameters of the weld, like hardness and

impact value, stick out exhibited significant main effects.

The ANOVA, however, shows that the direct effect of electrode stick out on yield strength and ultimate tensile strength of the joint is not significant.

The statistical analysis has been extended to generate histogram of residuals, normal probability plot of the residuals, main and interactive effects of the process parameters on the response variables etc. All these may contribute to the knowledge base of the submerged arc welding, so that the process can be controlled well through some appropriate control system. The paper highlights the statistical significance of parametric influence on various features of SAW weldment. MINITAB has been found efficient to analyze experimental data to infer some important conclusions, within the experimental domain.

NOMENCLATURE

Parameter	Unit	Notation
Bead width	mm	C4
Reinforcement	mm	C5
Penetration	mm	C6
Hardness	VHN	C7
Impact value	Kg	C8
Yield strength	N/mm ²	C9
Ultimate strength	N/mm ²	C10
DF	Degree of Freedom	
SS	Sum of Squares	
MS	Mean Square	
F	MS of each source / MS for error term (Fisher's F ratio)	

REFERENCES

1. B.G. Renwick and B.M. Patchett "Operating characteristics of submerged arc process", *Welding Journal*, **55**, 69S-76S (1976).
2. C.E. Jackson, The Science of Arc Welding.. 1959 Adam's Lecture. *Welding Journal*, 1960.
3. S.R. Gupta and N. Arora, "Influence of flux basicity on weld bead geometry and HAZ in submerged arc welding", *Indian Welding Journal*, 127-133 (1991).
4. V. Malin, "Root weld formation in modified refractory flux one-sided welding: Part 2: Effect of joint

- geometry", *Welding Research Supplement*, September 2001, pp 227-237.
5. V. Gunaraj and N. Murugan, "Prediction and optimization of weld bead volume for the submerged arc process-Part 1", *Welding Research Supplement*, October 2000, pp 286-294.
 6. V. Gunaraj and N. Murugan, "Prediction and optimization of weld bead volume for the submerged arc process-Part 2", *Welding Research Supplement*, November 2000. pp. 331-338.
 7. I.S. Kim, J.S. Son, C.E. Park, I.J. Kim, H.H. Kim, "An investigation into an intelligent system for predicting bead geometry in GMA welding process", *Journal of Material Processing Technology*, **159**, 113-118 (2005).
 8. Y.S. Tarang, S.C. Juang, C.H. Chang, "The use of grey-based Taguchi methods to determine submerged arc welding process parameters in hard facing", *Journal of Materials Processing Technology*, **128**, 1-6 (2002).
 9. Y.S. Tarang, H.L. Tsai, S.S. Yeh, " Modeling, optimization and classification of weld quality in tungsten inert gas welding", *International Journal of Machine Tools and Manufacture*, **39**, 1427-1438 (1999).
 10. M.H. Robinson, "Observation on electrode melting rate during submerged arc welding", *Welding Journal*, **40**, 503s-513s (1961).
 11. G.M. Reddy, P.K. Ghosh, A. Khanna, "The influence of electrode polarity and welding current on mechanical properties of submerged arc welding", *Indian Welding Journal*, 145-150 (1991).
 12. S. V. Nadkarni, "*Modern Arc Welding Technology*", Oxford and IBH Publishing Co. Pvt. Ltd, 1988.
 13. K. Masubuchi, "*Analysis of Welded Structure*", Pergamon Press, Oxford, 1980.
 14. O. L. Davis, "*Design and Analysis of Industrial Experiments*", Longman, New York, 1978.
 15. MINITAB Release 13.1 (User Manual).
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