Model Development for Prediction and Evolution of the Parametric Dependence of Bead Volume in Submerged Arc Butt Welding

by
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Abstract

A nonlinear mathematical model has been aimed to develop, for prediction as well as estimation of the parametric dependence of bead volume in submerged arc butt welding. Based on factorial design without replication, experiments have been performed with three different levels of process parameters like welding current, electrode stick out and voltage to obtain butt joints from Mild Steel plates. Parameters associated with bead geometry like bead width, reinforcement, depth of penetration etc. have been measured for each experimental runs. By incorporating certain assumptions on the bead geometry and assuming unit length of the work piece, bead volumes have been calculated. All the data thus obtained have been utilized to develop a nonlinear mathematical model for prediction of bead volume at different settings of factor level. The adequacy of the developed model have been tested by ANOVA (Analysis of Variance Method). Finally the effect of process variables on bead volume of the weldment have been determined quantitatively and represented graphically. The study reveals that all the selected process variables have positive effect on bead volume.

Keywords: Bead width, reinforcement, depth of penetration, ANOVA

1. 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. It is a multi-objective metal fabrication process which should ensure maximum penetration, minimum bead width, minimum reinforcement and minimum HAZ width, depending on the area of application. To obtain favorable quality weld bead, at a relatively low cost, the process parameters must be set at optimum values. In other words, to obtain optimum weld, the operator should know how to select and control the process variables properly.

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.

Renwick, B.G. and Patchett, B.M. [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. Jackson, C.E. [2] established that penetration decreased with the increase in electrode diameter at constant current because of reduced current density. Gupta, S.R. and Arora, N. [3] studied the effect of welding parameters on weld bead geometry and HAZ. Marlin, V. [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). Gunaraj, V. and Murugan,N. [5, 6] determined the main & interaction effects of process control variables on important bead geometry parameters quantitatively and represented the results graphically. Kim, I.S. et al. [7] 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. Tarng, Y.S. et al. [8] 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 in 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 [9-18].

The literature review depicts that huge investigations have been performed so far in the area of submerged arc welding in which emphasis has been made to study the effect of process parameters on bead geometry; more work is still being reported which indicates that there exists need for more understanding in this respect.

In the present work an attempt has been made to evaluate the effects of process parameters on bead volume of the weldment, through a nonlinear mathematical model, that have been derived by applying multiple linear regression method. Predicted data, as given by the models, have been used to reveal graphically the effects of the process parameters on selected response variable of submerged arc welding. The proposed model can be effectively utilized to reduce weld metal consumption, thereby obtaining favorable quality weld bead and achieving high productivity, more economically.

2. Design of Experiment

In the present study three independent process parameters-voltage, welding current and electrode stick out has been considered. Other parameters were assumed to be constant over the experimental domain. Experiments 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 listed in Table-1. The working ranges for the process parameters were selected from ASW handbook. Based on 3^3 factorial designs, the selected design matrix is a three level, three-factor full factorial design consisting of 27 sets of coded conditions.

Parameters	Unit	Notation	-1	0	1
For Backing Pass					
Current	A	C_1	450	465	480
Stick out	mm.	T	22	24	26
voltage	V	V_1	30	32	34
For Secondary Pass					
Current	A	C_2	470	485	500
Stick out	mm.	T	22	24	26
voltage	V	V_2	32	34	36

Table 1. Process Control Parameters and their Limits

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, depth of penetration reinforcement etc. have been measured. The data, obtained from the experiments mentioned above, have been used for determining the bead volume approximately and finally for developing the mathematical model, which is then analyzed in relation with the effect of process variables on bead volume of the weldment.

4. Determination of bead volume

Based on simple assumptions on the geometry of bead cross-sectional area, the bead volume can be calculated approximately with the help of known bead geometry parameters- reinforcement, penetration, bead width etc.

The simplified bead geometry is shown in Fig.1. The following notations are used:

R=Reinforcement

W=Bead Width

P=Depth of Penetration

A=Cross Sectional area of the bead

Suffix 1 and 2 represents bead geometry parameters for backing pass and secondary pass respectively.

Assuming upper boundary (also lower boundary) of the weld bead to be the shape of an arc with radius (R+P),

Therefore, $\tan\theta = (W/2P)$, (θ in degree)

$A_1=(R_1+P_1)^2\,\theta$ and $A_2 = (R_2+P_2)^2\,\theta$, ($\theta$ in radian)

Total bead cross sectional area $A=(A_1+A_2)$

Assuming unit length of the job, the value A represents total volume of the weld bead.

Evaluation of the value of bead volume were performed in MATLAB (7.0.0. 19920. R14) package.

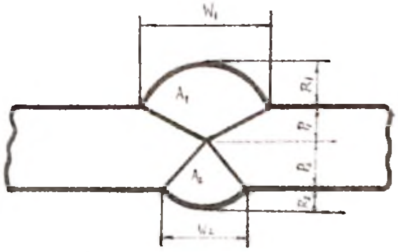

Figure 1 Simplified bead geometry

5. Development of mathematical model

The response function that represents bead volume can be expressed as Y=f(C,T,V).

A nonlinear mathematical model has been selected to establish the relationships between response variable and the predictors. It is intended to reflect the influence of parameters used in secondary pass on overall bead volume.

$V_{Bead} = aV_2^{\psi}C_2^{\varphi}T^{\xi}$ (i)

Where, a, ψ, φ, ξ are constants.

Taking logarithm on both sides, equation (i) becomes:

$\ln Y = \ln a + \varphi \ln C_2 + \xi \ln T + \psi \ln V_2$ (ii)

$Y_0 = \beta_0 + \varphi X_1 + \varphi X_2 + \xi X_3$,

where $Y_0 = \ln Y$, $\beta_0 = \ln a$ $X_1 = \ln C_2$, $X_2 = \ln T$, $X_3 = \ln V_2$.

The model becomes a multiple linear regression model.

Source	DF	SS	MS	F	P
lnV2	2	0.497688	0.248844	2236.79	0.000
lnC2	2	0.007970	0.003985	35.82	0.000
lnT	2	0.069108	0.034554	310.60	0.000
lnV2*lnC2	4	0.000919	0.000230	2.07	0.178
lnV2*lnT	4	0.005694	0.001423	12.79	0.001
lnC2*lnT	4	0.001089	0.000272	2.45	0.131
Error	8	0.000890	0.000111		
Total	26	0.583354			

Table 2. ANOVA for Bead Volume

In the present work, the values of the constants were calculated in MINITAB. Based on multiple linear regression, developed mathematical model for bead volume are shown below (Equation iii) The adequacy of the developed model has been tested by Analysis of Variance Method. (The relevant model statistics and ANOVA are shown in Appendix).

$$V_{Bead} = 11.195\text{x}10^{-6} V_2^{2.82} C_2^{0.679} T^{0.741} \quad \text{(iii)}$$

6. Analysis of variance method

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 or not. If P is less than or equal to the α-level (0.05) 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. ANOVA results for bead volume are shown in Table 2. The graphical representations showing the main effects and interactive effects of various process parameters on selected response variable are given in the Figures 2-11.

6. Graphical representations

Experimental data as well as predicted data have been used to show the effects of various process parameters on bead volume. The variations of bead volume with variations of the process parameters (as predicted by the model) are also shown to show the performance of the developed model.

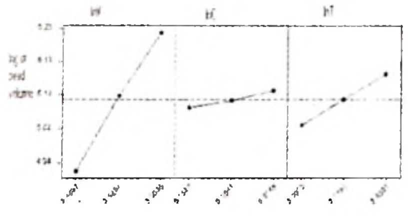

Figure 2 Direct effect of process parameters on bead volume

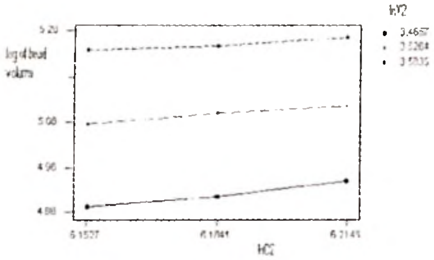

Figure 3 Interaction effect of current and voltage

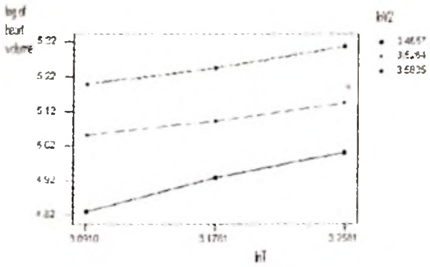

Figure 4 Interaction between voltage and stick out

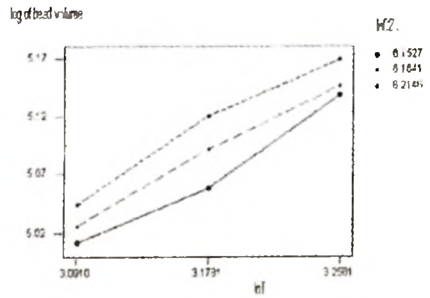

Figure 5 Interaction between current and stick out

Model Prediction

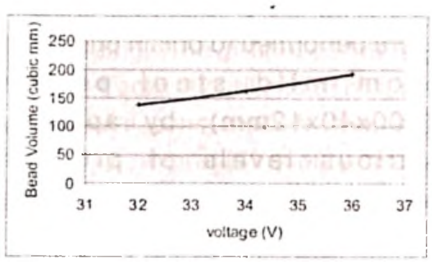

Figure 6 Direct effect of voltage on bead volume
(C_2=485A & T=24mm)

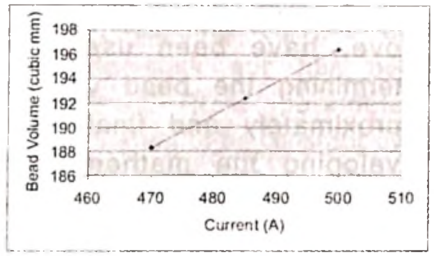

Figure 7 Direct effect of current on bead volume
(V_2=36V & T=24mm)

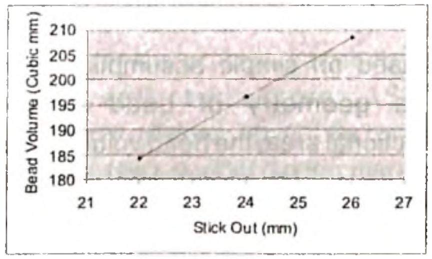

Figure 8 Direct effect of stick out on bead volume
(V_2=36V & C_2=500A)

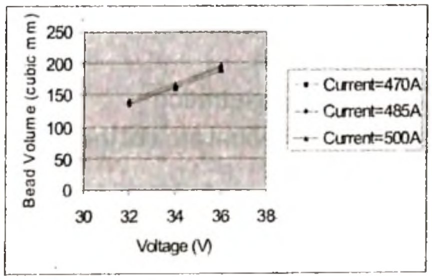

Figure 9 Interaction between voltage and current
(stick out=24mm)

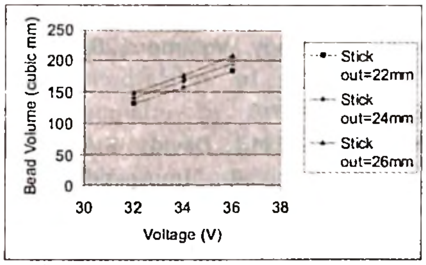

Figure 10 Interaction between voltage and stick out (Current=500A)

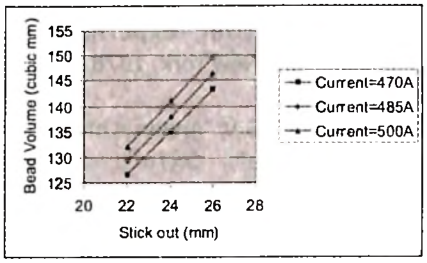

Figure 11 Interaction between stick out and current (Voltage=32V)

7 Discussions

7.1 On ANOVA

Table 2 shows the significant effect of process variables (as well as interaction of variables) on bead volume quantitatively. ANOVA is an efficient statistical technique which can infer some important conclusions, based on the experimental data.

However, it must be mentioned (a) that there are possibilities of experimental errors and (b) that some unknown factors might have been omitted in the modeling and experimentation processes, the effects of which might not be insignificant. Therefore ANOVA predictions are not absolute and are not free from certain errors. Still ANOVA serves as a very useful technique for forecasting the level of significance of the predictor variables on the output responses, generally.

In ANOVA table, based on the experimental data, for each direct effect and interaction terms of the predictors, F value is calculated. Depending on the F value, the P value (The probability of significance) is also calculated. If P value for a term (direct/interaction) becomes less than 0.05, then it can be concluded that the effect of that particular predictor (of interaction of predictors) is significant on 95% confidence level.

ANOVA table for bead volume depicts that, the direct effect of voltage, current and stick out on bead volume is very significant at 95% confidence level, for their P value 0.000, much less than 0.05.

The interactive effect of voltage-stick out on bead volume is significant, because this term has P value 0.001 (less than 0.05).

The interaction effect of voltage-current and current-stick out on bead volume are insignificant here.

7.2 Direct and interaction plots (Based on experimental as well as model predicted data)

Experimental data have been utilized to reveal graphically the direct as well as interactive effects of welding voltage, stick out and current on bead volume associated with submerged arc butt welding. The plots (Figures 2-5) have been obtained in statistical software package MINITAB environment.

Figure 2 shows the direct effect of process variables on bead volume. It is clear that all the parameters, considered in the study, impose positive effect on volume of the weldment. Keeping other parameters constant, increase in voltage, or current, or stick out results increase in bead volume. The same trend can be observed in Figures 6-8, the variation as predicted by the developed model, with in the experimental region.

Figure 3 reflects the interaction effect of welding current and voltage on bead volume. Though Table 2 shows that the interactive effect of current-voltage on bead volume is insignificant, the Figure 3 shows some remarkable interactive effect. Figure 9 supports the same. (With stick out =24mm) Increase in voltage results increase in bead volume, for constant current level.

Figure 4 describes the interactive effect of voltage-stick out on bead volume. The same trend is obtained in Figure 10. (For constant current of 500A) Increase in voltage results increase in bead volume, provided stick out is kept constant.

The interaction effect of current and stick out on bead volume is shown in Figure 5. The same nature is observed in Figure 11. The model predicts that for constant current, increase in electrode stick out results an increase in bead volume (voltage =32V).

8. Conclusions

Within experimental domain, the following conclusions can be drawn from the above investigation:

1. Welding current, voltage and electrode stick out appear to be the important process control parameters in SAW, with their direct and interactive effects on volume of the weld bead.
2. Statistical models followed by multiple linear regression have been proved fruitful in representing the effect of various predictors on the selected response variable i.e. bead volume in the present case, through the developed mathematical model.
3. MINITAB can be explored effectively to take care of only the significant factors (as well as interaction effects of factors) in the mathematical model.
4. Welding current, voltage and electrode stick out- all impose positive effect on the weld bead volume.
5. The interactive effect of stick out-voltage on bead volume is significant.
6. Most of the main and interactive effects of the process parameters on the bead volume of the weldment show convincing trends generally, between cause and effect.
7. The models developed in this reporting and the data thus obtained can be effectively utilized to perform automatic welding as well as robotic welding. More work towards this end need to be started and continued.

References

1. Renwick, B.G. and Patchett, B. M., 1976,"Operating Characteristics of Submerged Arc Process", Welding Journal.
2. Jackson, C.E.1960,"The Science of Arc Welding",1959 Adam's Lecture, Welding Journal.
3. Gupta, S.R. and Arora, N., 1991,"Influence of Flux Basicity on Weld Bead Geometry and HAZ in Submerged Arc Welding", Indian Welding Journal, 23: 127-133.
4. Marlin, V., 2001, "Root Weld Formation in Modified Refractory Flux One-Sided Welding: Part-2-Effect of Joint Geometry", Welding Research Supplement, pp 227-237.
5. Gunaraj, V. and Murugan, N., 2000,"Prediction and Optimization of Weld Bead Volume for the Submerged Arc Process-Part-1",Welding Research Supplement, pp 286-294.
6. Gunaraj,V. and Murugan,N., 2000, "Prediction and Optimization of Weld Bead Volume for the Submerged Arc Process-Part-2",Welding Research Supplement, pp.331-338.
7. Kim, I.S., Son, J.S., Park, C.E., Kim, I.J., Kim, H.H., 2005, "An investigation into an intelligent system for predicting bead geometry in GMA welding process", Journal of Material Processing technology, 159: 113-118.
8. Tarng, Y.S.; Juang, S.C.; Chang, C.H.; "The Use of Grey-Based Taguchi Methods to Determine Submerged Arc Welding Process Parameters in Hardfacing", Journal of Materials Processing Technology, Volume 128, 2002, pp. 1-6.
9. Vitek, J.M.; David, S.A.; and Hinman, C.R., "Improved Ferrite Number Prediction Model that Accounts for Cooling Rate Effects-Part 1: Model Development", Welding Journal, 2003, pp. 10s-17s.
10. Davis, O.L., "Design and Analysis of Industrial Experiments", Longman, New York, 1978.
11. Nadkarni, S.V, "Analysis of Welded Structure", Oxford & IBH Publishing Co. Pvt. Ltd., 1988.
12. Masubuchi, K., "Analysis of Welded Structure", Pergamon Press, Oxford, 1980.
13. DeRuntz, B.D., "Assessing the Benefits of Surface Tension Transfer Welding to Industry", Journal of Industrial Technology, Volume 19, Number 4, August 2003, pp. 1-7.
14. Quintana, M.A., and M.Q. Johnson, "The Effects of Intermixed Weld Metal on Mechanical Properties-Part 1", Welding research supplement, March 1999, pp. 87s-99s.
15. Fujita, M., Kinugawa, J., Okada, A. and Kasugai, T., "New Welding Information System on the Internet (Prediction of the Properties of Weld Heat Affected Zones)", Data Science Journal, Volume 2, 7th August 2003, pp. 136-145.
16. Jackson, C.E. and Shrubsall, A.E., "Control of Penetration and Melting Ratio with Welding Technique", 1953, Welding Journal, 32(4), pp. 172s-178s.

17. Datta, S., Biswas, A., Bandyopadhyay, A. and Pal, P.K., "Prediction of Weld Bead Geometry by Artificial Neural Network in Submerged Arc Welding", proceedings (Vol2) of the 14th ISME International Conference on Mechanical Engineering in Knowledge Age, held on December 12-14, 2005, at Delhi College of Engineering, Delhi.

18. Datta, S., Sundar, M., Bandyopadhyay, A., Pal, P.K., Nandi, G. and Roy, S.C., "Effect of Electrode Stick Out on Quality and Performance of Submerged Arc Welding-Experimental and Statistical Analyses", proceedings of the International Conference on Mechanical Engineering, held on 28-30 December, 2005, at Dhaka, Bangladesh.

Appendix

Model Statistics
(Corresponding to model equation (ii))

Predictor	**Coef**	**SE Coef**	**T**	**P**
Constant	-11.4077	0.9854	-11.58	0.000
V_2	2.82182	0.07891	35.76	0.000
C_2	0.6785	0.1502	4.52	0.000
T	0.74127	0.05562	13.33	0.000

S=0.01972
R-Sq=98.5%
R-Sq(adj) = 98.3%

Analysis of Variance (For the model)

Source	**DF**	**SS**	**MS**	**F**	**P**
Regression	3	0.57441	0.19147	492.29	0.000
Residual Error	23	0.00895	0.00039		
Total	26	0.58336			