Quadratic Response Surface Modeling For Prediction Of Bead Geometry In Submerged Arc Welding

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ABSTRACT

The effect of various process control parameters on bead geometry of submerged arc weldment has been aimed to investigate using quadratic response surface methodology. Each of the features of weld bead geometry has been assumed and expressed as a function of selected process parameters so that the function takes into account the linear, quadratic as well as interaction effects of the predictors. Experiments are conducted with different levels of process parameters like voltage, welding current, wirefeed rare and traverse speed to obtain bead-on-plate weld on mild steel plates. Based on multiple linear regression, mathematical models have been developed for prediction of bead geometry, for different settings of factor level. Using statistical software package MINITAB, reduced models are built up with significant factors and coefficients. MINITAB's Backward elimination option in stepwise regression is used to eliminate insignificant factors from the models and to recalculate the coefficients of the significant factors. Developed mathematical model for penetration has been optimized (maximized), considering (minimizing) the reinforcement, depth of HAZ and bead width as constraints. Sensitivity analysis was also carried out to study the change in value of the objective function (bead penetration) due to change of limit of the constraints from the optimum value. The direct and interactive effect of various process control parameters on the features of bead geometry and HAZ have been measured quantitatively and represented graphically. The methodology, proposed in the study can be used to obtain superior quality weld bead and also to achieve high productivity.

Keywords: quadratic response surface methodology, multiple linear regression

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.

Submerged arc welding is a multi-objective metal fabrication process which generally ensures 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. In most of the cases, the acceptability of a weld, in terms of its quality and performance depends on the operators past experience and working skill. But in present days, with the advent of automation it has become no longer a problem. It is now possible to operate a machine capable of receiving process parameters as input and producing optimum weld as output. It can also select optimum process parameters by itself, as per requirement of the weld. This, however, requires reliable data of knowledge.

B.G. Renwick and B.M. Patchett [1] studied the characteristics of the weld bead, penetration, and melting rate under variable operating current conditions and found that those increase with the increase in current. C.E. Jackson [2] established that penetration decreases with the increase in electrode diameter at constant current because of reduced current density. S.R. Gupta and N. Arora [3] studied the effect of welding parameters on weld bead geometry and HAZ. V. Marlin [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 and N. Murugan [5, 6] determined the main & interaction effects of process control variables on important bead geometry parameters quantitatively and represented the results graphically. I.S. Kim 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. Y.S. Tarng 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 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 [9-16]. 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 is need of more understanding in this respect. In the present work an attempt has been made to reevaluate the effects of process parameters on bead geometry of the weldment, through mathematical models, that have been derived by applying quadratic response surface methodology and multiple linear regression. MINITAB's step backward elimination option was used to eliminate insignificant coefficients of the models. The reduced models with significant coefficients are also developed. Predicted data, as given by the models, have been used to reveal graphically the direct and interactive effects of the process parameters on bead geometry of submerged arc welding. Moreover, an attempt has also been made to optimize bead penetration, taking reinforcement, width of HAZ and bead width as constraints. The proposed model can be effectively utilized to reduce weld metal consumption, thereby obtaining favorable quality weld bead and achieving high productivity.

EXPERIMENTAL PLAN AND DATA COLLECTION

The study was carried out using the following steps:

1. Identifying the important process control parameters and selecting their limits.
2. Developing the experimental model using different settings of factor level.
3. Conducting the experiment as per the design.
4. Recording the responses.
5. Developing the mathematical models.
6. Calculating the significance of the factors along with their coefficients and arriving at final mathematical model.
7. Determining the quantitative effects of the process variables on selected bead geometry parameters and representing the results graphically.

Four independent controllable process parameters have been considered for the present investigation. 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 used in this reporting, and values on different levels are furnished on Table-1. The working ranges for the process parameters have been selected from ASW handbook. Experiments have been performed to obtain bead-on-plate weld on mild steel plates (125x35x10 mm), by applying various levels of process parameters like voltage, traverse speed, wirefeed rate and current. Parameters associated with bead geometry like bead width, penetration, reinforcement and depth of HAZ etc. have been measured. In order to illustrate the method for analyzing the effects of process parameters the entries of Table 2 will be treated for the purpose. The data presented in

Sl. No	Factor	Unit	Levels					
1	Current (C)	Ampere	150	175	200	225	-	-
2	Voltage (V)	Volts	22	24	28	-	-	-
3	Wire feed rate (W	cm/min	57	65	75	80	91	100
4	Traverse speed (T)	cm/min	12.5	19.5	24	25	-	-

Table I : Process Parameters and their limits

TRAVERSE SPEED (cm/min)	WIRE FEED RATE (cm/min)	VOLTAGE (volt)	CURRENT (A)	REINFORCEMNET (mm)	PENETRATION (mm)	HAZ WIDTH (mm)	BEAD WIDTH (mm)
12.50	57	22	150	4.00	2.10	2.10	11.20
12.50	75	22	200	4.46	2.76	2.20	12.76
12.50	100	22	250	4.12	1.88	3.18	14.82
14.00	57	22	175	4.18	2.66	2.28	11.36
14.00	91	22	225	4.22	2.26	2.42	13.94
14.00	100	22	275	4.92	3.00	2.20	13.18
19.50	75	22	225	3.34	1.82	2.28	12.10
19.50	91	22	225	3.64	1.96	2.40	13.52
19.50	100	22	275	4.30	3.16	2.26	13.70
25.00	57	22	150	0.40	0.30	1.20	8.24
25.00	100	22	225	3.22	2.78	1.72	12.78
12.50	57	24	175	3.64	2.06	0.66	11.52
12.50	75	24	175	4.50	1.78	2.56	13.96
12.50	91	24	325	4.00	4.40	2.56	19.50
12.50	100	24	225	4.24	4.10	2.56	16.70
14.00	57	24	175	3.20	1.44	2.50	11.70
14.00	75	24	175	3.40	3.00	3.10	13.40
14.00	91	24	250	3.78	3.22	2.62	16.00
14.00	100	24	250	3.78	3.28	3.60	17.00
19.50	57	24	200	2.42	1.10	1.90	10.42
19.50	75	24	225	3.10	2.24	2.62	14.16
19.50	91	24	225	2.80	3.00	1.70	13.40
19.50	100	24	250	3.72	3.78	2.26	14.20
25.00	57	24	200	2.36	1.38	2.00	8.80
25.00	75	24	200	2.20	2.70	1.78	12.20
25.00	91	24	225	2.40	2.26	2.16	13.94
12.50	57	28	175	3.00	1.75	4.35	13.30
12.50	91	28	275	3.00	1.90	5.06	18.12
12.50	100	28	275	3.78	3.72	5.06	20.64
14.00	57	28	175	3.10	2.06	5.06	13.74
14.00	75	28	150	3.04	2.54	5.68	17.52
14.00	91	28	250	3.12	4.60	5.68	19.34
14.00	100	28	300	3.24	3.20	5.68	20.72
19.50	57	28	175	2.56	2.00	2.94	12.28
19.50	75	28	200	2.48	1.92	3.80	15.22
19.50	91	28	275	2.70	3.46	5.00	12.32
19.50	100	28	275	2.86	3.40	5.00	17.92
25.00	57	28	200	2.54	1.00	2.12	9.98
25.00	75	28	200	2.58	2.42	2.00	13.42
25.00	91	28	250	2.26	2.00	3.80	15.88
12.50	57	26	200	4.40	3.00	4.32	15.48
12.50	75	26	200	3.62	2.66	4.30	15.34
12.50	91	26	250	3.66	3.00	4.10	19.00
12.50	100	26	300	4.00	4.78	4.30	20.00
14.00	57	26	300	3.00	2.00	3.30	12.92
14.00	75	26	200	3.50	1.18	3.10	10.00
14.00	91	26	250	3.38	4.10	2.90	16.38
14.00	100	26	275	3.62	2.24	2.70	19.22
19.50	57	26	175	2.56	2.00	1.78	11.74
19.50	75	26	200	2.40	2.60	3.50	15.50
19.50	91	26	250	3.00	1.70	3.82	15.18
19.50	100	26	300	3.20	2.70	5.32	16.88
25.00	57	26	175	2.26	1.74	1.92	11.62
25.00	75	26	200	2.42	4.22	1.90	13.60
25.00	91	26	275	2.20	1.72	3.82	14.70
25.00	100	26	300	3.40	1.92	4.72	14..62
19.50	65	22	175	2.70	2.35	2.12	10.48
19.50	75	22	175	3.12	2.56	2.30	10.33
19.50	85	22	175	3.21	2.94	2.49	10.71
19.50	91	22	175	3.59	3.00	2.50	11.35
25.00	91	28	300	2.93	2.51	2.70	16.80
25.00	80	28	300	3.58	2.29	4.50	16.40
25.00	75	28	300	3.70	2.12	4.33	15.89
25.00	65	28	300	4.10	2.10	3.71	15.84
25.00	57	28	300	3.75	1.78	3.55	15.00
12.50	57	22	175	4.68	3.46	1.98	8.41
12.50	57	24	175	3.60	2.00	2.40	11.10
12.50	57	26	175	3.33	1.91	3.94	12.32
12.50	57	28	175	2.89	1.68	4.36	13.91
19.50	57	24	175	4.46	2.45	3.22	11.12
12.50	91	22	225	4.54	2.30	2.50	14.30
14.00	75	22	200	3.70	2.62	2.20	11.23
19.50	67	22	175	2.34	2.32	2.10	10.20
25.00	75	22	200	2.76	2.20	1.85	10.38
25.00	91	22	225	3.14	1.78	1.96	10.74
25.00	100	24	275	3.0	2.75	2.40	13.20
12.50	75	28	200	3.46	2.20	5.06	17.12
25.00	100	28	300	2.22	2.65	4.30	17.46

Table II : Experimental Data

Table 2, obtained from the experiments mentioned above, have been used for developing, analyzing and explaining the mathematical model concerning the effect of process parameters on response variables.

DEVELOPMENT OF MATHEMATICAL MODELS

MULTIPLE LINEAR REGRESSION

The response function that represents any of the features of bead geometry can be expressed as Y=f(V,C,W,T). The selected relationship is a second-degree response surface, which is expressed as follows:

$Y=\beta_0 + b_1 V + b_2 C + b_3 W + b_4 T + b_{11} V^2 + b_{22} C^2 + b_{33} W^2 + b_{44} T^2 + b_{12}VC + b_{13}VW + b_{14}VT + b_{23}CW + b_{24}CT+b_{34}WT$ .... (i)

The response surface methodology (RSM) is widely applied for modeling the output response(s) of a process in terms of the important controllable variables and then finding the operating conditions that optimize the response.

Considering the above equation, the second order model with interaction, it is assumed that V=x1, C=x2, W=x3 and T=x4.

Then,

$Y=\beta_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_4 x_4 + b_{11} x_1^2 + b_{22} x_2^2 + b_{33} x_3^2 + b_{44}x_4^2 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{14}x_1x_4 + b_{23}x_2x_3 + b_{24}x_2x_4 + b_{34}x_3x_4$ .... (ii)

If, it is considered that $x_1^2=x_5$, $x_2^2=x_6$, $x_3^2=x_7$, $x_4^2=x^8$, $x_1x_2=x_9$, $x_1x_3=x_{10}$, $x_1x_4=x_{11}$, $x_2x_3=x_{12}$, $x_2x_4=x_{13}$, $x_3x_4=x_{14}$ and $b_1=\beta_1$, $b_2= \beta_2$, $b_3= \beta_3$, $b_4= \beta_4$, $b_{11}= \beta_5$, $b_{22}= \beta_6$, $b_{33}= \beta_7$, $b_{44}= \beta_8$, $b_{12}= \beta_9$, $b_{13}= \beta_{10}$, $b_{14}= \beta_{11}$, $b_{23}= \beta_{12}$, $b_{24}= \beta_{13}$, $b_{34}= \beta_{14}$, the equation (ii) can be written as a multiple linear regression model as follows:

$Y= \beta_0 + \beta_1x_1 + \beta_2x_2 + \beta_3x_3 + \beta_4x_4 + \beta_5x_5 + \beta_6x_6 + \beta_7x_7 + \beta_8x_8 + \beta_9x_9 + \beta_{10}x_{10} + \beta_{11}x_{11} + \beta_{12}x_{12} + \beta_{13}x_{13} +\beta_{14}x_{14}$ .... (iii)

EVALUATION OF THE COEFFICIENTS OF MODELS

The method of least squares can be used to estimate the regression coefficients in equation (iii). In matrix notation, the model given by equation (iii) is:

$$Y=X\ \beta + \varepsilon$$

Where $Y = [\ Y_1\ Y_2\ Y_3.....Y_n\ ]^T$

$$X = \begin{bmatrix} 1 & x_{11} & x_{12} & \cdot & \cdot & x_{1k} \\ 1 & x_{21} & x_{22} & \cdot & \cdot & x_{2k} \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ 1 & x_{n1} & x_{n2} & \cdot & \cdot & x_{nk} \end{bmatrix}$$

$\beta = [\ \beta_0\ \ \beta_1\ \ \beta_2\ ....\ \beta k\ ]^T$

$\varepsilon = [\varepsilon_1\ \ \varepsilon_2\ \ ....\ \varepsilon_n\ ]^T$

Where Y_i denote the ith observed response and x_{ij} denote the ith observation or level of regressor x_j. ε indicates error. In general, Y is an n x 1 vector of the observations, X is an n x p matrix of the levels of the regressor variables, β is a p x 1 vector of the regression coefficients, and e is an n x 1 vector of random errors. There are p=k+1 normal equations, one for each of the unknown regression coefficients.

To find the vector of least-squares estimators, $\hat{\beta}$, that minimizes

$S(\beta) = \sum_{i=1}^{n} \varepsilon_i^2 = \varepsilon'\varepsilon = (Y - X\beta)'(Y - X\beta)$

It is to be noted that S(β) may be expressed in the following manner

$$S(\beta) = Y'Y - 2\beta'X'Y + \beta'X'X\beta$$

The least-square estimators must satisfy

Which simplifies to

$$X'X\hat{\beta} = X'Y \qquad ....(iv)$$

Equations (iv) are the least-squares normal equation. The solution of the normal equations are $\hat{\beta} = (X'X)^{-1}X'Y$

The value of the coefficients were calculated in MINITAB. They are presented in

Table 3. Developed mathematical models are shown below.

Reinforcement = 3.61 + 0.192V- 0.0153C + 0.146W - 0.549T - .0038V² - 0.000019C² + 0.000008W² + 0.00111T² + 0.00031VC - 0.00482VW + 0.00995VT + 0.000002CW + 0.00119CT - 0.00143WT .... (v)

Penetration = -2.99 + 0.539V + 0.0015C - 0.026W - 0.153T - 0.0178V² + 0.000063C² + 0.000071W² - 0.00175T² -0.00002VC + 0.00261VW + 0.0106VT - 0.000195CW - 0.000872CT + 0.0013WT .... (vi)

Depth of HAZ = 2.65 - 0.709 V - 0.044C + 0.05W + 0.873T + 0.0303V² + 0.000049C² - 0.000406W² - 0.00874T² - 0.00017VC + 0.00216VW - 0.0337VT + 0.000021CW + 0.00159CT - 0.00177WT .... (vii)

Bead Width $= -11.4 + 1.13V - 0.003C + 0.052W - 0.156T - 0.0111V^2 + 0.000211C^2 - 0.00033W^2 + 0.0143T^2 - 0.00274VC + 0.0113VW - 0.0136VT - 0.000397CW + 0.00082CT - 0.00538WT$ .... (viii)

DEVELOPMENT OF REDUCED MODELS

The MINITAB's Backward Elimination method of stepwise regression has been used to check the validity of the models. Stepwise regression is a technique for choosing the variables, i.e., terms, to be included in a multiple regression model. Backward stepwise regression starts with all the terms in the model and removes the least significant terms until all the remaining terms are statistically significant. An important assumption behind the method is that some input variables in a multiple regression do not have an important explanatory effect on the response. If this assumption is true, then it is a convenient simplification to keep only the statistically significant terms in the model.

The reduced models with significant coefficients are presented below:

Reinforcement$= 5.224+ 0.123W - 0.551T -0.00415VW + 0.011VT + 0.00115CT - 0.00109WT$ .... (ix)

Penetration $= 1.7523 - 0.00134V^2 + 0.00001C^2 + 0.00098VW - 0.00023CT$ .... (x)

Depth of HAZ $= -3.0135 - 0.044C + 0.71T + 0.0163V^2 + 0.00006C^2 - 0.0086T^2 + 0.00065VW - 0.0289VT +0.00117CT$ .... (xi)

Bead Width$= -11.86 + 1.18V - 0.0191V^2 + 0.00003C^2 + 0.0053VW - 0.00268WT$ .... (xii)

Sl No.	Coefficient	Reinforcement	Penetration	HAZ width	Bead width
1	b_0	3.613	-2.995	2.652	-11.43
2	b_1	0.1925	0.5392	-0.7092	1.128
3	b_2	-0.01526	0.00152	-0.04399	-0.00032
4	b_3	0.14591	-0.0257	0.0502	0.0520
5	b_4	-0.5487	-0.1526	0.8728	-0.1563
6	b_5	-0.00379	-0.01782	0.03025	-0.01105
7	b_6	-0.00001855	0.00006277	0.00004874	0.0002110
8	b_7	0.0000076	0.0000710	-0.0004062	-0.000328
9	b_8	0.001106	-0.001753	-0.008736	0.014267
10	b_9	0.000306	-0.000023	-0.000170	-0.002744
11	b_{10}	-0.004821	0.002609	0.002157	0.011257
12	b_{11}	0.009948	0.010561	-0.033720	-0.01360
13	b_{12}	0.0000018	-0.0001948	0.0000208	-0.0003968
14	b_{13}	0.0011946	-0.0008720	0.0015903	0.000817
15	b_{14}	-0.0014265	0.001300	-0.001773	-0.005378

Table III : Regression Coefficients Of Models

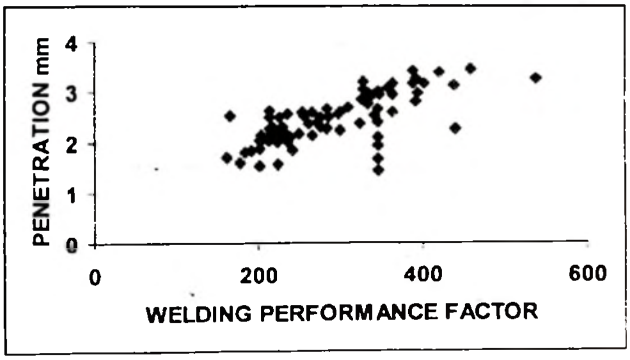

Fig.1 Effect of welding performance factor on penetration

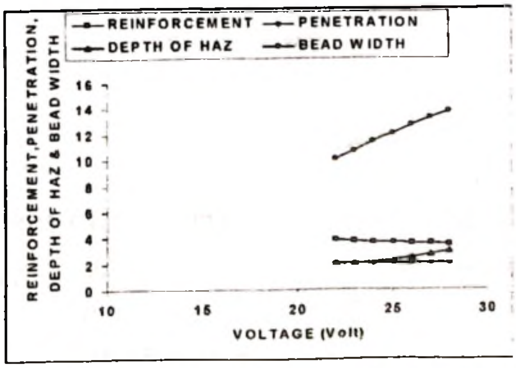

Fig.2 Direct effect of voltage on bead parameters (mm) (C=200A, W=75cm/min & T=24cm/min)

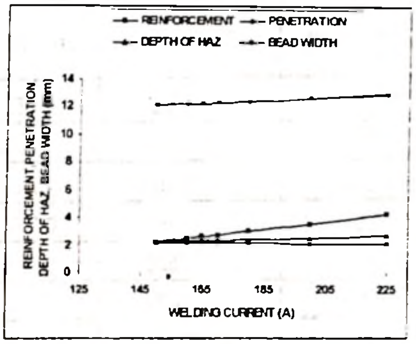

Fig.3 : Direct effect of Current on bead parameters (V=26Volt, W=75cm/min & T=24cm/min)

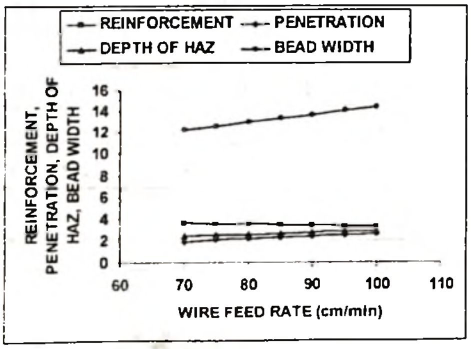

Fig.4 : Direct effect of wirefeed rate on bead parameters (mm) (V=26Volt, C=200A & T=24cm/min)

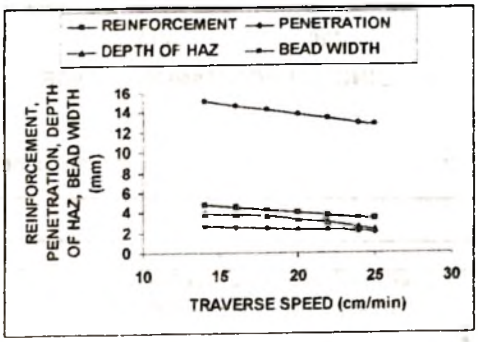

Fig.5 : Direct effect of traverse speed on bead parameters (V=26Volt, C=200A & W=80cm/min)

GRAPHICAL REPRESENTATIONS

The above equations developed from the statistical analysis of the available data are now presented below graphically.

RESULTS AND DISCUSSIONS

Developed mathematical models can be effectively utilized to predict weld bead geometry by substituting the values of the predictors. The responses calculated from the developed models shown in (Figs 1-16), would be helpful to understand the direct and interaction effect of process parameters on response variables associated with bead geometry of submerged arc weldment.

WELDING TECHNIQUE PERFORMANCE FACTOR

As reported by Jackson [16], there is a relationship between penetration, welding voltage, current and welding speed, by a welding technique performance factor, given as:

$\sqrt{\frac{I^4}{SE^2}}$, where, I=welding Current (amps), S=welding speed (m/min) and E=welding voltage (volts). Fig. 1 represents the relation between penetration and welding technique performance factor, which shows the same trend as reported by Jackson. With increase in performance factor, penetration tends to increase. Gunaraj and Murugan [5] also achieved the same conclusion. The regression equation, obtained from the experimental data, indicating the interdependence of penetration and welding technique performance factor is given below:

Penetration = 1.13 + 0.00446*(performance factor) .... (xiii)

DIRECT EFFECT OF PROCESS CONTROL PARAMETERS

Direct effect of welding voltage on bead parameters

Fig. 2 reveals that penetration and reinforcement decrease slightly, whereas a marginal increase in depth of HAZ and significant increase in bead width is observed as voltage increases. Increase in voltage results in increased arc length, which results in more melting at the surface, therefore penetration decreases. Gunaraj and Murugan [5], also observed the same trend. Moreover, due to increase in arc length, spreading of the arc cone occurs. Therefore bead width increases considerably as voltage increases. As the rate of increase in bead width is more than the rate of decrease in penetration, increase in voltage results an increase in size of weld pool and spreading at the base of the arc cone, which results decrease in bead reinforcement. The increase in voltage results slight increase in depth of HAZ. This behavior can be explained by the fact that, increase in voltage results larger weld pool thereby producing large area through which heat would be conducted to cool the weld pool down to room temperature. This increases larger heat affected zone and consequently increased depth of HAZ.

Direct effect of welding current on bead parameters

Fig. 3 shows that, with increase in welding current, bead width, reinforcement, depth of HAZ increases slowly but within experimental domain penetration remains more or less constant. Increase in welding current results increase in heat input rate as well as electrode melting rate at the tip of the electrode, so that more metal deposits at the base, resulting increase in bead width, reinforcement, depth of HAZ and constant bead penetration.

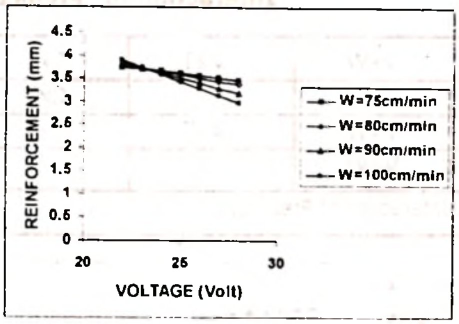

Fig.6 : Interaction effect of voltage and wirefeed rate on reinforcement (C=200A & T=24cm/min)

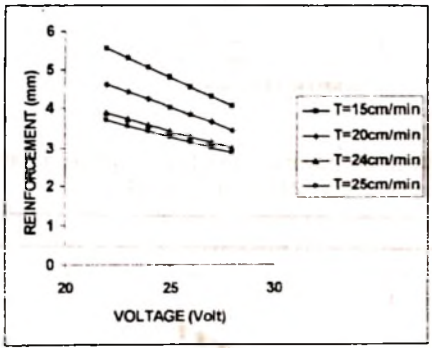

Fig.7 : Interaction effect of voltage and traverse speed on reinforcement (C=200A & W=100cm/min)

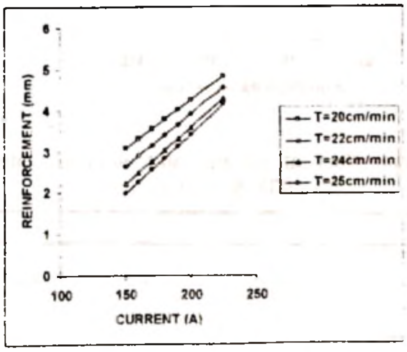

Fig.8 : Interaction effect of current & traverse speed on reinforcement (V=24Volt & W=100cm/min)

Direct effect of wirefeed rate on bead parameters

It is evident from Fig. 4 that, with increase in wirefeed rate, bead width, penetration and depth of HAZ increase, whereas reinforcement remains more or less constant. This is because that the arc current and, hence, the heat input increases with increase in wirefeed rate. Moreover, the wire melting rate and deposition rate

Response Variable(s)	Interaction of Predictors			
Reinforcement	VxW	VxT	CxT	WxT
Penetration	VxW		CxT	
Depth of HAZ	VxW	VxT	CxT	
Bead Width	VxW			WxT

Table 4 : Significant Interaction of Predictors

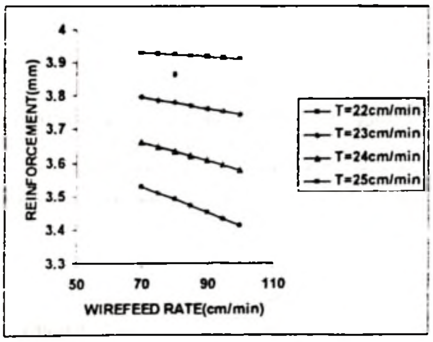

Fig.9 : Interaction effect of traverse speed and wirefeed rate on reinforcement (V=24Volt & C=200A)

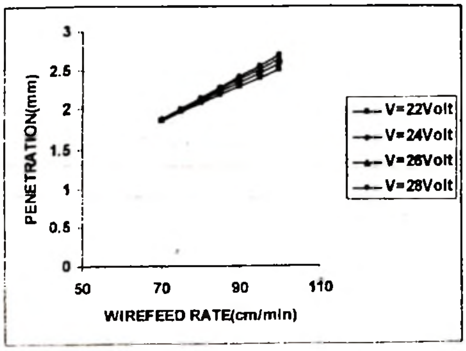

Fig.10 : Interaction effect of voltage and wirefeed rate on penetration (C=200A & T=25cm/min)

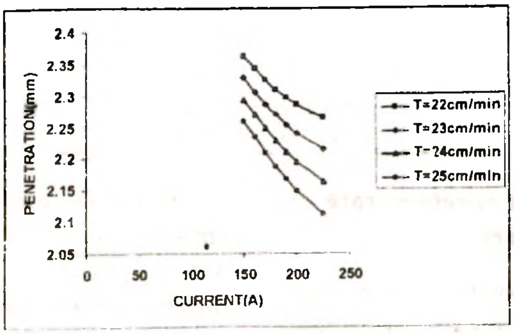

Fig.11 : Interaction effect of current and traverse speed on penetration (V=28Volt & W=80cm/min)

increase as wirefeed rate increases. Therefore, it can be concluded that due to high heat input and metal deposition rate, the bead geometry parameters tend to increase as wirefeed rate increases. Within the experimental domain, bead width increases at a moderate rate but penetration increases very slowly, therefore, constant reinforcement, is quite feasible in the present case.

Direct effect of traverse speed on bead parameters

Fig. 5 shows that traverse speed has a negative effect on bead geometry parameters. This is because when traverse speed increases, the welding torch travels at a greater speed over the base metal, as a consequence, metal deposition rate and heat input rate decrease. Therefore, because of less heat input and low metal deposition rate, reinforcement, penetration, depth of HAZ and bead width decrease, as traverse speed increases.

INTERACTION EFFECT OF PROCESS PARAMETERS

The interaction effects of various process parameters on selected features of weld bead geometry are shown in Figs. 6-16. According to the modified mathematical models (equations (ix) to (xii)), the significant interaction effects of the predictors on selected response variables are shown in Table 4.

The following inferences can also be drawn from Figs. 6-16.

** With increase in welding voltage, reinforcement decreases, while wirefeed rate is kept constant. (Fig. 6)

**Increase in welding voltage results gradual decrease in bead reinforcement for constant traverse speed rate.(Fig. 7)

**For constant traverse speed, increase welding current results remarkable increase in bead reinforcement. (fig. 8)

**For constant traverse speed, as wirefeed rate increases reinforcement decreases.(Fig. 9)

**With increase in wirefeed rate, penetration increases, when m/c is operated at a constant voltage mode. (Fig. 10)

**As welding current increases, bead penetration decreases, provided traverse speed is kept constant (Fig. 11). However, this contradicts the actual behavior, as welding current increases, penetration tends to increase. The deviation observed in the present case may be due to the experimental error, may be due to the influence of other factors and their combined effects. This seems to be a peculiar trend observed with in the experimental domain. So the mathematical model for penetration is modified using equation (xiii). The direct and interaction effects of welding current, traverse speed and voltage on bead penetration are represented below graphically.

It is clear that with increase in welding current bead penetration increases due to increased heat input rate at the weld pool. Fig. 17-18 match with the conventional trend.

**Increase in wirefeed rate results increase in bead width, while the voltage is kept constant. (Fig. 12)

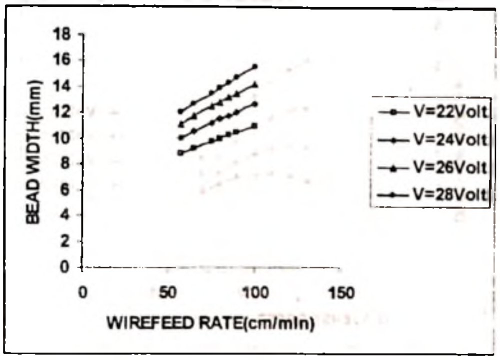

Fig.12 : Interaction effect of voltage and wirefeed rate on bead width (C=200A & T=25cm/min)

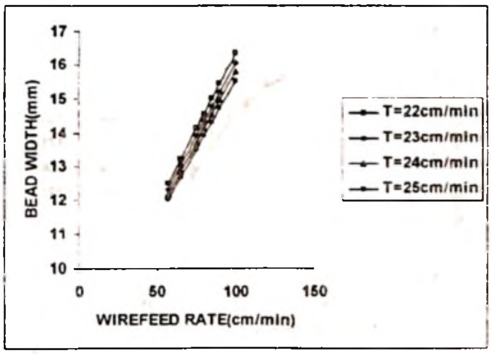

Fig.13 : Interaction effect of wirefeed and traverse speed on bead width (V=28Volt & C=200A)

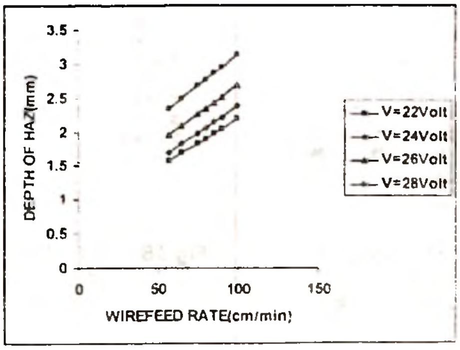

Fig.14 : Interaction effect of voltage and wirefeed rate on depth of HAZ (C=200A & T=25cm/min)

**For constant traverse speed, increase in wirefeed rate results increase in bead width. (Fig. 13)

**At constant voltage, while wirefeed rate is increased, depth of HAZ also increases. (Fig. 14)

**For constant voltage, increase in traverse speed results decrease in depth of HAZ. (Fig.15)

**Increase in traverse speed results decrease in depth of HAZ, when current is kept constant. (Fig. 16)

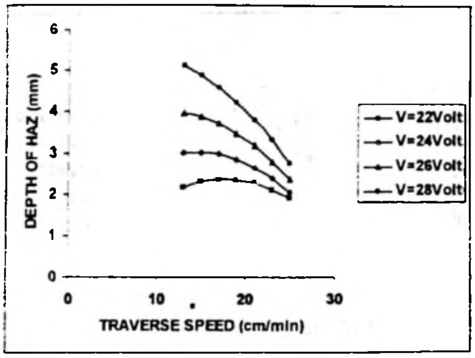

Fig.15 : Interaction effect of voltage and traverse speed on depth of HAZ (C=200A & W=80cm/min)

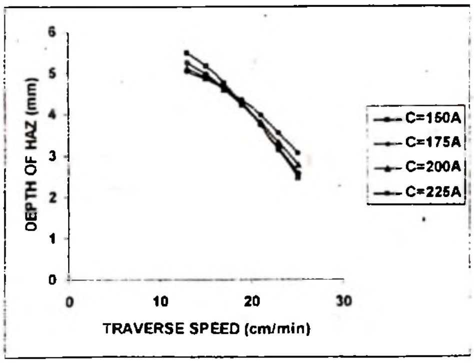

Fig.16 : IInteraction effect of current and traverse speed on depth of HAZ (V=28Volt & W=80cm/min)

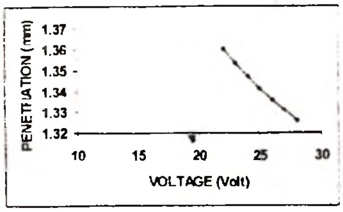

Fig.17 Direct effect of voltage on bead parameters (C=200A,W=75cm/min & T=24cm/min)

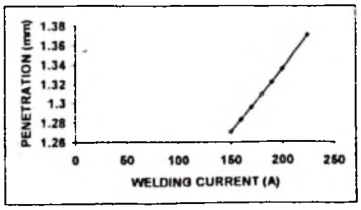

Fig.18 Direct effect of Current on bead penetration (V=26Volt, W=75cm/min & T=24cm/min)

CONCLUSIONS

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

1. Welding current, voltage, wirefeed rate and traverse speed appear to be the important process control parameters in SAW, with their direct as well as interactive effect on features of bead geometry and HAZ like reinforcement, penetration, bead width and depth of HAZ.
2. Quadratic response surface methodology followed by multiple linear regression has been proved fruitful in representing the effect of various predictors on selected response variables through mathematical models.
3. MINITAB can be explored effectively to take care of only the significant factors as well as interaction of factors in the mathematical model.
4. Bead penetration increases with increase in welding technique performance factor.
5. Traverse speed has a negative effect whereas wirefeed rate has a positive effect on all the bead parameters. This is in agreement with published report.
6. Bead width increases, as welding voltage, current and wirefeed rate increases. But it has a decreasing trend as traverse speed increases.
7. With increase in welding voltage and traverse speed reinforcement decreases.
8. The interactive effect of voltage and wirefeed rate is significant for all bead geometry parameters.
9. The reduced models developed can be employed easily in automatic and robotic welding to obtain desired high quality weld.
10. Acceptability of weld bead, with desired quality and performance, lies in the fact that, the weldment should ensure maximum penetration, minimum reinforcement, minimum bead width and minimum depth of HAZ. Therefore, here exists a scope

for optimization of bead parameters to obtain favorable quality weld bead at a relatively low cost with reduced metal consumption. New work is being planned towards this end.

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