WELDING CURRENT IN SUBMERGED ARC WELDING

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ABSTRACT

A relationship between welding current and various welding parameters has been proposed. The relationship can be used to predict welding current and melting rates in submerged arc welding process. Two-level half-fractional factorial design was used to investigate and quantify the direct and interaction effects of four process parameters on welding current in SAW of mild steel.

Wire feed rate, open circuit voltage, welding speed and plate thickness were taken as the welding parameters to investigate the main and interaction effects on the welding current. A model has been proposed for predicting the welding current in submerged arc welding. The adequacy of the model was tested by the use of analysis of variance technique and the significance of the coefficients was tested by the student's 't' test. The estimated and observed values of the weakling current have been compared through a scatter diagram. The main and interaction effects of different parameters involved have been presented in graphical form.

Keyword : Submerged arc welding, Welding current, Melting rates, Process Parameters, modelling.

INTRODUCTION

Welding current significantly affects the weld characteristics such as penetration, pool size & shape, extent of heat affected zone, microstructure, metal transfer, droplet size, frequency of transfer, arc force, burn off rate and equilibrium in semi automatic arc welding processes. It also affects bead geometry & shape relationships, which have a definite effect on the load carrying capacity of the weldment [1] (Figure-1&2).

The burn off rate and equilibrium between burn off rate and wire feed rate in submerged arc welding processes is mainly dependent on the welding current. The constant potential power

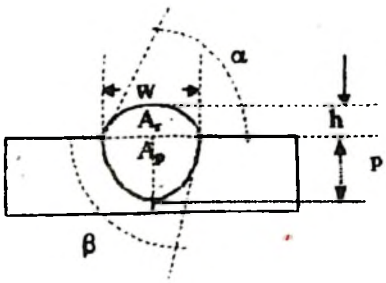

Fig.1 : Bead Geometry and Shape Relationships (Bg&Sr)

BEAD GEOMETRY

W = Bead width

P = Bead penetration / Depth of penetration

h = Bead height / Crown height / Height of reinforcement

α = Angle of convexity

β = Angle of entry

Rate of heat input per unit length (RHI)

$$RHI = \eta \frac{VI}{S} \cos\phi \ J/mm$$

η = Arc efficiency

V = Arc voltage, volts

I = Welding current, amps.

S = Welding speed, mm/sec.

$\cos\phi$ = Power factor

SHAPE RELATIONSHIPS

WPSF (w/p) = Weld penetration shape factor

WRFF (w/h) = Weld reinforcement form factor

Ar = Area of reinforcement

Ap = Area of penetration

At = Ar+Ap = Total bead area

$\% D = \frac{Ap}{At} 100$ = Percent dilution source delivers the desired magnitude of the welding current so as to establish the equilibrium between burn off rate and the wire feed rate. The process will remain stable as long as the equilibrium is maintained. Since welding current is an important parameter affecting various weld characteristics, it is important to exactly know its magnitude such that meaningful correlations can be developed between the welding current and various weld characteristics.

The following relationship between wire feed rate and welding current developed by Holmoy already exists [2,3].

$$W = \alpha I + \frac{\beta^{1} I^{2}}{a} \quad ....(1)$$

Where :

W = Wire feed rate, m/min

I = Welding Current, A

l = Electrode stick-out, mm

a = Area of cross section of the wire, mm2

a = Constant of proportionality for anode or cathode heating.

β = Constant of proportionality for electrical resistance heating.

This is quadratic in nature and it is also important to measure stick out and know the welding current in advance. One can very easily visualise that measuring stick out in submerged arc welding is not an easy task and hence there are practical difficulties in using this relationship in submerged arc welding.

Fig. 2 : Typical weld bead penetration in SAW.

The main objective of this work was developing another relationship that is simple and can be very effectively used in submerged arc welding. The welding current is a function of various welding parameters, which can be both direct and indirect. In the present investigations it was decided to study the effect of wire feed rate (W), arc voltage (V), welding speed (S) and plate thickness (T) on the welding current (I). Therefore a relationship of the type I=f(W,V,S,T) was developed and analyzed. Conventional methods of experimentation with multiple parameters and responses are time consuming, costly and even inadequate for the prediction of welding current accurately. The aim of this paper was also to quantify the main and interaction effects of wire feed rate, open circuit voltage, welding speed and plate thickness on welding current.

A two-level half-fractional factorial design was selected to gain the complete insight into the combined, main and interaction effects of the parameters on welding current. In addition, interactions between two or more parameters can also be quantified, which is not possible with the conventional experimental approach.

PLAN OF INVESTIGATION

Investigations were planned according to the steps given below :

DESIGN OF EXPERIMENTS

- Selection of two levels of the welding parameters.
- Development of a design matrix.

EXPERIMENTAL PROCEDURE

SELECTION OF A MODEL

DEVELOPMENT OF MODEL

- Evaluation of the coefficients.
- The developed model
- Adequacy of model.
- Significance of the coefficients of the model.

RESULTS

- Proposed model
- Significant main effects and interactions.

ANALYSIS OF RESULTS

CONCLUSIONS

DESIGN OF EXPERIMENTS

A two-level half-factorial design of eight trials, which is a standard statistical tool to investigate the effects of a number of parameters on the required response, was selected for determining the effect of four independent direct welding parameters. The commonly employed method of varying one parameter at a time, though popular, does not give any information about interaction amongst the parameters. The selection of two-level half-fractional factorial design also helped in reducing the experimental runs to the minimum possible [4,5].

Selection of two levels of the welding parameters

The range, covering the lowest and the highest level of the direct welding parameters was carefully selected so as to maintain equilibrium between wire feed rate and burn-off rate along with good bead appearance and configurations. The basis of selection of given range for various welding parameters was that the resultant weld bead should be free from the following visual defects.

1. Undercut
2. Overlåp
3. Excessive crown height
4. Excessive convexity
5. Non uniform ripples on the bead
6. Macro cracking
7. Surface porosity
8. Non uniform width

All other direct and indirect parameters except the ones under consideration were kept constant. Welding parameters were coded as (+1) and (-1) or simply (+) and (-) corresponding to the high and low levels for the ease of recording and processing of the data using Equation-1. The units, symbols, designations and limits of the welding parameters have been given in Table-1 [4,5,6].

$$Xj = \frac{Xjn \quad Xj0}{Jj} \qquad ...(1)$$

Where,

Xj = Coded value of the parameter
Xjn = Natural value of the parameter
Xj0 = Value of the basic level
Jj = Variation interval
j = Number of the parameter

Development of a design matrix

The design matrix developed to conduct the eight trials of 2^{4-1} fractional factorial design mentioned earlier is given in Table-2. For the sake of further simplicity the parameters from X_1 to X_4 were represented only by the subscripts 1 to 4 throughout this paper. The main effect of the parameter 4 was confounded with the three-parameter interaction effect 123. The confounding patterns were expressed as 4=123 on top of 4th column in the design matrix. The signs under the columns 1,2,3 were arranged in standard Yate's order, while those under column 4 were obtained by taking the product of their respective interacting parameters. The defining relation for the design was 1=123. Assuming three parameter and higher order interactions as negligible the fractional factorial design of eight runs provided eleven estimates for the effects of four welding parameters on welding current. Out of these estimates, one estimate was for the mean effect of all the parameters on response, four estimates for the main effects and the remaining estimates (confounded) for two parameter interactions. The complete confounding pattern for the design is shown in Table-3 [4,5,6,7,8].

EXPERIMENTAL PROCEDURE

Weld beads were deposited using a bead-on plate technique on a 150 x 300mm mild steel plate, using 3.2mm diameter mild steel wire and general purpose agglomerated acidic flux with a basicity index of 0.6 [AWS SFA A-5.17]. Each one of the well-cleaned plates was welded employing an electrode positive polarity. A constant potential transformer-rectifier type power source with a current capacity of 600A at 60% duty bicycle and an O.C.V., of 12-48 volts was used. The plates were cleaned chemically and mechanically to remove oxide layer and any other source of hydrogen, before weldig. Weld beads were deposited using a mechanised SAW station to ensure the reproducibility of the data. This also eliminated the effect of welder's skill on the results.

The complete set of eight trials was repeated twice for the sake of determining the 'variance of optimisation parameter' and 'variance of adequacy' for the model. The experiments were performed in a random order to avoid any systematic error. The complete design matrix along with responses for two sets of experiments and their averages is given in Table-4.

SELECTION OF A MATHEMATICAL MODEL

The model of the type, I=f(V,W,S,T) where 'I' is the welding current, could be developed to facilitate the prediction of a response 'I' within the specified dimensional tolerance for a particular set of direct process parameters. Assuming a linear relationship in the first instance and taking into account all the possible two factor interactions and confounded interactions, it could be written as:

$$I = b_0 + b_1W + b_2V + b_3S + b_4T + b_{12}WV + b_{13}WS + b_{14}WT + b_{23}VS + b_{24}VT + b_{34}ST$$

Using the confounding pattern as given in Table-2, the model can be rewritten as:

$$I = b_0+b_1W+b_2V+b_3S+b_4T+b_5(WV+ST)+ b_6(WS+VT)+b_7(WT+VS)$$

Where $b_5 = b_{12}+b_{34}$
$b_6 = b_{13}+b_{24}$
$b_7 = b_{14}+b_{23}$

DEVELOPMENT OF MODEL

Model was developed by the method of regression. Adequacy of the model and significance of coefficients was tested by the analysis of variance technique and student's 't' test respectively. Computer software was developed to carry out the above steps. All intermediate natural values can be converted to coded values with the help of the Equation-1 [2,3,6,7]

Evaluation of the coefficients

The regression coefficients of the selected model were calculated using Equation-2 [6]. This is based on the method of least squares.

$$b_j = \frac{\sum_{i=1}^{N} X_{ji} Y_i}{N}, j=0,1,2,....,k \quad .....(2)$$

Where,

X_{ji} = Value of a factor or interaction in coded form.

Y_i = Average value of the response parameter that is, the welding current in this case.

N = Number of observations.

k = Number of coefficients of the model.

The calculated coefficients of the model are given in Table-5.

Developed Model

The developed model is :

I = 334.4 + 140.5W − 9.4V + 9.4S − 3.12T − 3.12WV + 3.12WS + 3.12WT + 3.12VS + 3.12VT − 3.12ST

Adequacy of the model

The adequacy of the model was determined by the analysis of variance technique. The regression coefficients were determined by the method of least squares, from which the 'F'-ratio for the polynomial was found. Table-6&7 gives the procedure for calculating the variance of optimisation parameter and 'F' ratio. The 'F'-ratio of the model was compared with the corresponding 'F'-ratio from the standard tables and it was found that the model was adequate within 95% level of confidence, thus justifying the use of assumed polynomial. Details of analysis of variance are given in Table-8.

Significance of coefficients of the model

It is important at this stage to determine whether the coefficients are statistically significant or not. The statistical significance of the coefficients was tested by applying 't' test. Coefficients having calculated 't' values less than or equal to the 't' value from tables for eight degrees of freedom and 95% confidence level, were the members of the reference distribution, that is, they could be merely due to the intrinsic variations of the experimentation and hence were insignificant. The level of significance of a particular parameter is assessed by the magnitude of the 't' value associated with it. Higher the value of 't' the more significant it becomes. The value of 't' from tables at (8,0.05) = 2.3. The calculated 't' values for the coefficients have been given in Table-9. The 't' values less than 2.3 have been underlined in Table-9. The insignificant main effects and interactions have been underlined in Table 5.

RESULTS

The proposed model for the prediction of welding current after dropping the statistically insignificant coefficients, in the coded form is :

I = 334.4+140.5W

The main effect of wire feed rate and welding current has been graphically shown in Figure-3.

The adequacy of the proposed model at 5% significance level has also been

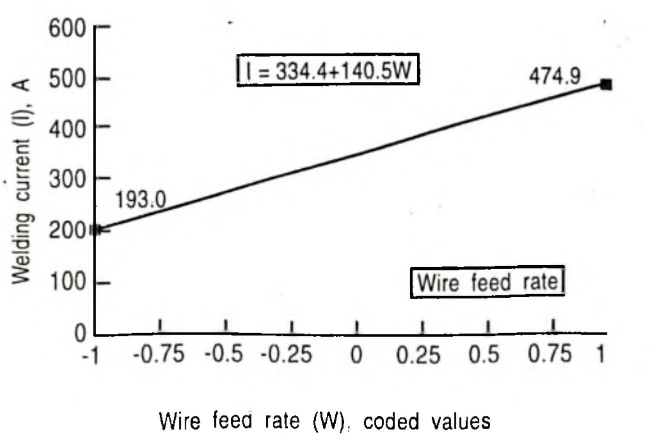

Fig. 3 : Main effect of wire feed rate (W) on welding current (I).

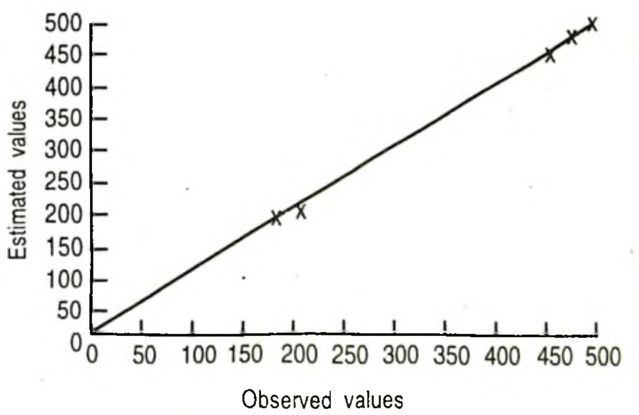

Fig. 4 : Scatter diagram between the observed and estimated values of welding current

Table 1 : Welding parameters and their limits.

Parameter	Units	Symbol	Designation	Limits	
				Low(-1)	High(+1)
Wire feed rate	m/min.	W	X1	0.75	2.25
Open circuit voltage	Volts	V	X2	36.0	40.0
Welding speed	cm/min.	S	X3	26.5	58.5
Plate thickness	mm.	T	X4	12.0	20.0

Table 2 : Design Matrix

S.No.	W 1	V 2	S 3	T 4 = 123
1.	+	+	+	+
2.	–	+	+	–
3.	+	–	+	–
4.	–	–	+	+
5.	+	+	–	–
6.	–	+	–	+
7.	+	–	–	+
8.	–	–	–	–

Table 3 : Confounding pattern

1	+	234
2	+	134
3	+	124
4	+	123
12	+	34
13	+	24
14	+	23

shown with the help of a scatter diagram in Figure-4.

ANALYSIS OF RESULTS

The level of significance of a particular parameter is assessed by the magnitude of the 't' value associated with it. Higher the value of 't' the more significant it becomes. The insignificant main effects and interactions have been underlined in Table-5.

The hypothesis adopted for identifying the parameters, which were mainly and predominantly responsible for the interaction effect in a confounded pattern, was to first drop those interactions that were due to the parameters having insignificant main effects and if there were still two or more interactions left in the confounded pattern then the interaction due to the parameter with the most predominant main effect was selected [4].

Based on this hypothesis, none of the interactions in the confounded pattern for welding current were statistically significant and hence were dropped. This resulted in a simple to use linear relationship between the welding current and wire feed rate. The main effect of wire feed rate on welding current is fairly well expected, i.e., this indicates the expected qualitative trend reported elsewhere.

Increase in wire feed rate from 0.75m/min to 2.25m/min, resulted in an increase in the welding current by a magnitude of 281 amperes as shown in

Table 4 : Design matrix for calculating the coefficients.

S.No.	b_0	b1 W	b2 V	b3 S	b4 T	b5 (WV+ST)	b6 (WS+VT)	b7 (WT+VS)	I'	I"	I
1.	+	+	+	+	+	+	+	+	450	500	475
2.	+	-	+	+	-	-	-	+	150	250	200
3.	+	+	-	+	-	-	+	-	450	550	500
4.	+	-	-	+	+	+	-	-	150	250	200
5.	+	+	+	-	-	+	-	-	400	500	450
6.	+	-	+	-	+	-	+	-	150	200	175
7.	+	+	-	-	+	-	-	+	450	500	475
8.	+	-	-	-	-	+	+	+	150	250	200

Table 5 : Coefficients of the model.

Coefficient	Due to	Value
b_0	Combined effect of all the parameters.	334.4
	Main effects	
b_1	Wire feed rate.	140.5
b_2	Open circuit voltage.	-9.38
b_3	Welding Speed.	9.38
b_4	Plate thickness.	-3.125
	Interactions effects	
b_5	12+34.	-3.125
b_6	13+24.	3.125
b_7	14+23.	3.125

Table 6 : Calculation of variance of optimization (S_I^2)

S. No.	Welding Current (A)			ΔI	$(\Delta I)^2$	$S_I^2 = \frac{2\sum_1^8(\Delta I_i)^2}{8}$
	I'	I''	$\bar{I}$			
1	450	500	475	-25	625	
2	150	250	200	-50	2500	
3	450	550	500	-50	2500	
4	150	250	200	-50	2500	
5	400	500	450	-50	2500	
6	150	200	175	-25	625	
7	450	500	475	-25	625	
8	150	250	200	-50	2500	
$\sum_1^8 (\Delta I_i)^2 = 14375$						3593.75

the Fig.3. This increase in welding current with the increase in wire feed rate is to maintain the equilibrium between burn off rate and wire feed rate.

CONCLUSIONS

The following conclusions may be drawn from this analysis.

1. A linear model has been developed to predict welding current in submerged arc welding.
2. The model is problem specific. However, the technique can be applied very effectively.
3. The proposed model is adequate to predict the welding current with a significance level of 5%.
4. The two-level half-fractional factorial design is found to be very effective tool for quantifying the main and interaction effects of welding parameters on welding current.
5. Wire feed rate is the only statistically significant parameter affecting the welding current.
6. It was observed that welding speed, open circuit voltage and plate thickness didn't have statistically significant main effects on the welding current.
7. It was also observed that none of the interactions were statistically significant so as to affect the welding current.

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Table 7 : Calculation of variance of adequacy (S^2_{ad})

S. No.	Welding Current (A)		$\Delta I = I - \hat{I}$	$(\Delta I)^2$	$S^2_{ad} = \frac{\sum_{i=1}^{8} \Delta I_i^2}{3}$
	Estimated values, I	Observed values, $\hat{I}$			
1	478.12	500	-21.88	478.73	
2	203.14	175	28.14	791.86	
3	503.14	475	28.14	791.86	
4	190.64	250	-59.36	3523.61	
5	440.62	475	-34.38	1181.98	
6	178.12	200	-21.88	478.73	
7	478.12	500	-21.88	478.73	
8	203.14	250	-46.86	2195.86	
$\sum_{i=1}^{8} \Delta I_i^2 = 9921.36$					3307.12

Table 9 : 't' values for the Coefficients.

Coefficient	Due to	't' Value
b_0	Combined effect of all the parameters.	15.76
	Main effects	
b_1	Wire feed rate.	6.63
b_2	Open circuit voltage.	0.44
b_3	Welding Speed.	0.44
b_4	Plate thickness.	0.15
	Interactions effects	
b_5	12+34.	0.15
b_6	13+24.	0.15
b_7	14+23.	0.15

Table 8 : Analysis of variance for welding current.

Degrees of Freedom		Variance of Response	Standard Deviation of Coefficients	Variance of Adequacy	'F' Ratio Model	'F' Ratio Table	Adequacy of Model
S^2_I	S^2_a	S^2_I	$S_{bj} = \sqrt{\frac{S^2_I}{df}}$	S^2_{ad}	$F_m = \frac{S^2_a}{S^2_I}$	at 3,8,0.05	Whether Fm < Ft
8	3	3593.75	21.19	3307.12	0.92	4.1	Yes

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