EFFECTS OF PROCESS PARAMETERS ON WELD BEAD PENETRATION IN SAW

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ABSTRACT

A two-level half fractional design is used to investigate and quantify the direct and interaction effects of four process parameters on weld bead penetration 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 effect on the weld bead penetration. The analysis indicated that of the four parameters investigated, only wire feed rate had the statistically significant main effect on weld penetration. It was also observed that wire feed rate & welding speed and open circuit voltage & plate thickness interact to affect the weld penetration. A model has been proposed for predicting the weld penetration. 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 bead penetration have been compared in a scatter diagram. The main and interaction effects of different parameters involved have been presented in graphical form

Keywords : Submerged arc welding, Bead geometry, Bead penetration, Process parameters, modelling, design of experiments.

INTRODUCTION

The study of weld bead penetration occupies an important place in defining a welding procedure as it helps in deciding the level of welding parameters and consequently the metal deposition rate, heat input per unit length and number of runs to make a welded joint. It also affects the load carrying capacity of the weldment [1]. It is greatly influenced by direct process parameters, viz wire feed rate/welding current, open circuit voltage, nozzle to plate distance/stand off, torch angle/electrode to plate angle, welding speed and type of flux. The thermo-physical properties of the alloy, alloy & filler wire combination and the behavior of the welding power source also influence it. The alloy & filler wire combination includes plate thickness and size, joint design wire diameter and the composition of a plate and filler wire. The need for the analysis of the effects of direct process parameters on the weld penetration is felt greatly due to the advances made in mechanisation & automation of the welding processes. The desired values of the direct process parameters can now be set precisely and the resulting bead geometry or the load bearing capacity of a Weldment, predicted with a certain degree of confidence.

It was therefore necessary to analyse the effects of some of the direct welding parameters and plate thickness on weld bead penetration to be able to define a welding procedure accurately. Conventional methods of experimentation with multiple parameters and responses are time consuming, costly and even inadequate for the prediction of weld bead penetration. The aim of this paper was to quantify the main and interaction effects of wire feed rate, open circuit voltage, welding speed and plate thickness on weld bead penetration using two-level half fractional factorial design.

The factorial design was selected to gain the complete insight into the combined, main and interaction effects of the parameters on the response under investigation. In addition, the quantification of interactions between two or more parameters can also be done, which is not possible with the conventional experimental approach.

PLAN OF INVESTIGATION

Investigations were planned according to the steps given below:

1. DESIGN OF EXPERIMENTS
   - 1.1 Selection of two levels of the welding parameters.
   - 1.2 Development of a design matrix.
2. EXPERIMENTAL PROCEDURE
3. SELECTION OF A MODEL
4. DEVELOPMENT OF MODEL
   - 4.1 Evaluation of the coefficients
   - 4.2 The developed model
   - 4.3 Adequacy of model.
   - 4.4 Significance of the coefficients of the model.
5. RESULTS
   - 5.1 Proposed model.
   - 5.2 Significant main effects and interactions.
6. ANALYSIS OF RESULTS
7. 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 minium possible [2,3].

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. 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 I [2, 3, 4].

$$x_j \quad \frac{x_{jn} - x_{j0}}{J_j}$$

Where,

x_j = Coded value of the parameter

x_{jn} = Natural value of the parameter

x_{j0} = Value of the basic level

J_j = Variation interval

j = Number of the parameter

Table-1 : Welding parameters and their limits

Parameters	Units	Symbol	Designation	Limits	
				Low (−1)	High (+1)
Wire feed rate	m/min.	W	1	0.75	2.25
Open circuit voltage	Volts	V	2	36.0	40.0
Welding Speed	cm/min	S	3	26.5	58.5
Plate thickness	mm.	T	4	12.0	20.0

Table-2 : Design Matrix

	Direct Parameters			
Sl.	W	V	S	T
	1	2	3	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

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 X1 to X4 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 inter acting parameters. The defining relation for the design was I=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 weld penetration. 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 [2, 3, 4, 5, 6].

EXPERIMENTAL PROCEDURE

Weld beads were deposited using a bead-on plate technique on a 150 x 300-mm mild steel plate, using 3.2 mm 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 wellcleaned 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 cycle 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 welding. 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 were repeated twice for the sake of determining the 'variance of optimisation parameter' and 'variance of adequacy' for the model.

Table-4 : Design Matrix for calculating the coefficients

Sl.	b0	b1 W	b2 V	b3 S	b4 T	b5 (WV+ST)	b6 (WS+VT)	b7 (WT+VS)	P' mm	P" mm	$\bar{p}$ mm
1	+	+	+	+	+	+	+	+	4.8	6.4	5.6
2	+	–	+	+	–	–	–	+	2.2	1.6	1.9
3	+	+	–	+	–	–	+	–	6.5	6.6	6.55
4	+	–	–	+	+	+	–	–	1.4	2.4	1.9
5	+	+	+	–	–	+	–	–	9.0	8.0	8.5
6	+	–	+	–	+	–	+	–	1.0	1.2	1.1
7	+	+	–	–	+	–	–	+	8.5	7.2	7.85
8	+	–	–	–	–	+	+	+	2.5	1.7	2.1

The experiments were performed in a random order to avoid any systematic error. Three test pieces cut from each welded plate and prepared by the usual metallurgical polishing procedure for macrographic investigation. 5% Nital was used as an etchant. The outlines of weld beads were traced using a profile projector at x10 magnification. Weld bead penetration shown in Figure-1&2 was measured for all the test conditions of the design matrix [2, 3]. The complete design matrix along with responses and their averages is given in Table 4.

SELECTION OF A MATHEMATICAL MODEL

The model of the type, p = f(V, W, S, T) where 'p' is the weld penetration, could be developed to facilitate the prediction of a response 'p' 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:

$$P = b_0 + b_1 W + b_2 V + b_3 S + b_4 T + b_{12}WV + b_{13}WS + b_{14}WT + b_{23}VS + b_{24}VT + b_{34}ST$$

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

$$p = b_0+b_1 W+b_2 V+b_3S+b_4T+b_5(WV+ST)+b_6(WS+ VT)+b_7(WT+VS)$$

Where $b_5 = b_{12} + b_{34}$, $b_6 = b_{13} + b_{24}$, $b7 = b_{14} + b_{23}$

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 [4, 5].

Evaluation of the coefficients

The regression coefficients of the selected model are calculated using Equation-2 [4]. This is based on the method of least squares.

$$bj = \frac{\sum_{i=1}^{N} Xji\ Yi}{N}, \quad j = 0,1,2......k \qquad (2)$$

Where, Xji = Value of a factor or interaction in coded form.
Yi = 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.

Table-5 : Coefficients of the model

Coefficient	Due to	Value
b_0	Combined effect of all the parameters	4.4
	Main effects	
b_1	Wire feed rate	2.7
b_2	Open circuit voltage	– 0.2
b_3	Welding Speed	– 0.4
b_4	Plate thickness	– 0.3
	Interaction effects	
b_5	12 + 34	0.09
b_6	13 + 24	– 0.6
b_7	14 + 23	– 0.08

Developed model

The developed model is:

$$p = 4.4 + 2.7W - 0.2V - 0.4S - 0.3T + 0.09WV - 0.6WS - 0.08WT - 0.08VS - 0.6VT + 0.09ST$$

Adequacy of the model

The adequacy of the model wae determined by the analysis of variance technique. The regression

Table 6 : Calculation of variance of optimisation parameters (S_p^2)

S No.	Bead penetration (mm)			$\Delta p = \bar{p} - p''$	$(\Delta p)^2$	$S_P^2 = \frac{2\sum_1^8 (\Delta pi)^2}{8}$
	P'	P"	$\bar{P}$			
1	4.8	6.4	5.6	-0.8	0.64	
2	2.2	1.6	1.9	0.3	0.09	
3	6.5	6.6	6.55	-0.05	0.0025	
4	1.4	2.4	1.9	-0.5	0.25	
5	9.0	8.0	8.5	0.5	0.25	
6	1.0	1.2	1.1	0.1	0.01	
7	8.5	7.2	7.85	0.65	0.4225	
8	2.5	1.7	2.1	0.4	0.16	
	$\sum_1^8 (\Delta pi)^2 = 1.825$					0.456

Table 7 : Calculation of variance of adequacy (S_{ad}^2).

S No.	Bead penetration (mm)		$\Delta p = p - \hat{p}$	$(\Delta p)^2$	$S_{ad}^2 = \frac{\sum_{i=1}^8 \Delta pi^2}{3}$
	Estimated Values P	Observed Values, $\hat{P}$			
1	5.02	6.0	-0.98	0.9604	
2	2.34	2.0	0.34	0.1156	
3	5.94	6.2	-0.26	0.067	
4	2.66	2.8	-0.14	0.019	
5	9.27	8.6	0.67	0.449	
6	0.49	1.0	-0.51	0.26	
7	8.29	8.2	0.09	0.008	
8	1.51	1.5	0.01	0.0001	
	$\sum_{i=1}^8 \Delta pi^2 = 1.879$				0.626

Table 8 : Analysis of variance for penetration

Degree of Freedom		Variance of Response	Standard Deviation of Coefficients	Variance of Adequacy	'F' Ratio Model	'F' Ratio Table	Adequacy of Model
S^2_P	S^2_{ad}	S^2_P	$S_{bj} = \sqrt{\frac{S^2_P}{d_f}}$	S^2_{ad}	$Fm = \frac{S^2_{ad}}{S^2_P}$	at (3,8,0.05)	Whether Fm < Ft
8	3	0.456	0.239	0.626	1.372	4.1	Yes

Table 9 : 't' values for the coefficients

Coefficient	Due to	't' Value
b_0	Combined effect of all the parameters	18.4
	Main effects	
b_1	Wire feed rate	11.297
b_2	Open circuit voltage	0.837
b_3	Welding Speed	1.674
b_4	Plate thickness	1.255
	Interaction effects	
b_5	12 + 34	0.376
b_6	13 + 24	2.51
b_7	14 + 23	0.335

coefficients were determined by the method of least squares, from which the 'F'- ratio for the polynominal was found. Table-6&7 give 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 adaquate within 95% level of confidence, thus justifying the use of assumed polynominal. Details of analysis of variance are given in Table-8.

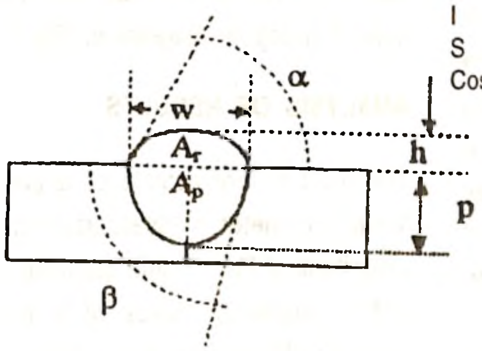

Fig 1 : Bead geometry and shape relationships (BG&SR)

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

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, min/sec
$\cos\phi$ = Power factor

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

Fig 2 : Typical weld bead penetration in SAW

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 weld bead penetration in the coded form is :

$$p = 4.4 + 2.7\ W - 0.6WS - 0.6VT$$

The main effect of wire feed rate on weld bead penetration has been plotted graphically in Figure-3. Interactions between wire feed rate & welding speed and open circuit voltage & plate thickness have been plotted graphically in Figure - 4&5 respectively. The adequacy of the proposed model at 5% significance level has also been shown with the help of a scatter diagram in Fig. 6.

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 [2].

Based on this hypothesis, the predominant interactions in the confounded pattem for weld bead penetration were 13 & 14. The meaning of a negative sign associated with the main and interaction effects is that, the particular response would decrease with the increase in the levels of the associated parameters. The magnitudes, by which the response would increase or decrease with the increase in the levels of the parameters, will be twice that of corresponding coefficients.

The main effect of parameters on the weld bead penetration was fairly well expected, i.e., they indicate the expected qualitative trends reported elsewhere. Figure-3 is used to show the quantitative effect of wire feed rate on penetration. Weld penetration increased from 1.7 mm to 7,1 mm when the wire feed rate was increased from 2.4 m/min to 5.0 m/min. It was found that the main

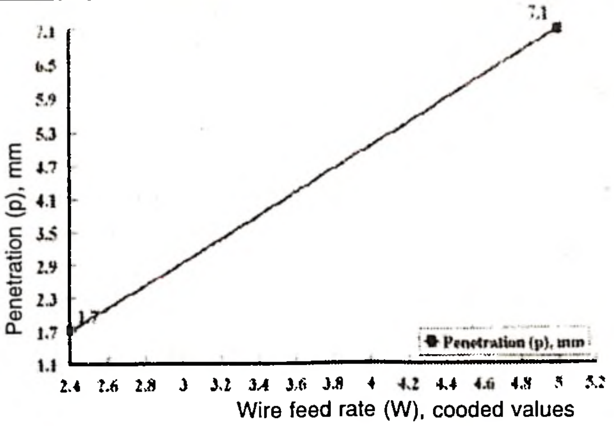

Fig 3 : Main effect of wire feed rate on penetration

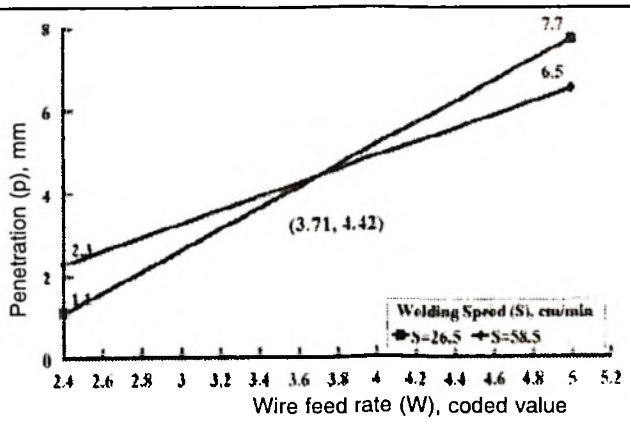

Fig 4 : Interaction of wire feed rate and welding speed on penetration

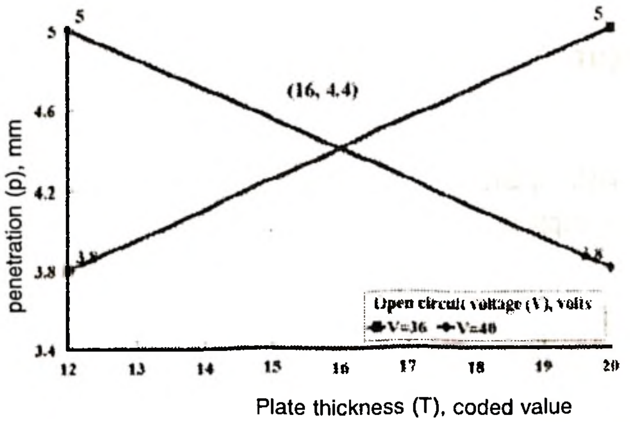

Fig 5 : Interaction of plate thickness and voltage on penetration

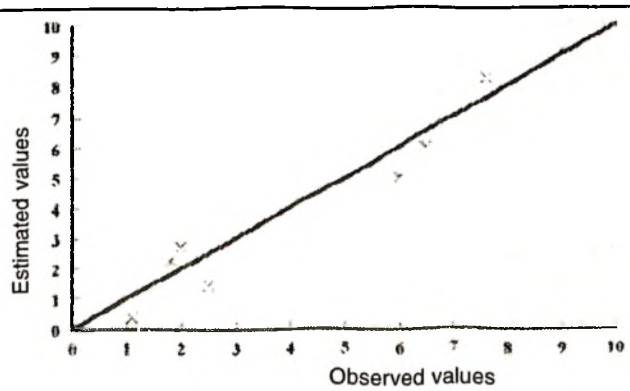

Fig 6 : Scatter diagram for penetration

effects due to welding speed, open circuit voltage and plate thickness were statistically insignificant for the selected range of parameters.

The present investigations however also revealed the existence of statistically significant interactions of parameters as mentioned earlier and need further discussion The 13&24 interactions on penetration have been illustrated graphically with the help of interaction graphs as shown in Figures- 4&5 respectivety.

Figure 4 shows that at the low level of parameter 1, i.e., wire feed rate of 2.4 m/min, increase in welding speed from 26.5 cm/min to 58.5 cm/min would increase the penetration from 1.1 mm to 2.3 mm. At the high level of wire feed rate of 5.0 m/min, however, the effect of welding speed is reversed. The penetration decreased from 7.7 mm to 6.5 mm The wire feed rate has a positive effect on penetration for any level of welding speed within the range, however, the slope decreases with the increase in the levels of welding speed, giving a cross over point as shown in Figure-4. This indicates that, there exists a value of wire feed rate between 2.4 m/min and 5.0 m/min at which welding speed has no effect on penetration. This shows that the two parameters do not behave independently but interact.

Figure-5 shows the other interaction of open circuit voltage and plate thickness on penetration. At low level of plate thickness of 12.0 mm, the increase in open circuit voltage from 36 V to 40 V increased penetration from 3.8 mm to 5.0 mm At the high level of plate thickness of 20.0 mm, the effect of open circuit voltage got reversed. The penetration decreased from 5.0 mm to 3.8 mm. Different slopes or convergence/divergence of the lines for low and high levels of parameters are indicative of the interaction between the parameters.

The validity of the proposed model can also be judged from the scatter diagram given in Figure-6. The observed values have been plotted on X-axis and the estimated values using the proposed model have been taken on Y-axis. It is evident from the scatter diagram that almost all the points are close to 45° line, indicating that the proposed model is adequate for predicting the weld bead penetration.

CONCLUSIONS

The following conclusions may be drawn from this analysis.

1. The two-level half-fractional factorial design is found to be very efficient for quantifying the main and interaction effects of welding parameters on weld bead penetration.
2. Wire feed rate is the most important parameter affecting the weld bead penetration.
3. It was observed that welding speed, open circuit voltage and plate thickness didn't have statistically significant main effects on the weld bead penetration.
4. Wire feed rate and welding speed interact to affect the weld bead penetration.
5. Arc voltage and plate thickness interact to affect the weld bead penetration.
6. The proposed model is adequate to predict the weld bead penetration with a significance level of 5%.

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