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Effects of Wire Feed Rate, Voltage and Nozzle to Plate Distance on Welding Current in a MIG Welding Process

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Abstract: *Metal Inert Gas Welding (MIG) is a fusion welding process having wide applications in Industry. In this process, proper selection of input welding parameters is necessary to obtain a good quality weld. One of the important input parameter is welding current. Constant voltage power sources, having flat or nearly flat V-I characteristics, are used for MIG welding. The current adjusts itself to burn off the quantity of wire delivered and therefore the amount of current drawn is proportional to the wire feed rate. Investigations however indicate the dependence of current on voltage and nozzle to plate distance (NPD) also. This dependence of current on these factors as well, needs to be clearly addressed and quantified in order not to make erroneous inferences during any further research. In this research paper, a mathematical model has been developed based on practical observations during MIG welding of Stainless Steel SS 409M, using two level factorial technique. The significance of coefficients and the adequacy of the model has been checked. The model is useful for estimating precisely the combined effects of wire feed rate, voltage and NPD on welding current.*

Keywords: *Mathematical model, factorial technique, wire feed rate, NPD, welding current.*

1. INTRODUCTION

The MIG welding process has got wide applications in industries due to the advantages such as high reliability, all position capability, low cost, high productivity, high deposition rate, ease of use, absence of fluxes, cleanliness and ease of mechanization. This process establishes an electric arc between a continuous filler metal electrode and the weld pool, with shielding from an externally supplied gas which may be an inert gas, an active gas or a mixture. The most important shielding gases are Helium, Argon and CO2. The heat of the arc melts the surface of the base metal and the tip of the electrode. The electrode molten metal is then transferred through the arc to the work piece where it combines with the molten metal of the base metal and forms a weld bead [1].

This process can be used satisfactorily with robotic welding hence its use in the future is bound to increase. Though almost all metals for which electrode wires are available can be welded, however this process finds extensive use mainly for welding Aluminum alloys, carbon and low alloy steels and stainless steels. Parmar [2].

In this welding process the quality of the weld joint is affected by many factors, current being the most significant one. It affects the metal transfer due to pinching effect. Welding current dictates the amount of heat generated by the arc, increasing the current increases the arc energy and therefore the heat input. This in turn increases fusion and penetration, consequently affecting the bead shape as well as the metallurgical and mechanical properties. Given the impact of welding current on weld quality and to avoid any serious effects on further research through the erroneous assumption of taking direct proportionality between welding current and wire feed rate only, it becomes imperative to ascertain other factors on which it depends besides the wire feed rate.

With a view to developing mathematical model, statistically designed experiments based on factorial techniques [3, 4] with full replications were used to obtain the required information about the direct and interaction effects on the response parameters [5].

2. PLAN OF INVESTIGATION

The research work was planned to be carried out in the following steps:

i.) Identification of the important process parameters and finding their upper and lower levels.

ii.) Developing the design matrix.

iii.) Conducting the experiments as per the design matrix and recording the responses

iv.) Developing the model and calculating the regression coefficients.

v.) Testing the significance of the coefficients and arriving at the final model.

vi.) Checking the adequacy of the developed model.

vii.) Presenting the direct and interaction effects of process parameters on welding current.

viii.) Validation of the developed model.

ix.) Presentation and analysis of the results.

2.1 IDENTIFICATION OF THE PROCESS PARAMETERS AND FINDING THEIR UPPER AND LOWER LEVELS

Preliminary experiments showed that although wire feed rate (W), voltage (V) and nozzle to plate distance (N) had affected the welding current, but no apparent effects of welding speed and gas flow rate were observed. The torch to workpiece inclination was kept 90° throughout the experimentations. Under these conditions the response parameter could be expressed as

$$I=f(W, V, N)$$

The upper and lower limits of the parameters were coded as (+1) and (-1) respectively. The selected parameters with their ranges are shown in Table 1.

TABLE 1: Welding parameters and their range

Parameter	Units	Symbol	Limits	
			Low(-1)	High(+1)
Wire feed rate	m/min	W	1.76	8.8
Voltage	Volts	V	16.0	27.5
Nozzle to plate distance	mm	N	10.0	20.0

2.2 DEVELOPING THE DESIGN MATRIX

The design matrix developed to conduct eight trials with three factors, two levels full factorial design ($2^3 = 8$). The selected design matrix presented in Table 2 is based on the procedures dealt with in [6].

TABLE 2: The design matrix

S.No.	W	V	N
1	-1	-1	-1
2	+1	-1	-1
3	-1	+1	-1
4	+1	+1	-1
5	-1	-1	+1
6	+1	-1	+1
7	-1	+1	+1
8	+1	+1	+1

2.3 CONDUCTING THE EXPERIMENTS AS PER THE DESIGN MATRIX

Beads on Steel plates of size 200mmx50mmx6mm were deposited as per the design matrix (above) by using 1.2mm diameter SS 308L wire on a power source with a rated current capacity of 400 amps at 60% duty cycle and OCV of 18-52 V. The complete experimental set up is shown in Fig.1. The experiments were conducted in a randomized manner to eliminate any systematic error.

Fig. 1. The Experimental Setup

The complete set of eight trials was repeated for the sake of determining the variance of parameters and the variance of adequacy for the models [7]. The welding current observations along with the trial conditions are given in Table 3.

TABLE 3: Design matrix and observed values of current.

S.No.	**W**	**V**	**N**	**Observed welding current (amps)**		**Average welding current**
				I1	**I2**	$\frac{I_1 + I_2}{2}$
1	-1	-1	-1	100.0	96.3	98.15
2	+1	-1	-1	143.3	137.2	140.25
3	-1	+1	-1	112.5	102.0	107.25
4	+1	+1	-1	207.0	212.0	209.50
5	-1	-1	+1	108.0	108.0	108.00
6	+1	-1	+1	160.5	169.0	164.75
7	-1	+1	+1	120.0	113.0	116.50
8	+1	+1	+1	220.0	221.0	220.50

2.4 DEVELOPING THE MATHEMATICAL MODEL AND CALCULATING ITS COEFFICIENTS

The response function representing welding current can be expressed as I=f(W,V,N) and assuming the linear relationship and taking into account all the possible two and three

factor interactions, it could be represented as;

$$I=\beta_o + \beta_1 W + \beta_2 V + \beta_3 N + \beta_{12} WV + \beta_{13} WN + \beta_{23} VN + \beta_{123} WVN$$

Where, $\beta_o, \beta_1, \dots\dots\dots, \beta_{123}$ are the regression coefficients to be calculated by the method of least squares as given by the following formula [4],

$$\beta_j = \frac{\sum_{i=1}^{N} x_{ji}\, y_i}{N},\ j=0, 1, 2\dots\dots\text{k}$$

Where,

N= Number of trials

K= Number of columns of design matrix

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

y_i = Average value of the response parameter

2.5 TESTING SIGNIFICANCE OF THE COEFFICIENTS

The value of the regression coefficients gives an idea as to what extent the control variables affect the response quantitatively. The less significant coefficients can be dropped along with the responses with which they are associated, without significantly sacrificing the accuracy. To achieve this, student's *t*-test is used. According to this test when the calculated value of *t* corresponding to a coefficient exceeds the standard tabulated value for the desired level of probability, say 95%, the coefficient becomes significant. The tabulated value of 't' at degree of freedom eight and 95% confidence level is 2.3. The coefficients, having calculated 't' value less than 2.3 can be conveniently dropped, Table 4.

TABLE 4: Coefficients of the model and their significance.

Coefficient	Value	*t*-value	Significance
β_1	38.14	24.60	Yes
β_2	17.83	11.50	Yes
β_3	6.83	4.40	Yes
β_{12}	13.43	8.66	Yes
β_{13}	2.05	1.32	No
β_{23}	-1.76	1.13	No
β_{123}	-1.61	1.03	No

Thus, the developed model is reduced to the following equation in coded form.

$$I=145.61 + 38.14W + 17.83V + 6.83N + 13.43WV$$

2.6 CHECKING THE ADEQUACY OF THE DEVELOPED MODEL

The adequacy of the model is tested by analysis of variance method. As per this technique, if the calculated value of model's F-ratio does not exceed its tabulated value for the desired level of confidence, then the model is considered to be adequate [7]. F-ratio for the model is the ratio of variance of adequacy to the variance of reproducibility.

TABLE 5: Calculation of variance for testing the adequacy of the model.

Response parameter	Degree of freedom		Variance of reproducibility	Standard deviation of coefficients	Variance of adequacy	F-ratio of model	Tabulated F-ratio at (4,8,0.05) (F_t)	Model adequacy $F_m < F_t$
Welding current	S_y^2	S_{ad}^2	S_y^2	1.55	S_{ad}^2	$F_m = \frac{S_Y^2}{S_{ad}^2}$	3.8	Yes
	8	4	19.27		19.27	1.00		

In the present case F-ratio for 95% confidence level at 4 degrees of freedom of variance of adequacy and 8 degrees of freedom of variance of reproducibility is 3.8. From the details of analysis of variance given in Table 5, it is found that the developed model is adequate.

2.7 DIRECT AND INTERACTION EFFECTS OF PROCESS PARAMETERS ON WELDING CURRENT.

The effects of wire feed rate, voltage, nozzle to plate distance and their interactions as determined through the model are given quantitatively in Table 6.

TABLE 6: Effects of process parameters on welding current.

Parameter	β_j	Effect on response (2xβ_j)
Main Effects		
Wire feed rate	38.14	76.28
Voltage	17.38	34.76
Nozzle to plate distance	6.38	12.76
Interaction effects		
WV	13.43	26.86
WN	2.05	4.10
VN	-1.76	-3.52
WVN	-1.61	-3.22

2.8 VALIDATION OF THE MODEL

To check the validity of the model, verification test runs were conducted by assigning different values to the process variables within their working limits. These values shown in **table 7** are other than what have been used in design matrix.

Actual values of welding current observed during these runs were compared against the predicted values obtained from the model equation. The deviation between the two have been calculated and expressed in the form of percentage errors. It is found that the average percentage error is less than 2%.

TABLE 7: % error between predicted and actual values of current

S.No.	Variables in coded form			Predicted value of current	Actual value of current	% Error
	W	V	N			
1.	0	+1	+1	170.27	174.50	2.48
2.	+1	0	-1	176.92	174.00	-1.60
3.	-1	-1	0	102.46	105.25	2.72
4.	0	0	0	145.61	149.25	2.49
Average % error						1.52

3. RESULTS AND THEIR ANALYSIS

The mathematical model developed can be employed to predict the effect of wire feed rate, voltage and nozzle to plate distance on welding current for the range of parameters used in the investigation. The main and interaction effects were plotted as depicted in Figs 2-7.

3.1 HALF NORMAL PLOT

The half normal plot Fig. 2 indicates the significance of the parameters and the interaction effects on the response parameter. The distance between the line and a parameter decides the significance of that parameter. In the present case, wire feed rate has the most significant effect on welding current and the significance reduces down to nozzle to plate distance as it is relatively close to the line .

3.2 PARETO CHART

The Pareto chart depicted in Fig. 3 further confirms the findings of the half normal plot above i.e. amongst the significant factors, wire feed rate is the most significant and nozzle to plate distance is the least.

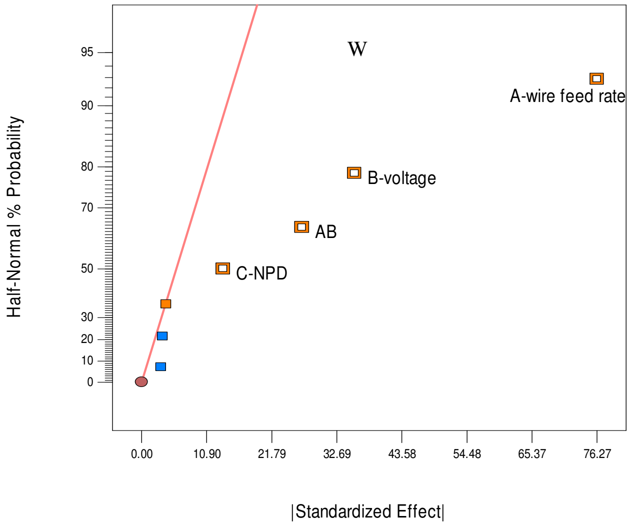

Fig. 2. Half normal plot

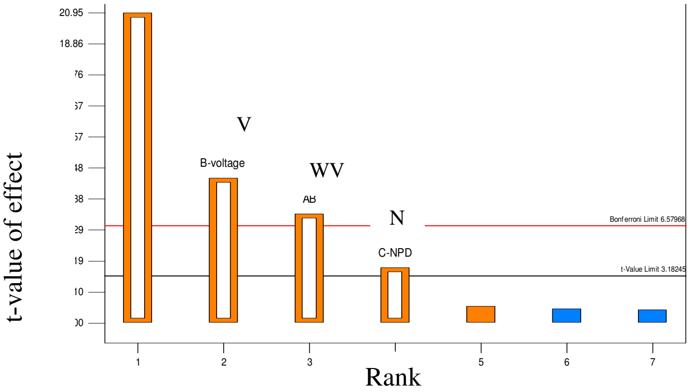

Fig. 3. Pareto Chart

3.3 SCATTER DIAGRAM

The scatter diagram Fig. 4, shows the predicted and the observed values of welding current are scattered close to the line passing through the origin, clearly indicating a perfect fit of the mathematical model developed.

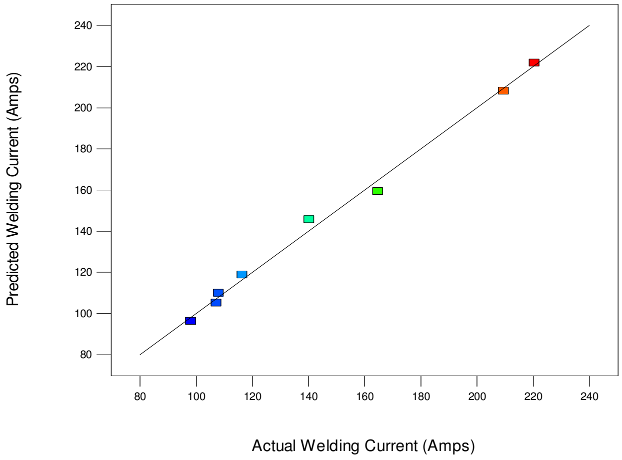

Fig. 4. Scatter Diagram

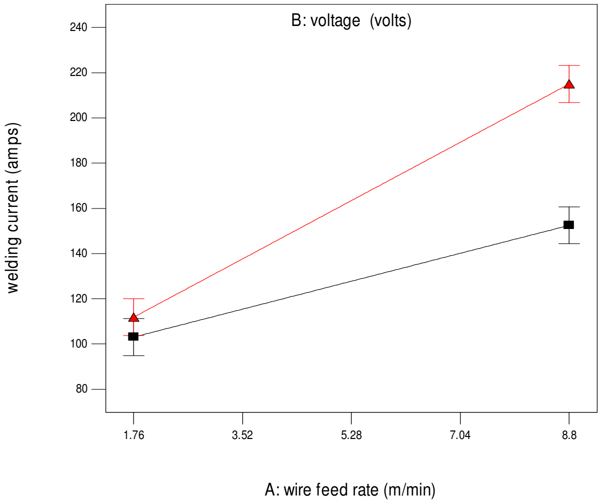

Fig. 5. Interaction Plot

3.4 INTERACTION PLOT

The interaction plot in Fig. 5 shows the interaction effect of wire feed rate and voltage on the welding current. It is evident that at voltage of 16V, the current varies steadily from 96.24 amps to 145.67 amps only when wire feed rate varies from 1.76 to 8.8 m/min. but for the same change in values of wire feed rate, the current increases steeply from about 105.04 amps to 208.17 amps when voltage is 27.5V, clearly indicating the interaction effect between wire feed rate and voltage.

3.5 SURFACE RESPONSE AND CONTOUR PLOTS

Figs. 6&7 present the response surface and contour plot for the welding current obtained from the regression model. Notice that the significant interaction effect between wire feed rate and voltage "twists" the plane. This twisting of the response surface results in curved contour lines of the response parameter welding current. Thus interaction is a form of curvature in the underlying response surface model for the experiment.

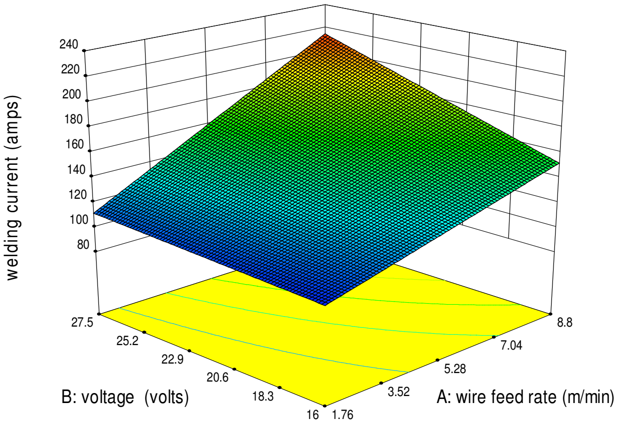

Fig. 6. Response surface plot

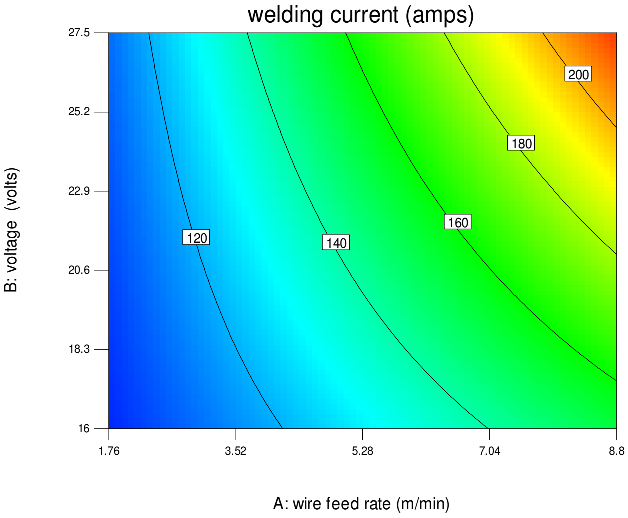

Fig. 7. Contour plot

4. CONCLUSIONS

The following conclusions were arrived at from the analysis of results of these experiments.

a) The increase in the levels of wire feed rate, voltage and nozzle to plate distance results in the corresponding increase in the level of welding current, both individually and collectively.

b) Out of the three process variables, wire feed rate is the most significant in affecting the welding current. From Table 5, it is evident that for an increase in wire feed rate from 1.76 to 8.8m/min, an increase of 76.28 amperes in welding current resulted. The current increases with wire feed rate to adjusts itself to burn off the quantity of wire delivered and therefore the amount of current drawn is proportional to the wire feed rate.

c) The next significant effect is of the voltage, which, for an increase from 16 to 27.5V, results in an increase of 34.76 amperes in welding current. This trend indicates rising V-I characteristic of the power source.

d) The third significant effect on welding current is exhibited by the interaction effect of wire feed rate and voltage which cause a significant increase of 26.86 amperes. The effect of wire feed rate on welding current at a voltage of 16V is less significant but it becomes quite significant at 27.5V. This is also evident from Fig. 5.

e) Nozzle to plate distance has a less significant effect on welding current than wire feed rate and voltage as is obvious from Table 5. It resulted in an increase of only 12.76 amperes of welding current. In fact an increase in nozzle to plate distance results in an increase in arc length which when gets auto corrected by increasing voltage (rising V-I characteristics), current also increases slightly.

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