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Research Article

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Prediction of Bead Profile Parameters for Submerged Arc Welding of Structural Pipe Steel

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Abstract—

In oil industries, submerged arc welding is the only primarily used process to weld high thickness, large distance structural oil pipes. Submerged arc welding process parameters play an important role in determining the quality of a weld joint. In the work presented here; on structural pipe steel (API 5L X65 grade) has been performed to estimate the effect of welding parameters on the weld bead geometry parameters. For design of experiments, response surface methodology (RSM) had been used. Mathematical models for bead geometry parameters; bead width, bead height and form factor in terms of welding parameters; welding current, arc voltage and welding speed had been formed and checked for adequacy with ANOVA (F-Test). It was found that welding current was the most significant parameter controlling all the responses and arc voltage had increasing effect.

Keywords— submerged arc welding, structural pipe steel, response surface methodology, form factor.

I. INTRODUCTION

Submerged arc welding (SAW) is used due to its inherent qualities like easy control of process variables, high quality, smooth finish, prevention of atmospheric contamination of weld pool, leak proof joints and ease of automation in welding of pipes ([1], [2], [3]). The material of large distance structural oil pipes should have good mechanical properties and excellent weldabilty ensuring crack free strong joints. In submerged arc welding, process parameters play a significant role in determining the quality of a weld. So for such applications, optimum welding process parameters must be selected providing optimum weld properties [4].

Parsad et al. [5] investigated the effect of welding current and welding speed at high heat input on toughness, hardness and microstructures of HSLA steel weld joints. The study revealed that toughness increased and hardness was seen to increase in fusion zone as well as in heat affected zone (HAZ) with increase of welding current. Also lower values of hardness near fusion centre whereas high value of hardness at distance away from weld center in HAZ had been observed. Murugan et al. [6] developed mathematical models for penetration, reinforcement, bead width and dilution in terms of input process parameters; voltage, speed, wire feed rate and nozzle to tip distance on IS 2062 steel using RSM technique.

Murugan et al. [2] studied the effect of weld parameters voltage, speed, wire feed rate and nozzle to tip distance penetration (P), reinforcement (R), bead width (W), penetration size factor, PSF (W/P) and reinforcement force factor, RFF (W/R) on IS 2062 steel. Prediction equations were developed for these parameters using RSM technique. The authors [7] suggested that; in high-strength and higher toughness materials, it is very important that the lowest possible heat input should be maintained during welding. Datta et al. [8] optimized bead geometry (bead width, reinforcement, depth of penetration and depth of HAZ) using grey relational analysis. Welding parameters are determined for bead width, reinforcement and depth of HAZ with lower-the-better and for depth of penetration with larger-the-better criterion. It had been observed that welds having high form factor (1.5) i.e. wide width and shallow depth have maximum resistance to centerline cracking [9].

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II. DESIGNOF EXPERIMENT AND EXPERIMENTATION

A. Experimental design

For design of experiment, three factor-five level central composite design of response surface methodology (RSM) had been used ([10], [11]). Response surface methodology (RSM) is a collection of mathematical and statistical techniques that are useful for the modeling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize this response. The central composite design (CCD) is a very efficient design for fitting the second-order model. Generally, the CCD consists of a 2k factorial runs (or fractional factorial) augmented with a group of 2k axial or star runs which allow estimation of curvature and n_c center runs. For a rotatable CCD, star runs are placed at a distance ±□, such that □ = [2k, No. of factorial runs]1/4 and |□|> 1, where k is the number of factors.

Three independently controllable process parameters; welding current (I), arc voltage (V) and weld speed (S) were selected on the basis of the importance of their effect on weld bead geometry and ease of control of being maintained at the desired level. Range of these parameters was decided by conducting the trial runs by varying one factor at a time while keeping the rest of them at constant value (One factor at a time, OFAT technique).

In the presented work; levels, units and notations of the selected parameters is presented in table 1.

TABLE I WELDING PARAMETERS AND THEIR LEVELS

Welding Parameters	Units	Levels of parameters				
		-1.682	**-1**	**0**	**+1**	**+1.682**
Current, I	A	311	340	382.5	425	454
Voltage, V	V	26	28	31	34	36
Weld Speed, S	m/h	22.6	25.2	29	32.8	35.4

B. Bead on plate

Weld beads were made on 13 mm thick HSLA steel (API 5L X65) plate of size 150×150mm. Twenty beads were taken using 3.2 mm diameter wire electrode (EH-14) with direct current reverse polarity (DCRP) keeping nozzle to tip distance constant at 25mm on submerged arc welding setup (ADOR Tornado SAW M-800).

C. Measurement of responses

The welded plates were cut transversely to observe the bead profiles by performing the common metallurgical polishing operations and then etching with 5% nital solution. The weld bead geometry parameters (Refer Fig. 2(a)); width of bead (W), height of bead (h), were measured using a profile projector. Form Factor ([1], [6], [9]) are calculated from the equations (1):

$$\text{Form Factor} = \frac{\text{Width of Bead, W}}{\text{Depth of Bead, d}} \qquad (1)$$

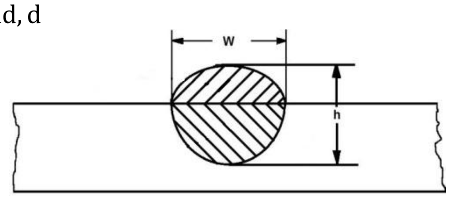


Fig. 1 Weld bead geometry, W-width of bead, h-height of bead

III. RESULTS

Results of output responses; bead width (W), bead height (h) and form factor are presented in Table 2.

A. Development of mathematical models

Using the observed values of output responses from experimentation, least square regression equations have been developed in terms of input weld parameters. Second order response surface models are formed which are expressed in terms of welding parameters; current I, voltage V and weld speed S as:

$$y = b_0 + b_1I + b_2V + b_3S + b_{11}I^2 + b_{22}V^2 + b_{33}S^2 + b_{12}IV + b_{13}IS + b_{23}VS \qquad (2)$$

The regression coefficients of the second order equation are obtained by using the experimental data (Table 2). The regression equations for the bead geometry responses as a function of three input process variables was developed using experimental data and is given below. The coefficients identified from ANOVA (Table 3) for various actual terms in the quadratic equation given as:

$$\text{Width, } W = -186.72942+0.26041I+9.94562V-0.41622S-.00022I^2-0.12886V^2+0.032558S^2-.00098IV-0.0019IS-0.033772VS \qquad (3)$$

$$\text{Height,} h =11.90187-0.093848I-4.20443V-1.45816S+.000165I^2+0.089234V^2+0.029919S^2-0.00146IV+0.000905IS-0.026645VS \qquad (4)$$

$$\text{Form factor, } ff= -43.63300+0.027405I+1.69730V+0.87412S-.000038I^2-0.026039V^2-0.014221S^2+0.000098IV-0.0000154IS-0.00087VS \qquad (5)$$

The coefficients (insignificant identified from ANOVA) of some terms of the quadratic equation have been omitted and given below:

$$\text{Width, } W = -83.01013+8.32356V-2.36253S-0.12454V^2+0.035304S^2 \qquad (6)$$

$$\text{Height, } h =+87.37629+0.013729 I-5.08910V-0.20248S+0.082028V^2 \qquad (7)$$

$$\text{Form factor, } ff=-36.95174+1.66255V+0.81316S-0.025284V^2-0.013741S^2 \qquad (8)$$

TABLE III DESIGN MATRIX WITH RESPONSE VALUES

Exp No.	Welding Current, I (Amp)	Arc Voltage, V (Volt)	Weld speed, S (m/hr)	Bead width W (mm)	Bead height h (mm)	Form factor ff
1	340.00	28.00	25.20	13.18	9.5	1.39
2	425.00	28.00	25.20	15.18	10.2	1.4
3	340.00	34.00	25.20	18.61	9.82	1.79
4	425.00	34.00	25.20	19.8	9.61	1.92
5	340.00	28.00	32.80	12.85	8.32	1.62

6	425.00	28.00	32.80	13.29	9.44	1.69
7	340.00	34.00	32.80	16.43	7.26	2.05
8	425.00	34.00	32.80	16.68	7.8	2.1
9	311.00	31.00	29.00	16.07	6.14	2.35
10	454.00	31.00	29.00	15.35	9.6	2.33
11	382.50	26.00	29.00	11.38	8.4	1.26
12	382.50	36.00	29.00	15.86	10.1	2.52
13	382.50	31.00	22.60	20.8	9.5	1.99
14	382.50	31.00	35.40	15.55	7	1.92
15	382.50	31.00	29.00	16.6	6.6	2.26
16	382.50	31.00	29.00	17.47	7.8	2.94
17	382.50	31.00	29.00	16.1	7.1	2.22
18	382.50	31.00	29.00	16.49	7.8	2.12
19	382.50	31.00	29.00	17.47	7.3	2.28
20	382.50	31.00	29.00	16.92	7.17	2.35

B. Analysis Of Results

The residual analysis as a primary diagnostic tool is also done. Normal probability plot of residuals have been drawn (as shown in figure 2) for all responses. All the data points are following the straight line. Thus the data is normally distributed. It can be seen from of figure 3 that all the actual values are following the predicted values and thus declaring model assumptions are correct.

Fig. 2 Normal probability plot of residuals for (a) Bead Width (b) Bead Height (c) Form Factor

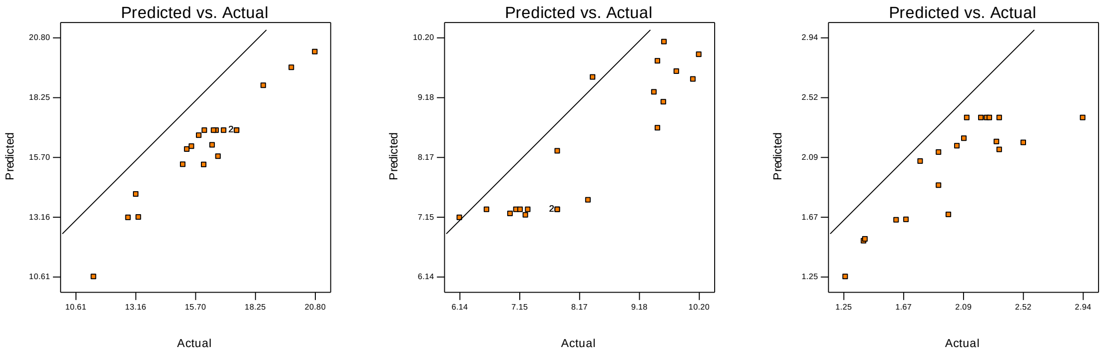


Fig. 3 Predicted versus actual values for (a) Bead Width (b) Bead Height (c) Form Factor

TABLE IIIII ANOVA TEST FOR BEAD WIDTH, BEAD HEIGHT AND FORM FACTOR

Parameter	Source	SS	DF	F value	P value	R-Square	Adequacy of model
Bead Width	Model	91.82	9	10.20	15.52	0.9332	Adequate
	I	0.52	1	0.52	0.79		
	V	44.15	1	44.15	67.18		
	S	19.57	1	19.57	29.78		
	I^2	2.36	1	2.36	3.59		
	V^2	18.85	1	18.85	28.68		
	S^2	3.14	1	3.14	4.78		
	IV	0.13	1	0.13	0.19		
	IS	0.78	1	0.78	1.19		
	VS	1.19	1	1.19	1.80		

	Lack of Fit	5.04	5	1.01	3.30		
	Pure Error	1.53	5	0.31			
Bead Height	Model	25.32	9	2.81	4.52	0.8027	Adequate
	I	4.65	1	4.65	7.47		
	V	0.00	1	0.00	0.00		
	S	8.10	1	8.10	13.01		
	I^2	1.31	1	1.31	2.11		
	V^2	8.99	1	8.99	14.44		
	S^2	2.74	1	2.74	4.40		
	IV	0.28	1	0.28	0.45		
	IS	0.17	1	0.17	0.27		
	VS	0.74	1	0.74	1.19		
	Lack of Fit	5.18	5	1.04	4.94		
	Pure Error	1.05	5	0.21			
Form Factor	Model	2.43	9	0.27	3.11	0.938	Adequate
	I	0.00	1	0.00	0.04		
	V	1.10	1	1.10	12.71		
	S	0.05	1	0.05	0.60		
	I^2	0.07	1	0.07	0.83		
	V^2	0.76	1	0.76	8.78		
	S^2	0.62	1	0.62	7.11		
	IV	0.00	1	0.00	0.01		
	IS	0.00	1	0.00	0.00		
	VS	0.00	1	0.00	0.01		
	Lack of Fit	0.44	5	0.09	1.02		
	Pure Error	0.43	5	0.09			

IV. DISCUSSION

A. Effect of welding current on bead geometry

It is observed from the figure 4 that bead width increases slightly with increase of current whereas the bead height increases at sharper rate with increase in current. Form factor also increases at a slower rate with current.
The increase in welding current increases the heat input, it results with increased penetration, deposition which causes increase in bead height.

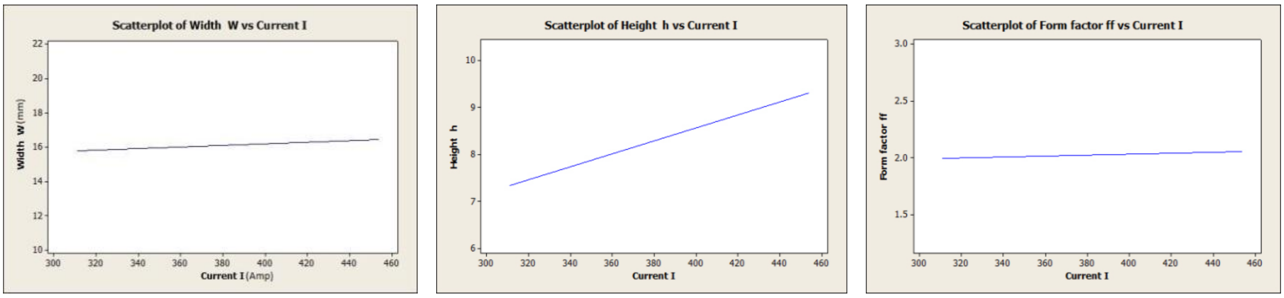


Fig. 4 Effect of welding current on Bead Width, Bead Height and Form factorReferences

B. Effect of arc voltage on bead geometry

Bead width and bead height both increase with increase of arc voltage from 26V at -1.682 level to 36V at +1.682 level as indicated in figure 5. Similar findings were reported by Kumar (2011) but increase in bead width is sharper than increase in height. Form factor also increases with voltage. Area of reinforcement decreases with increase in arc voltage. Arc voltage in submerged arc welding increases arc length and spreading of the arc on more area which results in much increase in bead width, area of penetration as compared to bead height, area of reinforcement.

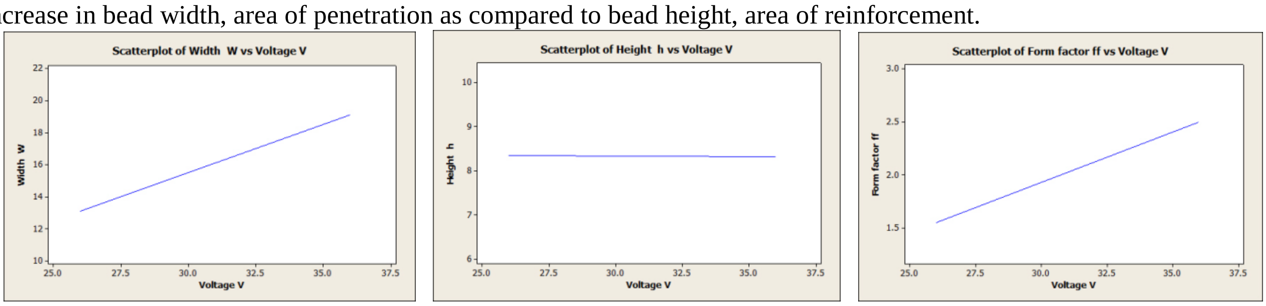


Fig. 5 Effect of Arc Voltage on Bead Width, Bead Height and Form factor

C. Effect of welding speed on weld bead geometry

Bead width and bead height both decrease with increase of welding speed from 17m/hr to 35m/hr as shown in figure 6, but decrease in height is much steeper than decrease in bead width. Form factor slightly increases with weld speed. As heat input in welding process is inversely proportional to the weld speed. With the increase in speed heat input to melt electrode wire and base metal decreases. Also at higher speeds welding head covers more distance for the same time and hence electrode wire gets lesser time to melt. Both lesser melting time and lesser heat input tend to reduce bead width and bead height.

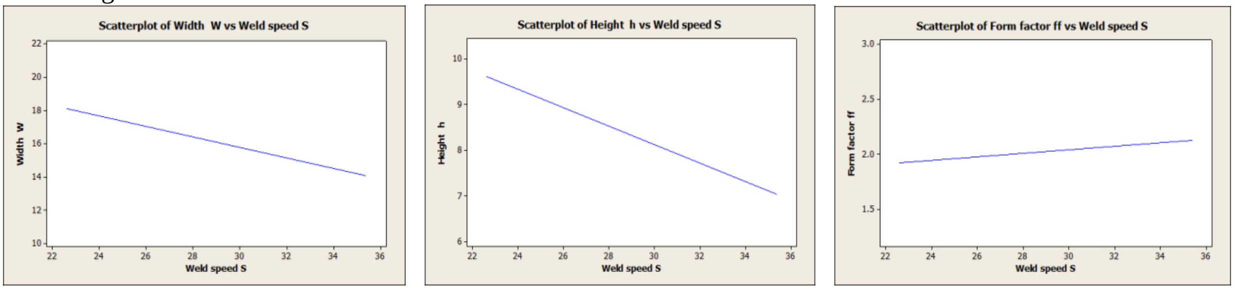


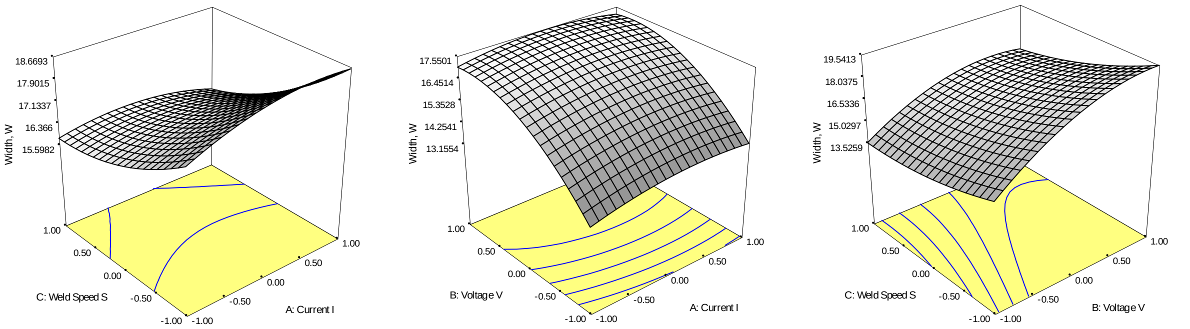
Fig. 6 Effect of weld speed on Bead Width, Bead Height and Form factor

D. Interaction effect of different parameters on bead width

Response surface plot (Figure 7) shows that bead width increases with increase in welding current at the lowest level of weld speed (-1.682 level) whereas with increase in speed from the lowest level (-1.682 level) of weld speed to the highest level of weld speed (+1.682 level) for all valued of current width decreases. At the highest level of weld speed (+1.682 level) bead width decreases with increase in welding current. Similar trend is shown for current with change of weld speed indicating significant interaction between parameters I and S.

Response surface plot (Figure 7) shows that bead width increases with increase in arc voltage from the lowest level of voltage (-1.682 level) to highest level of voltage for all values of current. A sharp increase of bead width is revealed from the graph. At the highest level of arc voltage (+1.682 level) bead width remains same with increase in welding current. The small increase in width is observed with increase in current at the lower values of voltage. Similar trend is shown with change of welding current at higher level of voltage indicating significant interaction between parameters V and I.

From figure 7 it is clear that bead width increases with increase in weld speed at lower level of arc voltage whereas the trend is opposite for higher values of voltage. Bead width decreases with decrease in voltage for all values of weld speed but increase of width is much sharper at the lowest level of speed than higher level of weld speed indicating interaction between factors V&S.



(a) (b) (c)

Fig. 7 Interaction effect of (a) welding current and weld speed on bead width (b) welding current and voltage on bead width (c) arc voltage and weld speed on bead width

E. Interaction effect of different parameters on bead height

From figure 8, it is clear that bead height decreases with increase in weld current for all values of arc voltage Bead height at the highest level of voltage and current (+1.682 level) i.e. at 36V, 454 A is minimum whereas at the lowest level of arc voltage and welding current (-1.682 level) i.e. at 26V,311 A it is maximum. Height decreases sharply at higher values of voltage than at lower values when the current increases from lower to higher side. With increase in arc voltage from 26V to 36V at all levels of welding current same trend is followed i.e. there is decrease of bead height with increase of arc voltage and current indicating interaction between parameters I and V.

Response surface plot (Figure 8) shows that bead height decreases with increase in weld speed for all values of current but it decreases sharply at the lowest level of welding current (-1.682 level) than at the highest level (+1.682 level). Plot also indicates that height decreases gradually with increase in current at all levels of weld speed indicating interaction between weld speed S and welding current I.

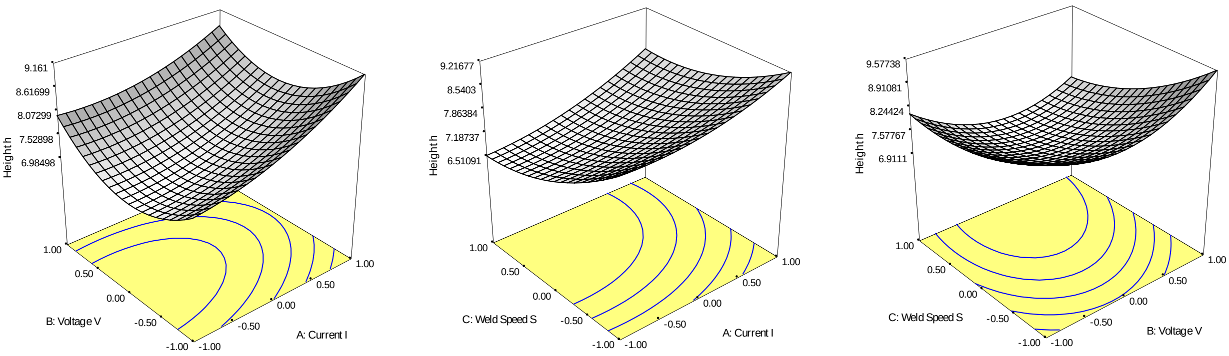
From Figure 8 it is clear that bead height decreases with increase in weld speed for all values of voltage and as indicated from the surface plot, the height value is minimum at 1.684 level of weld speed, arc voltage and it decreases with increase in voltage. The maximum height value is at the -1684 level of weld speed and -1,684 level of arc voltage indicating interaction between factors V& I.

F. Interaction effect of different parameters on bead width

From figure 9 it is clear that form factor increases with increase in arc voltage for all values of welding current from voltage level 28 V to 32.5 V and then it starts decreasing to 34V. Form factor increases at a low rate with increase in current for all values of voltage but increase is almost same from the lowest level of current to highest level of current indicating interaction between factors.

From figure 9 it is clear that form factor increases from -1-684 level i.e. 26.2 of weld speed to level 4 i.e. 30.9 value of weld speed for all values of current but it decreases from level 4 to level 5 value of weld speed for all values of current. There is increase of form factor with increase of current with increase in weld speed indicating interaction between factors S& I.

From figure 9 it is clear that form factor increases with increase in voltage for all values of weld speed .it also increases with increase in weld speed. Increase of form factor is sharper in increase in arc voltage than weld speed increment. Increase is much sharper at the lower level of speed indicating interaction between factors V&S.



(a) (b) (c)

Fig. 8Interaction effect of (a) welding current and arc voltage on bead height (b) welding current and weld speed on bead height (c) weld speed and arc voltage on bead height

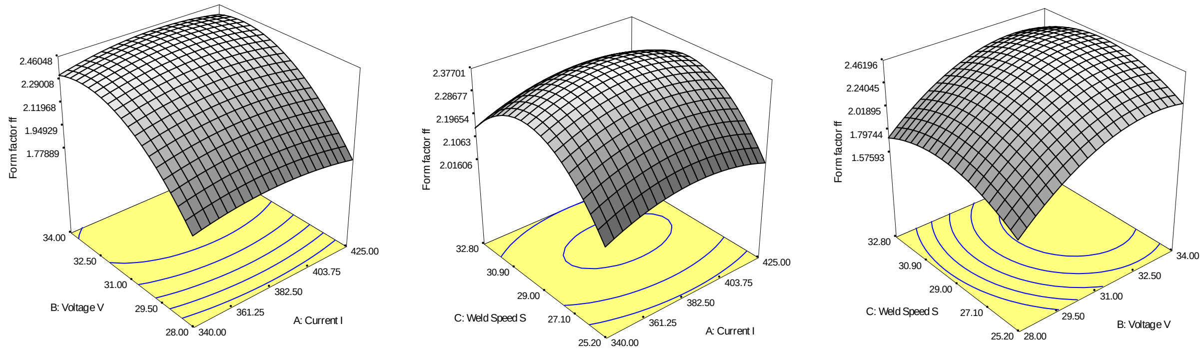


Fig. 9Interaction effect of (a) welding current and arc voltage on Form factor (b) welding current and weld speed on Form factor (c) weld speed and arc voltage on Form factor

V. CONCLUSIONS

- Response surface methodology can be employed easily for developing mathematical models for predicting important weld bead dimensions and shape relationships within the optimal range of process control variables for SAW.
- The models developed can be employed for obtaining the desired weld bead dimensions.
- Out of the three process variables considered, welding current had a significant positive effect but welding speed had an appreciable negative effect on most of the important bead parameters. .
- Arc voltage had a negative effect on penetration, but more significant negative effect was observed on reinforcement. Voltage had a significant positive effect on bead width and form factor.
- Difference between predicted values and experimental values of all the responses for weld metal is within significant range.
- Among the selected parameters, welding current is the most significant parameter controlling all the responses.

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