Submerged Arc Welding With a Mixture of Fresh Flux and Fused Slag-Modeling with Quadratic Response Surface Methodology

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Abstract

In the present research work the reconsumption of the slag, generated during conventional submerged arc welding, has been proposed during subsequent runs by incorporating appropriate treatment and mixing it with fresh flux, with certain proportions. Experiments have been carried out by using four different levels of process parameters like welding current, flux basisity index and slag-mix percentage (percentage of slag in the mixture of fresh flux and fused slag) to obtain bead-on-plate weldment on mild steel plates. Parameters associated with bead geometry like bead height, bead width, depth of penetration have been measured for each experimental run. Heat affected zone (HAZ) geometry in terms of HAZ width has also been obtained. Assuming simple geometry of the weld bead and unit length of the job, approximate bead volume has also been calculated. All these data have been efficiently utilized to develop mathematical models for prediction of geometry and quality of weld bead as well as heat affected zone. Quadratic response surface methodology (RSM) has been applied to develop the mathematical models between predictors and responses. Based on multiple linear regressions, the coefficients of the predictors, used in the models, have been determined. Analysis of Variance Method (ANOVA), F- test and Student's t test have checked the significance of the coefficients. Reduced models with significant coefficients have also been developed. Experimental data as well as generated data have been used to represent graphically the direct and interactive effects of process parameters (slag mix% has given special emphasis in this exercise) on selected response variables associated with weld bead and HAZ. Hardness Test has also been carried out to reflect graphically, the influence of using slag-mix in SAW process on mechanical property of the weldment i.e. hardness of weld metal as well as HAZ. Finally it has been concluded that effect of using slag-mix (up to 20%) do not impose any alarming adverse effect on features of bead geometry and HAZ. Therefore, the use of slag-mix, in submerged arc welding can be recommended to apply it in practical cases, which may make the process more economical.

Key words: SAW, slag-mix, HAZ, RSM, ANOVA

Nomenclature

Parameter	Notation
Bead Height (mm)	R
Penetration (mm)	P
Bead width (mm)	W
HAZ width (mm)	HW
Bead cross section (mm^2)	A
Bead volume (mm^3)	V

Introduction

Submerged arc welding is characterized by its wide area of application feasibility due to high heat input, deep penetration and ability to join thick plates in a single pass (or very few passes). The process consumes coarse, granular flux, which mainly consists of Calcium Oxide, Calcium Fluoride and Silicon Oxide. Heat is supplied by the welding arc due to electric discharge between wire electrode and base metal. A percentage of the heat input is utilized to melt the electrode as well as base metal. The remaining part melts the flux, which covers the molten weld pool and protects it from atmospheric contamination. Above the fused flux or slag layer there exists a blanket of unmelted / fresh flux. This typical arrangement ensures slower cooling rate resulting enhancement in bead quality required for various structural applications. During subsequent runs, fresh flux is consumed and the slag goes as waste. This causes storage and disposal problem, needs landfill space and environmental pollution apart from exhaust from non-renewable resources. Recycling/reuse of slag may not only solve these problems but also add to economy.

Today, Waste Management has taken a serious step to introduce a new concept for minimizing the waste by utilizing the waste (generated in a process), through appropriate treatment, resulting some value added product that may cause profit, or reusing the same in the parent process (which has generated the waste), thus reducing raw material cost. Zero Waste can be defined as the recycling off all materials back into the nature in a manner that protects human health and the environment.

Motivated by the zero waste concept, in the present work, it is intended to investigate the application feasibility of slag-mix in submerged arc welding process. In doing so, it is required to have an intensive knowledge about the effects of process parameters, generally employed in conventional SAW process, on geometry, quality as well as mechanical properties of the weld bead and HAZ. The results should be compared with that of SAW process consuming slag-mix. If it is revealed that the use of slag-mix would not impose any adverse effect, then the proposed process could be performed in reality for commercialization of the process. Research results contributed by the previous investigators would be helpful in this context.

Literature survey reveals that the use of recycled slag would be a new area of research because of less work is done so far in this respect. H. P. Beck, and A. R. Jackson, [1] concluded that according to code requirement, the properly processed slag could be reliable and could be used as an alternative for new flux. They further claimed a saving of 50% of the procured flux by recycled flux. L. G. Livshit and A. I. Shiryaev, [2] had shown that it was possible to use pulverized slag crust mixed with iron fillings for hard facing applications. In the present context research related to slag reconsumption in conventional SAW process have been carried out by S. C. Moi et al. [3], and P. K. Pal et al. [4].

In the present work an attempt has been made to examine the acceptability of using slag-mix in conventional SAW process and to show the direct as well as interactive effects of process variables including flux basicity index and welding current on features of bead geometry, bead volume and HAZ. In this context slag-mix% (percentage of fused slag mixed with fresh flux) has also been considered as one of the important process variables. Though main function of flux is to protect the weld pool, which intern is related to the features of bead geometry, bead quality as well as performance characteristics of the welded joint. Therefore, different bead geometry parameters: bead height, bead width, depth of penetration, bead volume, HAZ width and hardness of weld metal and HAZ have been selected in judging the effect of reusing of slag. Quadratic response surface methodology followed by multiple linear regression method has been applied for modeling of the welding phenomena. Relevant model statistics have also been determined. Finally the results have been represented graphically. The produced weld has been tested for its hardness. Hardness has been measured at weld metal and heat affected zone. The effect of slag-mix on hardness has been shown graphically.

Experimentation and Data Collection

Submerged arc welding is a multi factor metal fabrication technique. Various process parameters influencing bead geometry, bead quality as well as mechanical-metallurgical characteristics of the weldment include welding current, voltage, wire feed rate, traverse speed, electrode diameter, type of flux, height of flux layer etc. In a full factorial design, the number of experimental runs exponentially increases as the number for factors as well as their level increases [5]. This results huge experimentation cost and considerable time. So, in order to compromise these two adverse factors, the present study has been planned to use only two conventional process parameters, along with slag-mix%, treated as another process variable. It has been reported by previous researchers that among the conventional process parameters in SAW welding, current is the most significant factor that influences different quality characteristics of submerged arc weldment. As, flux basicity index is related to the chemical composition of flux, which intern effects mechanical properties and metallurgical features of the weld, it is also an important factor. Therefore, in the present case, welding current and flux basicity index have been chosen as conventional process parameters along with the newly introduced parameter i.e. slag-mix%. Based on full factorial design without replication, experiments have been conducted with four different levels of process parameters: welding current, flux basicity index (type of flux) and percentage of fused flux mixed with fresh flux (slag-mix%) to obtain bead-on-plate weldment on mild steel plates (100 X 40 X 12). Process parameters with their notations, unit and values at different levels are listed in Table 1. Selected design matrix is a four level-three factor full factorial design consisting of $4^3 = 64$ sets of factor combinations.

The experiments were performed in Submerged Arc Welding Machine (Maker: IOL Ltd., India).

The required number of plates has been kept aside for doing bead-on-plate welding with the mixture of fresh flux and fused slag, while the rest of the plates have been utilized for collecting fused slag. For the later purpose welding has been done on the plates with conventional use of unmelted fresh flux only, of four different types. The chemical composition of these four fluxes along with basicity indices are shown in Table 2

Sufficient amount of welding has been done to collect fused slag in desired quantities /volumes for each of the above fluxes. The slag have then been broken and finally crashed to the granular size almost as that of the original flux(es). Thus fused slag of four varieties was kept ready for subsequent welding. The parameters, which have kept invariant, are listed in table 3. Weld beads being done, the transverse sections of the weld beads have been taken from the middle portions of the plates as specimens. These middle portions have been polished by belt grinder, and subsequently by a series of finer grades of emery paper (grades 1G, 1, 1/0, 2/0, 3/0 and 4/0). Finally they have been smoothened by means of cloth polishing. The properly polished specimens have been etched with 2% Nital solution for about 30 sec duration, which has been followed by investigation and analysis. For each of the bead-on-plate specimens, the dimensions, of the weld bead geometry including the depth of penetration and HAZ width have been measured by optical Trinacular Metallurgical microscope (Make: Leica, India). Weld bead volume have been evaluated from simplified bead geometry. Hardness has also been measured at different zones of the specimens (base metal, HAZ and weld metal) on Eseway Hardness Tester. Collected data has been furnished in Tables 4.1 and 4.2.

Table 1 : Process parameters and their limits

Serial No.	Parameter	Notation	Unit	Level 1	Level 2	Level 3	Level 4
1	Current	C	Ampere	150	200	250	300
2	% of Slag-mix	S	-	0	10	15	20
3	Basisity Index	f	-	0.8	1.0	1.2	1.6

Table 2 : Chemical composition of fluxes used

Flux	Character	Type of Manufacture	Chemical Composition (%)				Basicity Index
			$Al_2O_3+MnO_2$	$CaO+MgO$	SiO_2+TiO_2	CaF_2	
F_1	Acid	Agglomerated	55	5	30	5	0.8
F_2	Neutral	Fused					1.0
F_3	Basic	Agglomerated	25	35	35	-	1.2
F_4	Basic	Agglomerated	35	25	20	15	1.6

Table 3: Constant parameters in the experiment

Travel Speed: 20 cm/min
Nozzle Angle: 90^0
Voltage: 28V
Electrode Wire: 3.15 mm Diameter Copper coated mild steel wire
Thickness of Flux Layer: Fairly constant.

DEVELOPMENT OF MATHEMATICAL MODELS

The response function Y that represents any of the features of bead geometry and HAZ can be expressed as $Y = \square\,(C,S,f)$. The selected relationship is a second-degree response surface, which is expressed as follows:

$$Y=\beta_0 + b_1 C + b_2 S + b_3 f + b_{11} C^2 + b_{22} S^2 + b_{33} f^2 + b_{12}CS + b_{13}Cf + b_{23}Sf \quad \text{(i)}$$

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 $C = x_1$, $S = x_2$, $f=x_3$

Then,

$$Y= \beta_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_{11} x_1^2 + b_{22} x_2^2 + b_{33} x_3^2 + b_{12} x_1 x_2 + b_{13} x_1 x_3 + b_{23} x_2 x_3 \quad \text{(ii)}$$

If, it is considered that $x_1^2=x_4$, $x_2^2=x_5$, $x_3^2=x_6$, $x_1x_2=x_7$, $x_1x_3=x_8$, $x_2x_3=x_9$ and $b_1=\beta_1$, $b_2= \beta_2$, $b_3= \beta_3$, $b_{11}= \beta_4$, $b_{22}=\beta_5$, $b_{33} =\beta_6$, $b_{12}=\beta_7$, $b_{13}=\beta_8$, $b_{23}= \beta_9$, the equation (ii) can be written as a multiple linear regression model as follows:

$$Y= \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + \beta_6 x_6 + \beta_7 x_7 + \beta_8 x_8 + \beta_9 x_9 \quad \text{(iii)}$$

The value of the coefficients was calculated in MINITAB based on the data obtained in the experimental part of the present work. Developed mathematical models are shown in equations (iv) to (vii).

$$R = 2.73 + 0.0175\ C + 0.0422\ S - 3.40\ f - 0.000025\ C^2 - 0.00120\ S^2 + 1.14\ f^2 -0.000055\ CS + 0.00322\ Cf + 0.0119\ Sf \quad \text{(iv)}$$

$$W = - 1.87 + 0.0876\ C + 0.0394\ S - 0.49\ f -0.000140\ C^2 + 0.00098\ S^2 - 0.97\ f^2 -0.000526\ CS + 0.0181\ Cf + 0.0692\ Sf \quad \text{(v)}$$

$$P = - 2.95 + 0.0119\ C - 0.0206\ S + 5.67\ f -0.000002\ C^2 + 0.00143\ S^2 - 2.03\ f^2 +0.000029\ CS - 0.00263\ Cf - 0.0137\ Sf \quad \text{(vi)}$$

$$HW = - 0.62 + 0.0322\ C - 0.0062\ S - 2.73\ f -0.000027\ C^2 + 0.00344\ S^2 + 1.21\ f^2 -0.000266\ CS - 0.00010\ Cf - 0.0129\ Sf \quad \text{(vii)}$$

Regression analysis has been used for determining the coefficients of the models. The statistical significance of the coefficients of the factors (or interaction of factors) included in the models have been tested by applying Fisher's 'F' and Student's 't' test respectively. The regression coefficients were calculated by the method of least squares. The MINITAB's Backward Elimination method of stepwise regression has been used to drop the insignificant coefficients from 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. The reduced models with significant coefficients are shown in equations (viii) to (xi). The relevant model statistics were given in appendix.

$$R = 2.156 + 0.0206\ C \quad 2.7\ f \quad 0.00003\ C^2 + 1.14\ f^2 + 0.0174\ Sf \quad \text{(viii)}$$

$$W = -1.745 + 0.087\ C \quad 0.00014\ C^2 \quad 1.24\ f^2 \quad 0.00039\ CS + 0.0176\ Cf + 0.092\ Sf \quad \text{(ix)}$$

$P = -2.162 + 0.00847\ C + 4.9\ f -$

Table 4.1 Experimental Data

C (A)	S (%)	f	R (mm)	P (mm)	W (mm)	HW (mm)	V (mm^3)
150	0	0.8	3.28	1.58	9.36	2.11	29.41
200	0	0.8	3.64	2.25	12.07	3.30	42.11
250	0	0.8	4.18	2.60	13.40	4.10	55.19
300	0	0.8	4.42	2.80	14.45	4.80	62.61
150	10	0.8	3.77	1.44	9.90	2.26	34.95
200	10	0.8	4.16	1.88	12.47	2.59	46.62
250	10	0.8	4.43	2.18	13.70	3.74	55.17
300	10	0.8	4.58	2.52	14.10	4.64	61.89
150	15	0.8	3.60	1.98	10.16	2.52	37.34
200	15	0.8	4.40	2.20	12.10	3.20	53.23
250	15	0.8	4.60	2.40	13.18	3.84	59.86
300	15	0.8	4.95	2.70	13.54	4.35	69.72
150	20	0.8	3.42	1.70	9.81	2.40	32.43
200	20	0.8	4.07	2.45	12.55	2.85	50.95
250	20	0.8	4.41	2.83	13.29	3.96	61.23
300	20	0.8	4.96	3.05	13.61	4.16	73.75
150	0	1.0	2.73	2.30	8.58	2.08	27.29
200	0	1.0	3.43	2.37	11.65	3.65	39.84
250	0	1.0	3.80	3.08	14.92	4.86	55.82
300	0	1.0	4.01	4.02	15.92	5.61	71.13
150	10	1.0	3.14	1.84	9.04	1.62	29.37
200	10	1.0	4.04	2.43	12.36	2.71	50.07
250	10	1.0	4.72	3.30	13.98	3.20	72.66
300	10	1.0	4.84	4.12	15.40	4.20	86.66
150	15	1.0	3.45	2.18	10.64	2.10	37.46
200	15	1.0	4.01	2.54	13.92	2.60	52.38
250	15	1.0	4.20	3.10	15.52	3.30	63.45
300	15	1.0	4.50	3.90	15.73	4.02	78.35
150	20	1.0	3.35	2.04	10.26	3.06	34.64
200	20	1.0	3.64	2.25	12.85	3.41	42.81
250	20	1.0	4.06	3.40	15.36	4.02	64.22
300	20	1.0	4.24	3.60	16.16	6.14	70.79
150	0	1.2	3.23	2.38	9.35	1.55	34.62
200	0	1.2	3.43	2.53	12.46	3.11	42.09
250	0	1.2	4.30	2.80	16.09	4.41	62.30
300	0	1.2	5.10	2.95	17.38	4.80	80.58
150	10	1.2	3.06	1.65	9.79	1.45	27.63
200	10	1.2	3.64	2.31	12.10	2.44	42.70
250	10	1.2	4.52	2.67	13.95	3.70	62.30
300	10	1.2	4.62	3.30	16.25	4.30	74.33
150	15	1.2	3.75	1.91	10.72	1.98	39.36
200	15	1.2	4.09	2.13	12.76	3.50	48.31
250	15	1.2	4.60	3.10	14.41	4.04	69.04
300	15	1.2	4.76	3.19	15.78	4.16	74.99
150	20	1.2	3.44	2.07	9.61	1.40	35.34
200	20	1.2	3.71	2.30	10.11	2.25	41.31
250	20	1.2	4.83	2.45	13.46	3.59	64.75
300	20	1.2	4.93	2.79	17.16	4.02	74.88
150	0	1.6	3.10	2.10	9.92	2.15	31.64
200	0	1.6	3.88	2.45	12.75	3.43	48.24
250	0	1.6	4.28	2.81	14.61	4.45	60.50
300	0	1.6	4.68	3.01	16.25	4.91	71.91
150	10	1.6	3.30	1.77	9.35	2.54	31.07
200	10	1.6	3.99	2.37	13.30	3.30	49.69
250	10	1.6	4.41	2.51	15.55	4.10	60.27
300	10	1.6	4.85	2.85	17.35	4.40	74.31
150	15	1.6	3.22	1.66	9.15	2.01	29.12
200	15	1.6	4.32	2.26	13.75	3.10	54.26
250	15	1.6	4.67	2.45	15.75	3.47	64.34
300	15	1.6	4.99	2.72	17.95	4.80	75.88
150	20	1.6	3.94	1.98	13.12	2.31	44.78
200	20	1.6	4.40	2.52	14.45	3.27	59.15
250	20	1.6	4.74	2.71	15.95	3.98	69.00
300	20	1.6	5.36	3.25	16.60	4.24	88.78

Table 4.2 Experimental Data obtained from Hardness Test

Flux	Current (A)	Slag-mix%	Hardness (VHN) at		
			Weld zone	HAZ	Parent metal
F_1	150	0	228	174	131
		10	241	185	
		15	222	140	
		20	219	138	
	300	0	176	158	
		10	194	168	
		15	178	148	
		20	176	134	
F_4	150	0	207	181	
		10	234	179	
		15	192	138	
		20	223	167	
	300	0	190	132	
		10	204	174	
		15	203	146	
		20	184	133	

$2.03 f^2$ (x)

HW = - 0.9052 + 0.0204 C + 0.00303 S^2 0.00032 CS (xI)

Evaluation of Bead Volume

Assuming the shape of bead cross section to be a circular sector with radius (P+R), from simple geometry, bead cross sectional area A can be easily evaluated approximately. Simplified bead geometry are shown in Figure 1.

$A = (P+R)^2\phi$, (in radian), the semi arc angle

Where, $\tan\phi = (W/2P)$, (ϕ in degree)

Assuming unit length of the job, the area A will also represent the bead volume.
Bead Volume (V) = A.1 = $(P+R)^2$, (in radian)

ANOVA and Mathematical Modeling for Bead Volume

Analysis of Variance technique has been used to predict whether the selected factors (or their interactions) influence significantly on bead volume. Based on statistics, some inferences can be made. Graphical presentations can also be made then. Table 5 indicates ANOVA for bead volume. The mathematical model for bead volume is given in equation (xii). The reduced model (for bead volume) with significant coefficients is also shown in equation (xiii).

In ANOVA table:

DF = Degree freedom of a factor / interaction of factors

SS = Sum of square deviation of a term about the mean

MS = Mean square = Sum of square / DF

F = Fisher's F ratio = MS for a term/ MS for the error term

P = Probability of significance

According to the theory of ANOVA, if P value for a term appears less than 0.05, then it can be concluded that, there is definitely some influence of the factor/ combination of factors on the particular response. Table 5 shows that the direct/main effect of current, slag-mix% and flux

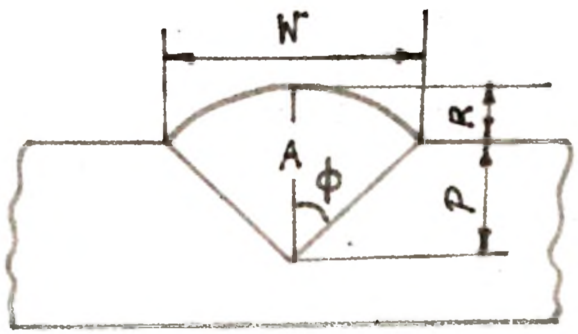

Figure 1: Simplification on geometry of bead cross section

Table 5: ANOVA for bead volume

Source	DF	SS	MS	F	P
C	3	5045.80	451.02	451.02	0.000*
S	3	123.97	11.08	11.08	0.000*
F	3	78.75	7.04	7.04	0.001*
C*S	9	8.57	0.77	0.77	0.648
C*f	9	41.35	3.70	3.70	0.004*
S*f	9	63.50	5.68	5.68	0.000*
Error	27	11.19			
Total	63				

*Significant at 95% confidence level.

basicity index, and interaction effect of current*flux basicity, slag-mix%*flux basicity impose significant effect on volume of the weld bead.

$$V= - 21.0 + 0.320 C + 0.303 S + 4.9 f -0.000230 C^2 - 0.0039 S^2 - 5.48 f^2- 0.00047 CS + 0.0558 Cf + 0.168Sf \quad (xii)$$

$$V= -11.20 + 0.275 C + 0.302 Sf \quad (xiii)$$

Graphical Representation and Interpretation

The predicted values of the response variables are generated by the developed models. These yield graphical presentations which help revealing direct effect of slag-mix% and interactive effects of the process parameters including slag-mix% on bead geometry, bead volume and width of HAZ. These are shown in Figs. 3-6 and Figs.7-14.

DIRECT EFFECT OF SLAG-MIX PERCENTAGE ON BEAD GEOMETRY, BEAD VOLUME AND HAZ:

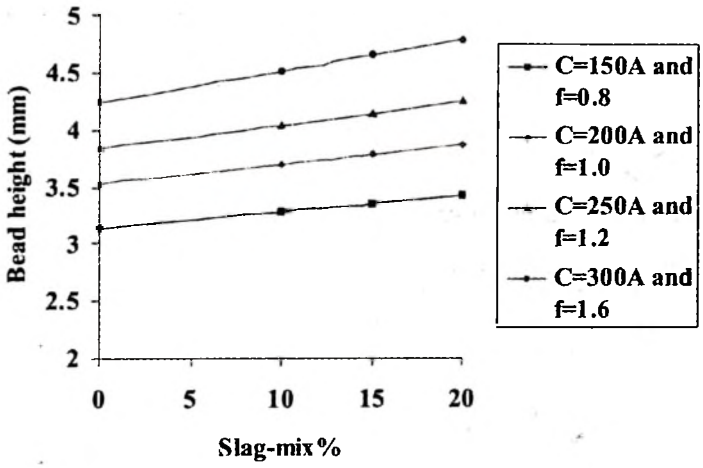

Fig. 2 Direct effect of slag-mix % on bead heigh

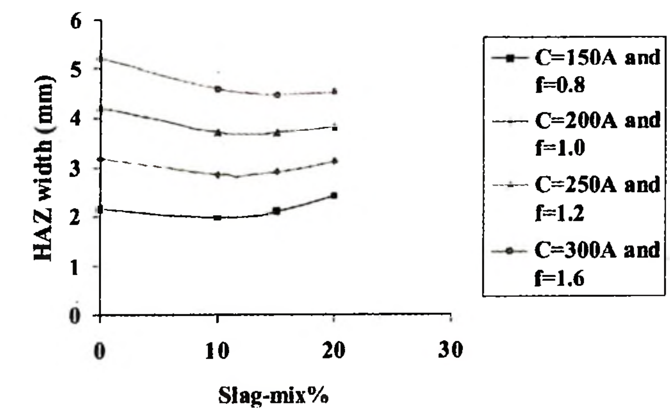

Fig. 3 Direct effect of slag-mix % on HAZ width

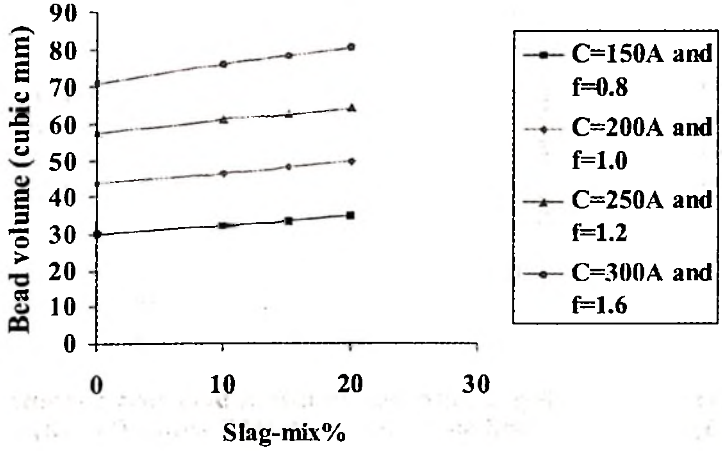

Fig. 4 Direct effect of slag-mix % on bead volume

It has already been mentioned that one of the objectives of the present work is to investigate the effect of the use of fused slag mixed in fresh flux on the results of the submerged arc welding process. It is therefore essential to study how bead geometry, HAZ width and bead volume change with increase in slag-mix % in fresh flux.

Fig. 2 shows the direct effect of slag-mix % on bead height. It is clear from the figure that increase in slag-mix % results in increase in bead height for constant current and flux basisity index (flux type). It was found that direct effect of slag-mix % on bead width is not so significant, for constant current and flux basisity index. For C=300A and f=1.6 (Flux F_4), increasing slag-mix % results slight increase in bead width. Therefore, from the point of view of bead width, consumption of slag-mix up to 20% is feasible.

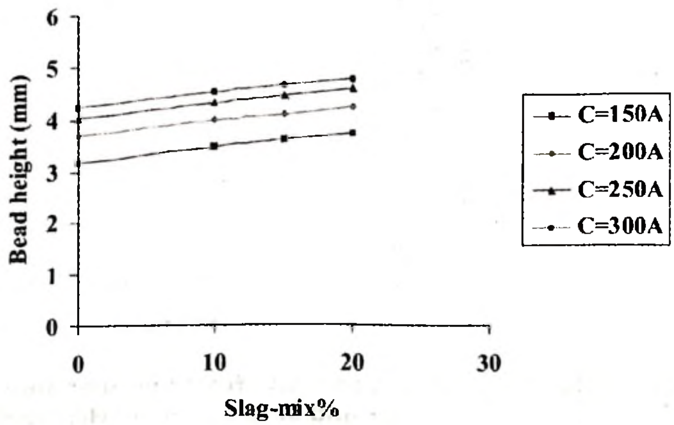

Fig. 5 Interaction effect between current and slag-mix % on bead height (f=1.6)

It is clear from equation (x), i.e. reduced model for P, that slag-mix % imposes negligible effect on depth of penetration. For constant current and for a particular flux type, with increase in slag-mix %, depth of penetration remains more or less constant.

Fig. 3 bears valuable information. For constant current and flux basicity index, HAZ width first decreases, then increases with increase in slag-mix%. When slag-mix is 10%, the HAZ width assumes a minimum value. It is well known that, there is a drastic change in microstructure and mechanical properties from weld bead to HAZ, therefore, a good quality weld always ensures minimum HAZ dimensions. This can be achieved with slag-mix at 10%.

From Table 5 (ANOVA for bead volume) it can be interpreted that the direct/main effects of current, slag-mix% and flux basisity index, all impose significant considerable effect on bead volume. (Because all have P value <0.05). The interaction effect of current-flux basisity index and slag-mix%-flux basicity index on bead volume is significant at 95% confidence level. The interaction between current-slag-mix% has negligible remarkable effect on bead volume.

Fig. 4 depicts direct effect of slag-mix% on bead volume. Keeping current and flux basicity index constant increase in slag-mix% causes increase in bead volume.

INTERACTION EFFECT OF CURRENT, SLAG-MIX PERCENTAGE AND FLUX BASISITY INDEX ON BEAD GEOMETRY, BEAD VOLUME AND HAZ:

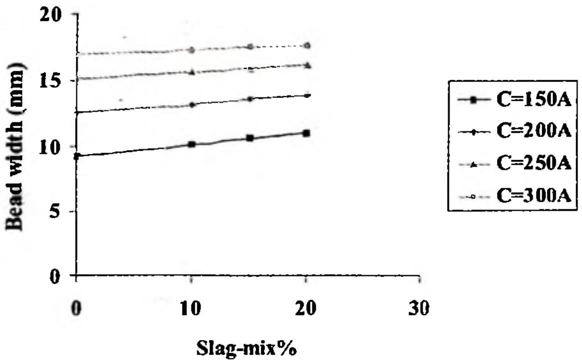

Fig. 6 Interaction effect between current and slag-mix % on bead width (f=1.6)

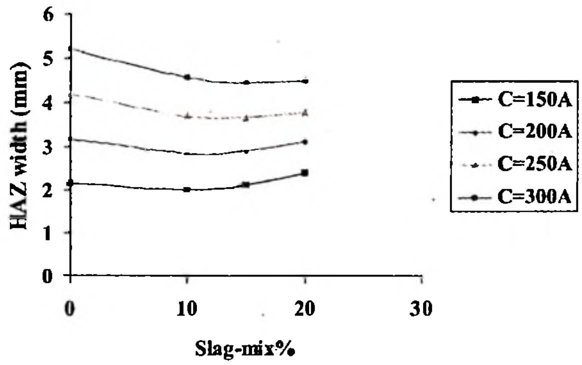

Fig. 7 Interaction effect between current and slag-mix % on HAZ width (f=1.2)

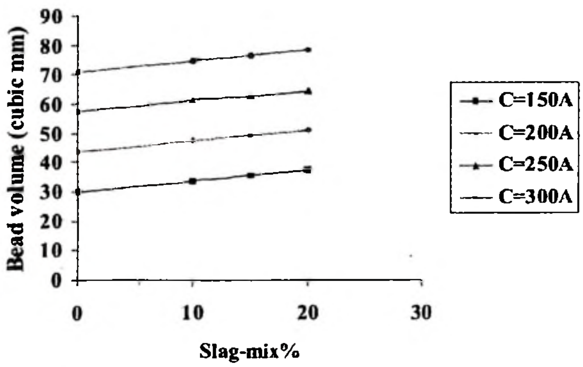

Fig. 8 Interaction effect between current and slag-mix % on bead volume (f=1.2)

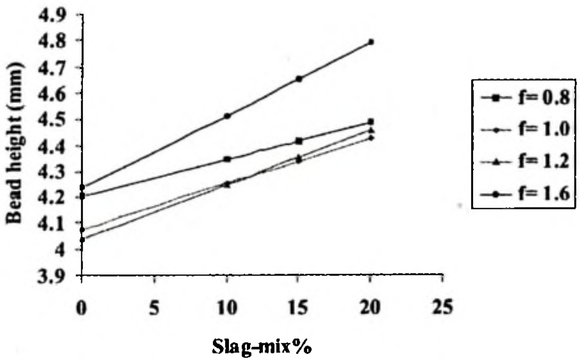

Fig. 9 Interaction effect between flux basicity index and slag-mix % on bead height (C=300A)

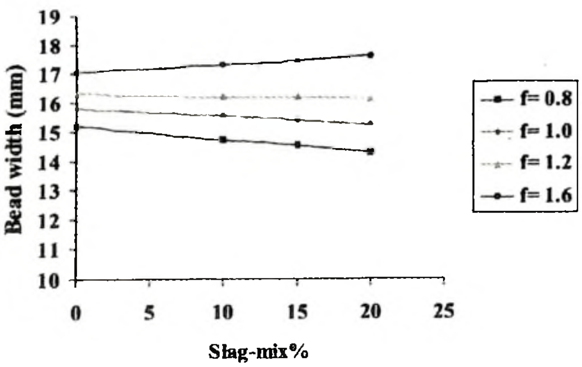

Fig. 10 Interaction effect between flux basicity index and slag-mix % on bead width (C=300A)

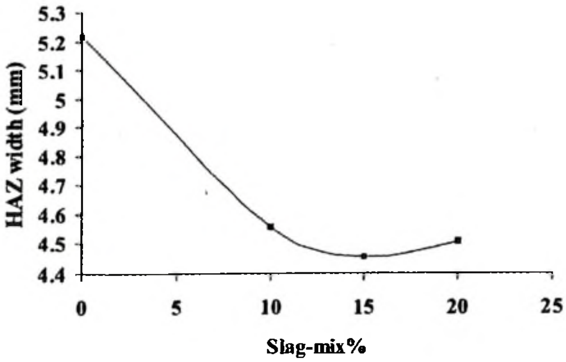

Fig. 11 Interaction effect between flux basicity index and slag-mix %on HAZ width (C=300A & 0.8 <= f <= 1.6)

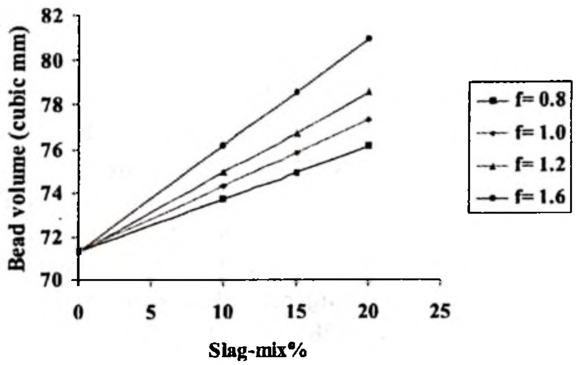

Fig. 12 Interaction effect between flux basicity index and slag-mix % on bead volume (C=300A)

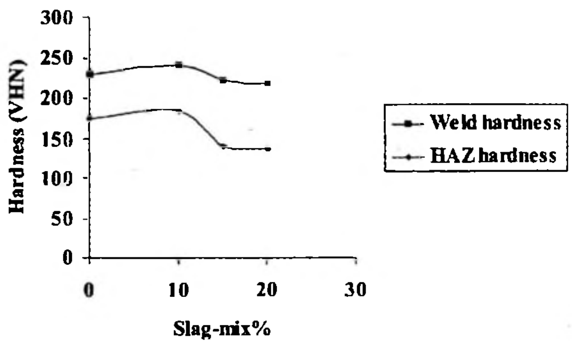

Fig. 13: Effect of slag-mix% on hardness of weldment and HAZ (Current= 150A and f= 0.8)

Fig. 5-12 shows interaction effects of (current-slag mix%) and (slag-mix%-flux basicity index) on features of weld bead geometry, HAZ as well as bead volume. Some important observations can be made from Figs. 5-12.

At constant welding current, increase in slag-mix% results increase in bead height. (Fig. 5)

Keeping current set at constant level, increase in slag-mix% results increase in bead width. (Fig. 6)

At constant welding current, with increase in slag-mix%, HAZ width first decreases, reaches a minimum value (slag-mix%=10%) and then increases. (Fig. 7)

For constant welding current, increase in slag-mix% results in increase in bead volume. (Fig. 8)

While using a particular type of flux (flux basisity index), increase in slag-mix% results increase in bead height. (Fig. 9)

Increase in slag-mix% results increase in bead width (For F_1 type of flux). For flux type F_2, bead width remains more or less constant. For F_3 and F_4 types of flux, increase in slag-mix% results in decrease in bead width. Therefore, no particular consistent trend can be stated from this plot. (Fig. 10)

For 0.8<= f <=1.6, increase in slag-mix% results drastic decrease in HAZ width. At 15% slag-mix it assumes a minimum value. It then increases with increase in slag-mix%. (Fig. 11)

For constant flux basisity index increase in slag-mix% results increase in bead volume. (Fig. 12)

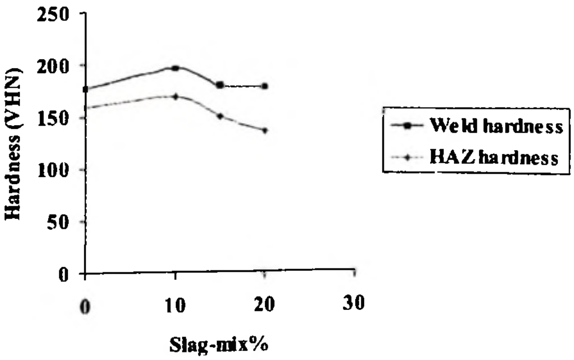

Fig. 14: Effect of slag-mix% on hardness of weldment and HAZ (Current= 300A and f= 0.8)

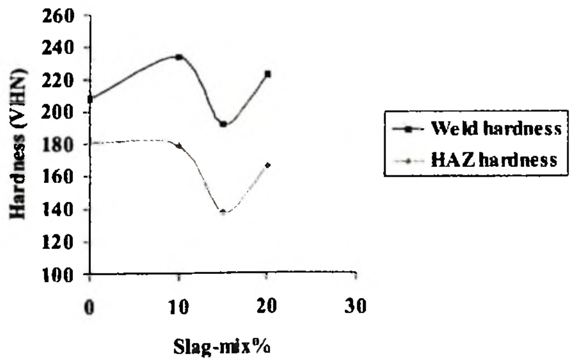

Fig. 15: Effect of slag-mix% on hardness of weldment and HAZ (Current= 150A and f= 1.6)

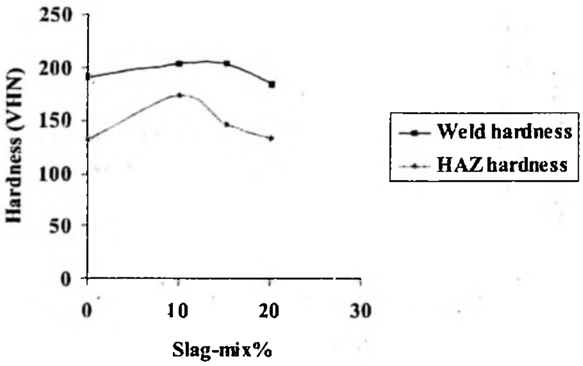

Fig. 16: Effect of slag-mix% on hardness of weldment and HAZ (Current= 300A and f= 1.6)

With respect to conventional SAW, the use of slag-mix, often effects increase in weld metal hardness, though no definite trend exists, between slag-mix (from 10-20%) and hardness values. VHN values of the heat-affected zones differ differently at different levels of flux and slag-mix. However, at 10% the hardness of HAZ in non-conventional SAW is comparable or more with respect to that which is found in conventional SAW with 0% slag-mix (Figures 13-16).

Conclusions

The following conclusions can be drawn from the results and analysis of the present work.

** Submerged arc welding process with a mixture of fresh flux and fused slag has been investigated and the results thereof bring about the trends between the process variables and (i) bead geometry, (ii) HAZ width (iii) bead volume and (iv) weld and HAZ hardness. Besides current and flux basicity, slag-mix% has also been considered as process variables.

** The application feasibility of slag-mix has been evaluated in terms of its direct as well as interaction effect with other parameters, namely welding current and flux basicity index, on various response variables.

** Experimental data have been utilized to develop predictive models (that represents mathematical relationships between predictors and responses) by applying quadratic response surface methodology followed by multiple linear regression.

** Statistical software package MINITAB is found to be useful for developing mathematical models and analyzing the model statistics that provides valuable information i.e. related to the behavior of the process. MINITAB's stepwise regression backward elimination method is helpful to eliminate the insignificant factors and coefficients from the model and to develop the reduced model with significant coefficients only.

** ANOVA table for bead volume reveals that direct effects of current, slag-mix% and flux basicity; the interactive effects of *current-flux basicity* and *slag-mix%-flux basicity index* are very significant at 95% confidence level. As bead volume depends on bead height, bead width and depth of penetration, the significant effect of slag-mix% on bead volume provides the possibility of having remarkable effect of slag-mix% on features of bead geometry and HAZ.

** For constant welding current and flux basicity index, slag-mix% provides positive effect on bead height and bead volume. For bead width and depth of penetration, the effects are found to be negligible.

** For a particular flux and constant welding current, use of 10% slag-mix produces minimum HAZ width and comparable sufficient hardness of weld metal and HAZ.

** Most of the plots for the interaction effects show generally convincing trends between cause and effect.

** The developed models have been found useful in connection with automatic or robotic submerged arc welding utilizing mixture of fresh flux and fused slag.

** As an extension of the work, more elaborate study may reveal whether the non-conventional submerged arc welding, which has been used in the present investigation, can provide quality weld without any alarming adverse effect on the microstructure, bead geometry, HAZ and performance characteristics (apart from hardness, other mechanical properties: toughness, strength) of the welded joint.

** The results of the present work

provide scope to initiate and solve the optimization problem regarding the parameters of the bead geometry and the desired weld quality.

** However, analysis for economy is to be rigorously done for this type of SAW process, use of fused slag in SAW process may lead to "waste to wealth" achievement.

Acknowledgement

Authors would like to acknowledge Sri Subhas Chandra Moi, Ex. P. G. Scholar, Department of Mechanical Engineering, Jadavpur University, Kolkata, India.

Sincere gratitude to the reviewer whose valuable suggestions helped a lot to improve presentation of the paper.

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