Recycled slag consumption in submerged arc welding and its effect on microstructure of weld metal

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ABSTRACT

Slag generated during conventional submerged arc weld was collected and processed by replenishing it with suitable alloying elements/deoxidizers by agglomeration. This replenished slag is referred to as recycled slag. Recycled slag in combination with EL-8 filler wire was used in these investigations. The effect of welding parameters on flux (recycled slag) consumption has been investigated. Mathematical model has been developed from the data generated using two level factorial technique. The significance of coefficients and adequacy of developed model have been checked by Students 't' test and F test respectively. The main effects of welding parameters on recycled slag consumption have been presented in graphical form for better understanding. The developed model is useful for controlling and predicting slag consumption in submerged arc welding. The physical behavior of recycled slag during welding was also observed. Microstructure of weld metal was analyzed.

Key words : Recycled slag, submerged arc welding, welding parameters, flux consumption, microstructure.

INTRODUCTION

Since the development of submerged arc welding attempts have been made by researchers and engineers to decrease welding cost. Flux contributes about 50% to the total welding cost in submerged arc welding. Flux consumption not only affects the welding cost but also governs the chemistry of weld metal which in turn influences metallurgical and mechanical properties [1]. The flux consumption is mainly dependent on physical properties of flux such as melting point, density, thermal and electrical conductivity [2]. Buttler et al. [3] found that flux consumption decreased as the melting temperature of flux increased. Thermal conductivity of molten flux also has pronounced effect on flux consumption. Higher the thermal conductivity of molten fluxes higher the flux consumption [4]. They further observed that the flux consumption was highest in acidic flux than neutral and basic fluxes. Gupta et al. [5, 6] reported that welding parameters have a significant effect on flux consumption. They found that flux consumption increased with increase in arc voltage and decreased with increase in welding current. Srinath, H. [7] reported that flux consumption Increases with increase in arc voltage. A comparative study conducted by Visvanath [8] indicates that rate of flux consumption is more in fused flux compared with agglomerated fluxes. Wittstock [9] also found that arc voltage controls the amount of fused flux. Pandey et al. [10] supported the above observations.

All the above researchers used commercial available fluxes in their investigations. It appears that almost no consideration has so for been made for the use of recycled slag in submerged arc welding. The use of recycled slag, if feasible, may economize the process without effecting the quality of weldment, consistent with some given or limited requirements, but the decision about this feasibility is dependent on exploration of various aspects associated with the process and the process-results.

PLAN OF INVESTIGATION

1. Processing of slag
2. Experiment design and execution

Processing of slag

Fused slag was crushed and subsequently milled in a ball mill to convert into powder form. Alloying elements and deoxidizers were added and dry mixed mechanically. Liquid potassium silicate was added as a binder to wet the powder. The wet mass agglomerated and passed through 10-mesh screen to convert into small pellets. These pellets were air dried for 24 hours and baked at 850 0C for two hours in a muffle furnace. The baked mass was then crushed and sieved to the required grain size and referred to as recycled slag. This recycled slag was used as a flux in these investigations.

Experiment design and execution

1. Identification of process parameters and finding their upper and lower levels;
2. Developing the design matrix;
3. Conducting the experiments as per design matrix;
4. Recording the response parameter;
5. Selecting the model;
6. Evaluation of the coefficients of the model;
7. Testing the significance of the coefficients and arriving at the final models;
8. Checking the adequacy of the developed model;
9. Presenting the results in graphical form.
10. Analysis of results.

Identification of process parameters and finding their upper and lower levels

Arc voltage (V), wire feed rate (W), travel speed (S) and nozzle to plate distance (N) were selected as direct welding parameters to study their effect on recycled slag consumption. The reason for their selection was that they govern the rate of heat input which is responsible for flux melting. Extensive trial runs were conducted to find their working range. The upper limit (highest level) and lower limit (lowest level) of a factor was coded as (+1) and (-1) or simply (+) and (-) respectively for the ease of processing the data. The selected parameters with their working range are given in Table-1.

Development of Design Matrix

The design matrix developed to conduct the eight trials of 24-1 (=8) two level half factorial design is shown in Table-2. The procedures of designing such a design matrix are dealt with Cochran et al. [11] and Adler et al. [12].

Conducting the experiments and recording the responses

Beads on mild steel plates having size 12×75×150 mm were deposited as per design matrix using 3.2mm diameter EL-8 wire in combination with recycled slag. Electrode positive polarity was used. A constant potential transformer-rectifier type power source with a current capacity of 600 amperes at 60% duty cycle and an OCV of 12 to 48 volts was used. The welding parameters were as dictated by design matrix. The experiments were performed in random manner to avoid any systematic error. The complete set of eight trials was repeated thrice for the sake of

Table 1 : Welding parameters and their working range

Parameters	Units	Symbol	Limits	
			Low (-1)	High (+)
Wire feed rate	m/min	W	0.88	1.68
Arc voltage	Volts	V	26	32
Travel speed	m/min	S	0.33	0.5
Contact tip-to-work distance	mm	N	18	25

Table 2: Design matrix

Trial No.	W 1	V 2	S 3	N 4 = 123
1	+	+	+	+
2	-	+	+	-
3	+	-	+	+
4	-	-	+	+
5	+	+	-	-
6	-	+	-	+
7	+	-	-	+
8	-	-	-	-

determining the variance of parameters and variance of adequacy for the model.

A measured quantity of flux (recycled slag) was used for each bead. The flux which is fused permanently and deposited on weld bead as a slag was collected and weighed. The initial and final weight of base plate ie before and after deposition of weld bead was noted. Then flux consumption (recycled slag) in kg/kg of weld metal deposited was calculated for each trial run and is recorded in Table-3.

Table - 3 : Flux consumption (kg/kg metal deposited)

Trial No	Recycled slag consumption (Kg/kg weld metal deposited)				
	Set-1(f^{I})	Set-II(f^{II})	Mean (f^{Mean})	Δf	$(\Delta f)^2$
1	1.67	1.50	1.58	-0.085	0.0072
2	2.05	1.85	1.95	-0.1	0.01
3	1.18	1.0	1.09	-0.09	0.0081
4	2.05	2.10	2.07	0.025	0.000625
5	1.27	1.32	1.30	0.025	0.000625
6	1.83	2.21	2.02	0.019	0.0361
7	0.90	1.18	1.04	0.14	0.0196
8	1.22	1.53	1.38	0.0155	0.0240
				$\sum(\Delta f)2 = 0.10625$	

Selection of mathematical model

The response function representing flux consumption (recycled slag) can be expressed as:

Y= f (W, V, S, N).

Assuming a linear relationship in the first instant and taking into account all the possible two factor interactions only, the above expression can be written as Equation-1.

$$Y = b_0 + b_1W + b_2V + b_3S + b_4N + b_{12}WV + b_{13}WS + b_{14}WN + b_{23}VS + b_{24}VN + b_{34}SN \quad (1)$$

After confounding the model can be written as :

$$Y = b_0 + b_1W + b_2V + b_3S + b_4N + b_5(WV + SN) + b_6(WS + VN) + b_7(WN + VS) \quad (2)$$

Evaluation of the Coefficients

The regression coefficients of the selected model were calculated using equation-3, which is based on the method of least squares. The calculated

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

Testing Significance of the Co-efficients

The statistical significance of the coefficients was tested by student 't' test. The value of 't' from the standard table for eight degree of freedom and 95% confidence level is 2.3. The calculated 't' values for the coefficients are given in Table-4. The coefficients having 't' value less than 2.3 are insignificant hence dropped in the final models.

Table - 4 : Coefficient of the model and their significance

Coefficient	b_0	b_1	b_2	b_3	b_4	b_5	b_6	b_7
Value	1.55	-0.301	0.158	0.118	0.123	0.028	0.036	-0.066
't' Value	27.02	5.2	2.7	2.06	2.15	0.50	0.63	1.152
Significant	Yes	Yes	Yes	No	No	No	No	No

Developed Models

Substituting the values of the coefficients in Equation-2 and dropping insignificant coefficient, the developed the model for flux consumption (recycled slag) is given in Equation-4.

Checking Adequacy of the Developed Models

The adequacy of developed models was then tested by the analysis of variance technique. As per this technique if the calculated value of model's F-ratio does not exceed its tabulated value for a desired level of confidence, then the model is considered to be adequate. The calculated 'F'- ratio of the models were compared with the corresponding 'F'- ratio from the standard table. In the present study, tabulated F- ratio for 95% confidence level at 3 degree of freedom of the variance of adequacy and 8 degree of freedom of variance of optimization respectively is 4.1. It has been found that the developed model is adequate. Details of analysis of variance are given in Table-5.

Table 5 : Analysis of variance

Response Parameter	Degree of freedom		Variance of optimn. parameter	Std. devi. of coefficient	Vari. of adequacy	F-Ratio Model Fm	F-Ratio from table Ft	Model whether adequate
	S_y^2	S_{ad}^2	S_y^2	S_{bj}	S_{ad}^2			$F_m < F_t$
Flux consumption	8	3	0.0265	0.0575	0.033	1.26	4.12	Yes

RESULTS AND DISCUSSIONS

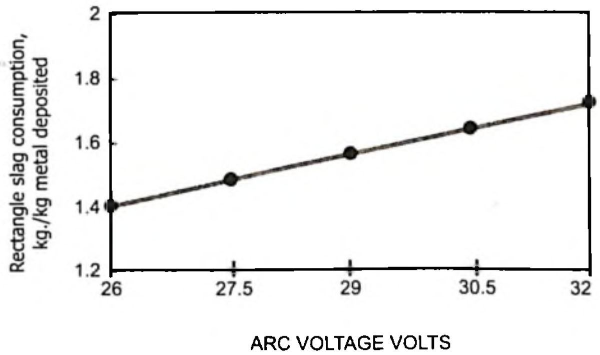

Figure 1 : Effect of arc voltage on slag consumption

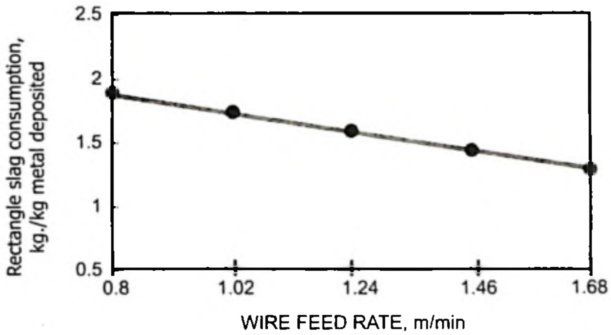

Figure 2 : Effect of wire feed rate on slag consumption

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Recycled slag consumption

Effect of arc voltage on flux (recycled slag) consumption

Fig. 1 indicates the effect of arc voltage on flux consumption. The flux consumption (recycled slag) increased from 1.4 to 1.7 kg/kg of metal deposited with an increase in arc voltage from 26 to 32 volts. The increase in recycled slag consumption with increase in arc voltage can be attributed to the fact that the increase in arc voltage increases arc length, thereby increasing the spread of arc and hence higher amount of flux coming in contact with the arc. Due to increased arc length arc strikes on a larger surface area causing wider and flatter bead hence increase in contact area between molten pool and flux resulting more flux to melt.

Effect of wire feed rate on flux (recycled slag) consumption

Fig. 2 indicates the effect of wire feed rate on flux consumption. It can be observed that flux consumption (recycled slag) decreases linearly from 1.85 to 1.25 kg/kg of weld metal deposited with an increase in wire feed rate from 1.12 to 1.68 m/min. This decrease in flux consumption is due to the fact that with the increase in wire feed rate, the metal deposition rate increases and consequently the overall ratio of flux consumption to the metal deposited decreases. Further, for the flat V-I characteristics, with the increase in wire feed rate, arc voltage and hence the arc length decreases. The reduced arc length reduces the surface area of the arc responsible for melting of flux.

Effect of travel speed and nozzle-to-plate distance

Travel speed and nozzle-to-plate distance has insignificant effect on flux consumption and hence dropped from the final model.

Microstructure of weld metal

Microstructure of base metal and weld metal has been shown in Figures-3 to 5. Figure 3 indicates a normal ferrite-pearlite structure of mild steel having 0.165% carbon. Figure 4 and 5 show the microstructure of weld metal deposited with recycled slag and fresh flux respectively. From the figures it is observed that the microstructure obtained with recycled slag is comparable with the microstructure of weld metal deposited with fresh flux which advocates the use of recycled slag instead of fresh flux.

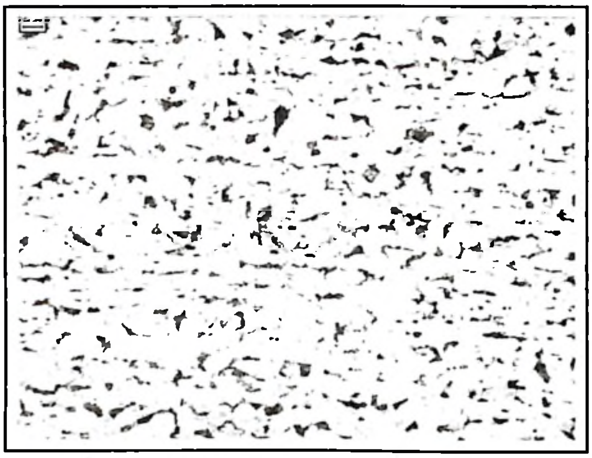

Fig 3 : Microstructure of base metal (X 100)

Fig. 4 : Miscrostructure of weld metal deposited with recycled slag : AF-acicular ferrite, GBF : grain boundary ferrite, PF : polygonal ferrite

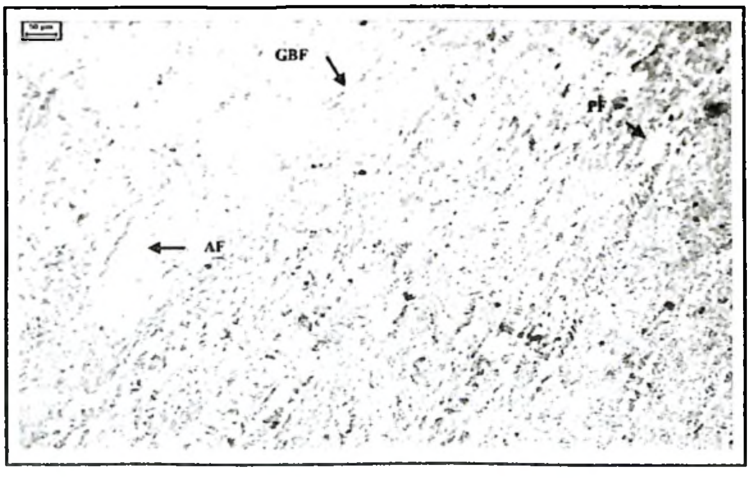

Fig. 5 : Miscrostructure of weld metal deposited with fresh flux : AF-acicular ferrite, GBF : grain boundary ferrite, PF : polygonal ferrite

Slag detachability and arc stability

Self detaching slag was observed during cleaning of weld beads. No fluctuation in arc voltage was indicated by the pointer of voltmeter fitted on equipment which indicates a stable arc during welding.

Bead appearance

Smooth beads with evenly distributed ripples were obtained. Weld bead were free from visible surface defects like pock marks, undercut, porosity. Overall bead appearance was considered to be acceptable.

CONCLUSIONS

1. Slag generated during submerged arc welding can be recycled for the use in same sub arc process after necessary modifications.
2. Recycled slag can produce desirable microstructure of weld metal containing acicular ferrite.
3. Slag detachability and arc stability both were satisfactory.
4. The recycled slag consumption behavior is similar to the behavior shown by commercial available fluxes.
5. Recycled slag consumption increased with increase in arc voltage.
6. Increase in wire feed rate decreased the rate of recycled slag consumption.
7. Travel speed and nozzle-to-plate distance have insignificant effect on recycled slag consumption.

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