Indian Journal of Science and Technology, Vol 9(28), DOI: 10.17485/ijst/2016/v9i28/95405, July 2016

ISSN (Print) : 0974-6846
ISSN (Online) : 0974-5645

Effects of Process Parameters and Recycled Slag on Flux Consumption in Submerged Arc Stainless Steel Cladding

Jatinder Garg[1*] and Kulwant Singh[2]

[1]Baba Hira Singh Bhattal Institute of Engineering and Technology, Lehragaga, Sangrur - 148031, Punjab, India; jatindergarg@yahoo.com
[2]Sant Longowal Institute of Engineering and Technology, Longowal, Sangrur - 148106, Punjab, India; engrkulwant@yahoo.co.in

Abstract

Objective: Slag generated during submerged arc cladding is discarded as waste. It creates problems like environmental pollution, wastage of natural resources and need landfill space for its dumping. A technology for recycling of slag generated during submerged arc cladding of stainless steel was developed. In the present study the effects of process parameters and recycled slag on flux consumption has been studied. **Methods/Analysis:** The experiments were conducted using fractional factorial design with type of flux (fresh flux/recycled slag) as one of the controllable factors. Mathematical model for flux consumption was developed. Developed model was tested for its adequacy by *F*-test. The significance of the coefficients was tested by Student's *t*-test. The results have been thoroughly analysed and presented graphically. The methodology for recycling the slag has also been discussed briefly. **Findings:** It was found that flux consumption increases with increase in open circuit voltage, decreases with increase in welding current and remains unaffected of travel speed. The results also proved that recycled slag does not produce any significant effects on the flux consumption. **Novelty/Improvement:** The work presented in this paper is essentially a novel technology developed by the authors originally. No work carried out by any other researcher on recycling of slag generated during stainless steel welding/cladding and its effects on flux consumption has been reported anywhere in literature.

Keywords: Cladding, Factorial Design of Experiments, Flux Consumption, Submerged Arc Welding, Slag Recycling, Stainless Steel

1. Introduction

Recycling and reutilization of industrial by-products is gaining ground due to rising price of raw materials, increased cost of waste disposal and growing environmental awareness in society[1–3]. Besides cost reduction it also prevents useful material resources being wasted, reduces the energy usage and hence greenhouse gas emissions[1].

Cladding is a process wherein a thick layer of an anticorrosive metal like Stainless Steel (SS) is deposited on the surface of a substrate to improve its corrosion resistance. Submerged arc welding with its inherent features like high metal deposition rate, cladding of larger area in single pass and ease of automation, is the most commonly used process for these applications. The process generates large amount of waste in the form of slag which is a by-product. The slag being non biodegradable does not decay with time and becomes a major source of environmental pollution. Additional cost is needed to be incurred on handling, storage, transportation and disposal of this by-product. It also leads to wastage of minerals and other natural resources which are major constituents of the flux. A technology capable of recycling such slag generated during submerged arc cladding of stainless steel flux has been developed by the authors[4].

*Author for correspondence

In submerged arc welding/cladding of stainless steels, the cost of flux forms a major chunk of the overall process cost. Controlling its consumption can thus lead to a significant amount of savings. In assessment of overall productivity of the process, flux consumption also plays an important role[5]. Besides financial considerations, extent of flux consumption also affects the pickup or loss of alloying elements by the clad metal, which in turn affects its mechanical and metallurgical properties. All these factors call for a proper evaluation of the flux consumption behavior of 'recycled slag' and its comparison with the fresh flux. This paper investigates the effects of process parameters and use of recycled flux on flux consumption in submerged arc cladding of stainless steel. The flux consumption was measured in terms of weight of flux/recycled slag used per unit weight of metal deposited (kg/kg), since it is a more practical indicator of flux consumption as compared to measurement of its absolute value[6]. The experiments were conducted using fractional factorial design and a mathematical model for flux consumption was developed. The results have been thoroughly analyzed and discussed in detail. Methodology adopted for recycling the slag has also been discussed briefly.

2. Materials and Methods

2.1 Recycling of Slag

In the past scientists and researchers have tried to develop various methods by which the slag waste can be recycled or reused. Experiments were conducted to explore the possibilities of mixing pulverized slag in civil construction material[7]. It was found that around 5-10 % of slag can be mixed in the building materials without affecting their quality significantly. Trials[8] were also made to reuse the slag as flux simply by crushing it to the particle size of the original flux; however the chemistry of the deposited metal was not found within acceptable limits. Surface quality and slag detachability were also found inferior. Some researchers[9] tried to use a mixture of crushed slag and fresh flux as a replacement of fresh flux. They found that a slag-flux mixture containing only up to 20% slag can be utilised without affecting the quality of the end product. A complete elimination of slag can be achieved only by developing some technology using which the entire slag is recycled for its reuse as flux in the same process. Such a technology for recycling of slag generated during submerged arc cladding of SS has been developed by the authors. The flow chart of methodology used for recycling the slag has been presented in Figure 1. The details have been described in the proceeding paragraphs.

30 kg slag produced during stainless steel cladding in inner lining of a pressure vessel was taken from a reputed Indian industry. The slag was crushed and sieved so that its grains size distribution is similar to that of the original flux. Two separate weld pads were prepared using the crushed slag and the original flux (Adore S-33) as per the guidelines of ASME SFA 5.4/5.9/5.17 specifications. The schematic diagram of such a weld pad is shown in Figure 2. Boiler grade High Strength Low Alloy (HSLA) steel base plates (SA-516, Grade 70) of size 150×75×12 mm along with Subinox-309L (3.2 mm diameter) wire electrode of Adore made make were used for experimentation. A constant potential power source of transformer-rectifier type having 900 amperes current capacity at 100% duty cycle and open circuit voltage of 12-48 volts was employed. Welding current at 400 A, open circuit voltage at 26 V, travel speed at 0.55 m/min and nozzle to plate distance at 25 mm were maintained during the entire experimentation. Straight current reverse polarity was used. Chemical composition of top surfaces of both the weld pads was determined by spectroscopy. The results were critically analysed and compared with ASME specifications. Based on the infor-

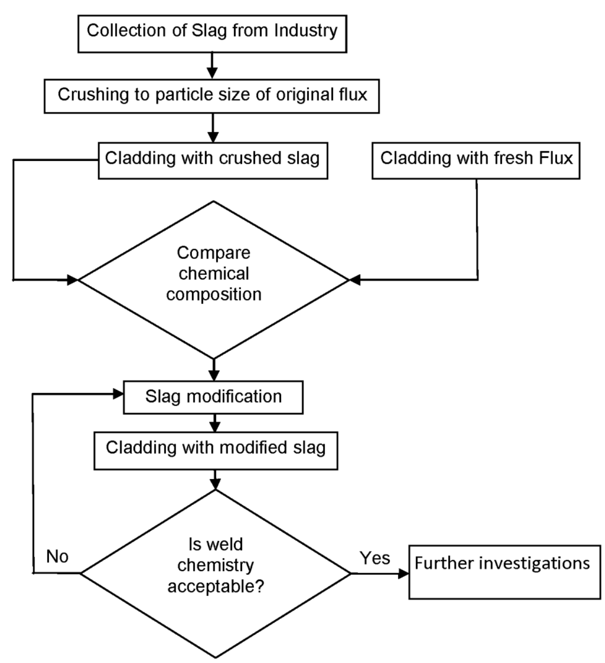

Figure 1. Flow diagram of methodology used for recycling the slag.

mation on loss and gain of elements provided by the above experiments, slag modification was carried out.

For modification/recycling, the slag was milled to a fine powder of 250 micron grain size using a ball mill. Alloying elements and deoxidisers were mixed with this powder and the mass was thoroughly mixed in a ball mill for 15 minutes. Liquid potassium silicate (20% solution) was added to the mass as binder. The wet mass was made to pass through a standard test sieve (ASTM 10 no.) to form pellets which were dried in open air for 24 hours. These pallets were baked for 2 hours in a muffle furnace at 800°C. The baked mass was crushed and sieved such that its particle size distribution is similar to that of the original flux. This mass was termed as "modified slag-*n*", where '*n*' is the trial number. The modified slag was then used to prepare a weld pad similar to the one prepared earlier (Figure 2). The chemical composition of the top surface of this weld pad was determined and compared with ASME specifications. Based upon the results of this comparison, the slag modification was repeated again, till the chemistry of the cladded metal satisfies ASME specifications. The modified slag composition corresponding to the final trial was termed as 'recycled slag'.

To ensure the quality of claddings produced using 'recycled slag', a proper evaluation of their mechanical, corrosion and other important properties were needed. For this purpose the claddings produced using recycled slag were subjected to ductility evaluation, corrosion test and microstructure/microhardness evaluation. In addition, the arc stability and slag detachability was also observed for every sample. The results indicated that various properties of claddings produced using recycled are at par with those produced using fresh flux.

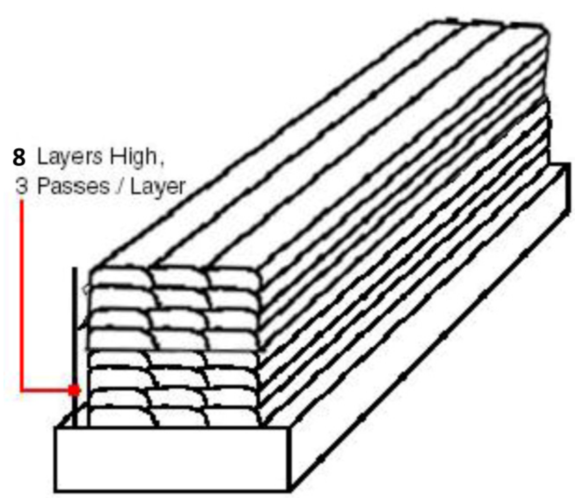

Figure 2. Schematic diagram of weld pad.

2.2 Development of Mathematical Model for Flux Consumption

Due to financial and time constraints it is practical, economic and sometimes essential to derive rules or conclusions by performing lesser number of experiments. Design of Experiment (DOE) is a structured, organized method for determining the significant and insignificant factors as well as the relationship between the different input factors affecting the outputs of a process by conducting optimum number of experimental runs[10,11]. For the present study, fractional (half) factorial design of experiment technique was used. The mathematical model for flux consumption was developed in following steps:-

2.2.1 Identification of Factors and Responses

Important independently controllable process parameters that has influence on welding quality in cladding, namely welding current (I), travel speed (S) and open circuit voltage (V) were chosen as controllable factors. Working range of these parameters was identified by conducting extensive trails runs. In addition to these factors type of flux (fresh flux vs. recycled slag) was chosen as a categorical factor and was denoted by 'T'. This addition factor was taken to investigate the effect of replacing fresh flux by recycled slag, on flux consumption. The upper and lower limits of these factors were coded as +1 and −1 respectively. Table 1 lists all these factors along with their upper and lower limits. Flux consumption in terms of weight of flux/recycled slag consumed per unit weight of metal deposited (kg/kg) was chosen as the response variable as was denoted as 'F_C'.

Table 1. Factors and their working ranges

Factor	Units	Notation	Upper Level (+1)	Lower Level (-1)
Open circuit voltage	Volts	V	38	30
Welding current	Amp.	I	550	400
Travel speed	m/min	S	0.76	0.4
Type of flux	--	T	Fresh flux	Recycled slag

2.2.2 Development of Design Matrix

Since there are 4 factors with 2 levels each, as per fractional factorial design principal the design matrix consists of eight ($2^{4-1} = 8$) experimental runs[9]. The design matrix developed for conducting the study has been presented in Table 2.

2.2.3 Conducting Experimentation as per the Design Matrix

The experiments were conducted as per the design matrix developed in the previous step. During experimentation it was ensured that runs were conducted at random and the settings of welding machine were disturbed intentionally after every run so as to avoid any systematic error to creep into the results. Single beads were deposited on boiler grade (SA-516, Grade 70) high strength low alloy steel (HSLA) base plate of size 150×75×12 mm. The surfaces of plates were thoroughly cleaned before making the deposits. Stainless steel Subinox-309L (3.2 mm diameter) wire electrode in combination with recycled slag/fresh flux (as per the design matrix) was used. Direct current electrode positive polarity was maintained. The complete set of eight trials was repeated thrice for the sake of determining the variance of parameters and variance of adequacy for the model.

2.2.4 Recording the Responses

The weight of flux or recycled slag consumed and the corresponding weight of metal deposited in each experimental run were recorded carefully. The ratio of these two values was taken as a measure of flux consumption i.e. the response variable (F_C). The results have been presented in Table 3.

Table 2. Design matrix for conducting the experiments

Trial No.	Factor Levels			
	V	T	I	S
1	+1	+1	+1	+1
2	-1	+1	+1	-1
3	+1	-1	+1	-1
4	-1	-1	+1	+1
5	+1	+1	-1	-1
6	-1	+1	-1	+1
7	+1	-1	-1	+1
8	-1	-1	-1	-1

2.2.5 Development of Mathematical Models

The response function can be expressed using Equation (1) given below:-

$$F_C = f\,(V, S, I, T) \quad (1)$$

The above relationship could be expanded as shown in Equation (2), given below:-

$$F_C = b_0 + b_1V + b_2S + b_3I + b_4T + b_{12}VS + b_{13}VI + b_{14}VT + b_{23}SI + b_{24}ST + b_{34}IT \quad (2)$$

where b_0 is the free term of regression equation, the coefficients b_1, b_2, b_3 & b_4 are linear terms, b_{12}, b_{13}, b_{23} etc. are interactive terms. Due to fractional nature of the design, some of the interaction affects are confounded. According to confounding pattern 12 = 34, 13 = 24 and 14 = 23, taking this into consideration the above model is reduced to:

$$F_C = b_0 + b_1V + b_2S + b_3I + b_4T + b_5(VS + IT) + b_6(VI + ST) + b_7(VT + SI) \quad (3)$$

2.2.6 Estimation of Coefficients and Testing their Significance

Equation (4) which is based on the method of least squares was used to calculate the regression coefficients for the selected model.

$$b_j = \frac{\sum_{i=j}^{N} X_j Y_i}{N}, \; j = 0,1\ldots,k \quad (4)$$

Where,

X_{ji}= Value of a factor or interaction in coded form.
Y_i= Average value of the response parameter.
N= Number of observations.
k= Number of coefficients of the model.

Table 3. Observed values of flux consumption

Trial No.	Flux Consumption (kg/kg)		
	1st Set	*2nd Set*	*3rd Set*
1.	1.0	0.8	0.95
2.	0.636	0.625	0.6
3.	1.0	0.9	0.91
4.	0.6428	0.73	0.66
5.	1.21	1.267	1.27
6.	1.143	1.11	1.1
7.	1.43	1.714	1.3
8.	1.06	1.0	1.0

The design matrix for calculating regression coefficients for the model is given in Table 4. The values of coefficients thus calculated gives an idea of the extent to which the factors affect the response.

The insignificance coefficients can be safely eliminated from the model without sacrificing the accuracy to large extent. The significance of the coefficients was tested by student's '*t-test*'. The value of '*t*' from the standard table for eight degree of freedom and 95% confidence level is 2.3. The coefficients having '*t*' value less than 2.3 are insignificant and hence were dropped in the final models. The coefficients of the model and their significance have been tabulated in Table 5.

2.2.7 Development of Final Model

The final mathematical model obtained by putting the values of various coefficients calculated in previous step and dropping the insignificant coefficients is given below in Equation (5).

$$Fc = 1.017 + 0.148\ V - 0.225\ I \quad (5)$$

2.2.8 Testing the Adequacy of Final Model

Adequacy of developed model was tested by conducting *F*-test. Third set of observed values was utilised in conducting this test by Analysis of Variance (ANOVA) technique. The predicted and observed values have been tabulated in Table 6.

3. Results and Discussion

From the results of *F*-test, tabulated in Table 7, the developed model was found to be adequate within 95% confidence level. A scatter diagram drawn between the observed and predicted values of flux consumption is shown in Figure 3. From the diagram it can be clearly seen that the predicted and observed values of flux consumption are in close agreement with each other, which indicates a perfect fit of the empirically developed model.

The model thus developed was used to investigate the effects of various parameters on the consumption of flux/recycled slag. The relationships between responses and factors were derived at the middle value of other variables (by putting 0 for their middle values in coded form). These results have been discussed in details in the following subsections.

Table 5. Coefficients of the model and their significance

Coefficient	b_0	b_1 V	b_2 T	b_3 I	b_4 S	b_5 (VT)	b_6 (VI)	b_7 (VS)
Value	1.017	0.148	-0.043	-0.225	-0.054	-0.053	-0.015	0.016
't' Value	30.07	4.39	-1.27	-6.66	1.61	-1.57	-0.45	0.48
Significant	Yes	Yes	No	Yes	No	No	No	No

Table 6. Predicted and observed values of response

Flux Consumption (kg/kg)	Trial No.							
	1	2	3	4	5	6	7	8
Predicted	0.94	0.64	0.94	0.64	1.39	1.09	1.39	1.09
Observed	0.95	0.6	0.91	0.66	1.27	1.1	1.3	1.0

Table 7. Applying the F-test on the model for testing its adequacy

Variance of optimising parameter (S_y^2)	*SD of Coefficient* (S_{bj})	*Variance of adequacy* (S_{ad}^2)	*F-ratio model* $F_m = \frac{S_d^2}{S_y^2}$	*F-ratio from table* (F_t)	*If model adequate* $F_m < F_t$
0.00914	0.03381	0.023	2.51	4.12	Yes

Table 4. Design matrix for calculating the coefficients

Trial No.	b_0	b_1 *V*	b_2 *T*	b_3 *I*	b_4 *S*	b_5 *(VT+IS)*	b_6 *(VI+TS)*	b_7 *(VS+TI)*	Responses		
									p^{I}	p^{II}	p^{mean}
1	+1	+1	+1	+1	+1	+1	+1	+1	1	0.8	0.9
2	+1	-1	+1	+1	-1	-1	-1	+1	0.636	0.625	0.6305
3	+1	+1	-1	+1	-1	-1	+1	-1	1	0.9	0.95
4	+1	-1	-1	+1	+1	+1	-1	-1	0.643	0.73	0.6865
5	+1	+1	+1	-1	-1	+1	-1	-1	1.21	1.267	1.2385
6	+1	-1	+1	-1	+1	-1	+1	-1	1.143	1.11	1.1265
7	+1	+1	-1	-1	+1	-1	-1	+1	1.43	1.714	1.572
8	+1	-1	-1	-1	-1	+1	+1	+1	1.06	1	1.03

3.1 Effect of Open Circuit Voltage (V) on Flux Consumption

Since the value of coefficient associated with open circuit voltage (V) in the developed model is positive. It means that there is positive effect of increase in V on the flux consumption. In other words it signifies that the flux consumption increases with an increase in open circuit voltage. It can also be clearly seen in the plot of flux consumption vs. open circuit voltage presented in Figure 4. The graph reveals that the flux consumption increases from 0.869 to 1.165 kg/kg with the increase in V from 30 to 38 volts.

It is a well known fact that changes in voltage affects the shape of the weld bead without significantly affecting the melting rate[5]. Increase in arc voltage causes an increase in the arc length and hence an increase in the spread of the arc[12] as shown in Figure 5. It causes larger amount of flux coming in contact with the arc thereby increasing the flux consumption[13]. Further at lower voltage arc remains smaller and stiffer, which results in a smaller arc envelope and hence lesser flux consumption[5]. The results are in agreement with the findings of other researchers[14].

3.2 Effect of Welding Current (I) on Flux Consumption

The developed model shows that there is a negative effect of welding current on the flux consumption. It means that the flux consumption decreases with an increase in the welding current.

Based upon the developed mathematical model, the effect of welding current on the flux consumption has been presented graphically in Figure 6, which clearly

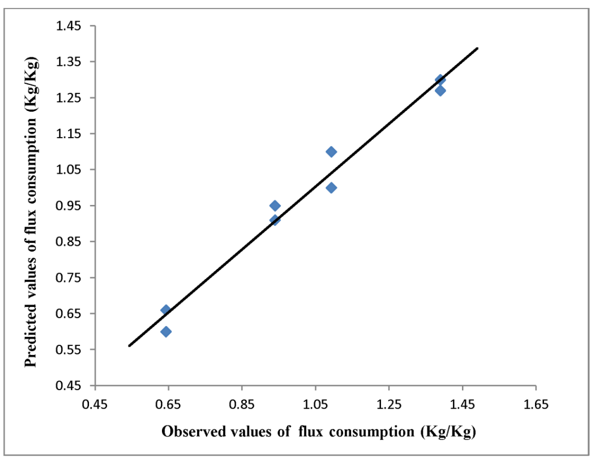

Figure 3. Scatter diagrams between observed and predicted values of flux consumption.

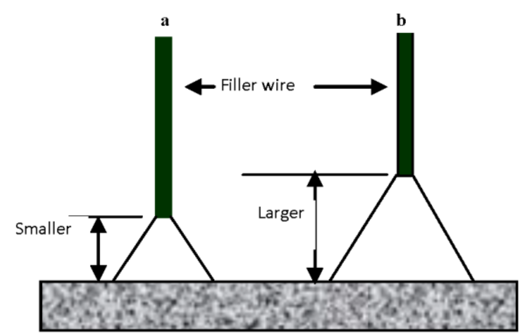

Figure 5. Arc shape at **(a)** Lower arc voltage **(b)** Higher arc voltage.

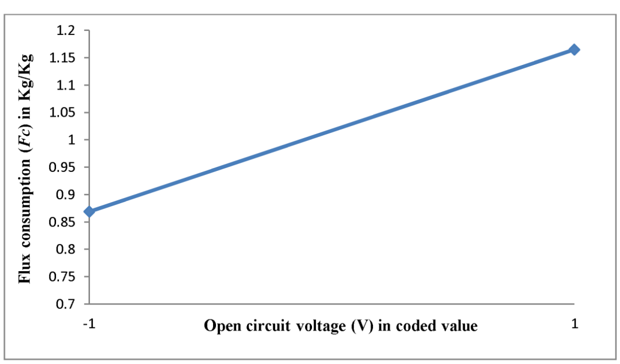

Figure 4. Effect of open circuit voltage (V) on flux consumption.

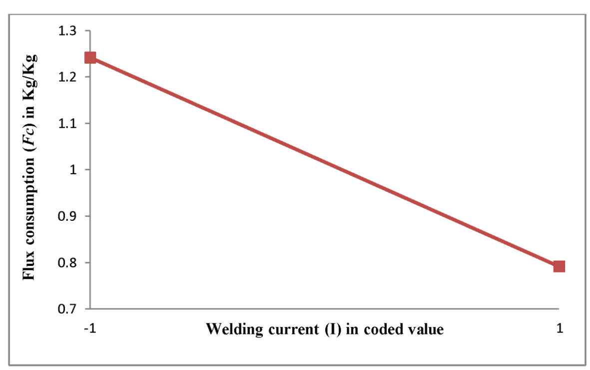

Figure 6. Effect of welding current (I) on flux consumption.

shows an inverse relation between the Flux Consumption (F_C) and welding current (I).

The inverse relationship between welding current and flux consumption is due to the fact that with the increase in welding current the wire feed rate and hence the metal deposition per unit length of the weld increases, but the flux melting do not increase to that extent and consequently the overall ratio of flux consumption to the metal deposited decreases[12–15]. 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, which in turn reduces the flux consumption[13].

3.3 Effect of Travel Speed on Flux Consumption

In the developed mathematical model, the coefficient corresponding to travel speed was found insignificant and hence has been dropped from the final model. In other words as per the developed model, the flux consumption remains independent of the travel speed (S).

With higher welding speed, the weld bead becomes narrow and simultaneously the length of the weld covered per unit time becomes longer[16]. It results in a decrease in metal deposition per unit length of the weld. At the same time due to decreased width and arc heat input, the amount of flux melted per unit length also decreases[13,15]. Therefore the net effect is a negligible change in the overall flux consumption rate[5].

3.4 Effect of Recycled Slag on Flux Consumption

From the final mathematical model for flux consumption presented in Equation (5), it can be seen that the term corresponding to type of flux used (T), being insignificant, does not appear in the final model. It proves that the use of recycled slag as replacement of fresh flux does not produce any adverse effect on the flux consumption or in other words the recycled slag is equivalent to fresh flux in its flux consumption behavior.

4. Conclusions

From the results of the above study the following conclusions can be drawn:

- In submerged arc cladding of stainless steel, the replacement of fresh flux with recycled slag does not produce any significant effect on its flux consumption behaviour.
- The results of *F*-test and the scatter diagram drawn between observed and predicted values of flux consumption prove that the developed mathematical model is able to predict the consumption of recycled slag with reasonable accuracy.
- The consumption of recycled slag increased from 0.869 to 1.165 kg/kg with an increased in open circuit voltage (V), which is due to spread of arc cone and thereby an increase in proportion of recycled slag coming in contact with the arc.
- The consumption of recycled slag shows a negative trend with welding current (I). The consumption decreased from 1.295 to 0.792 Kg/Kg with increase in welding current from 400 to 550 A.
- The welding speed has an insignificant effect on consumption of recycled slag.

5. References

1. Magram SF. Worldwide solid waste recycling strategies: A review. Indian Journal of Science and Technology. 2011 Jun; 4(6):692–702.
2. Dhanda U, Gupta S. Exploring the go green mantra in India. Indian Journal of Science and Technology. 2015 Feb; 8(S4):247–58.
3. Mahendran K, Arunachelam N. Performance of fly ash and copper slag based geopolymer concrete. Indian Journal of Science and Technology. 2016 Jan; 9(2):1–6.
4. Garg J, Singh K. Slag recycling in submerged arc welding and its effects on the quality of stainless steel claddings. Materials and Design. 2016; 108:689–98.
5. Sharma A, Arora N, Mishra BK. Mathematical modeling of flux consumption during twin-wire welding. Int J Adv Manuf Technol. 2008; 38(11):1114–24.
6. Chandel RS. The effect of process variables on the flux consumption in submerged arc welding. Mater Manuf Process. 1998; 13(2):181–8.
7. Viana CE, Dias DP, De Holanda JNF, Paranhos RPDR. The use of submerged-arc welding flux slag as raw material for the fabrication of multiple-use mortars and bricks. Soldag Inspecao. 2009; 14(3):257–62.
8. Garg J, Singh K. Reuse of slag in stainless steel cladding and its effect on chemistry of claddings. Journal of Environmental Research and Development. 2012; 3(A):674–80.
9. Datta S, Bandyopadhyay A, Pal PK. Solving multi-criteria optimization problem in submerged arc welding consuming a mixture of fresh flux and fused slag. Int J Adv Manuf Technol. 2008; 35(9-10):935–42.

10. Adler YP. The design of experiments to find optimal conditions. Moscow: Mir Publishers; 1975.
11. Montgomery DC. Design and analysis of experiments. 8th ed. Singapore: John Wiley and Sons Inc; 2012.
12. Yawar J, Lal H. Effect of various parameters on flux consumption, carbon and silicon in submerged arc welding. International Journal on Emerging Technologies. 2015; 6(2):176–80.
13. Kumar V. Use of response surface modeling in prediction and control of flux consumption in submerged arc weld deposits. Proceedings of the World Congress on Engineering and Computer Science, WCECS 2011; San Francisco, USA. 2011.
14. Jackson CE. Fluxes and slags in welding. Welding Research Council Bulletin. 1973; 190:1–25.
15. Singh J, Singh CD, Khamba JS, Singh FP. Influence of welding parameters on flux consumption in submerged arc welding. International Journal for Multi Disciplinary Engineering and Business Management. 2014; 2(1):1–3.
16. Gupta SR, Gupta PC, Reddy PC. Investigation into flux consumption in submerged arc welding. Indian Weld J. 1988; 365–9.