Study the Effect of SiO₂ Based Flux on Dilution in Submerged Arc Welding

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Abstract: This paper highlights the method for prediction of dilution in submerged arc welding (SAW). The most important factors of weld bead geometry are governed by the weld dilution which controls the chemical and mechanical properties. Submerged arc welding process is used generally due to its very easy control of process variables, good penetration, high weld quality, and smooth finish. Machining parameters, with suitable weld quality can be achieved with the different composition of the flux in the weld. In the present study SiO₂-Al₂O₃-CaO flux system was used. In SiO₂ based flux NiO, MnO, MgO were mixed in various proportions. The paper investigates the relationship between the process parameters like voltage, % of flux constituents and dilution with the help of Taguchi's method. The experiments were designed according to Taguchi L9 orthogonal array, while varying the voltage at two different levels in addition to alloying elements. Then the optimal results conditions were verified by confirmatory experiments.

Keywords: Optimization, Dilution, SAW, Taguchi analysis, ANOVA

1. INTRODUCTION

Submerged arc welding process is most widely used for heavy industrial application and structural work. The popular one is ship fabrication, welding of pipes, heavy structural work, and power systems. Weld is considered to be strong, if free from hydrogen induced cracking, fatigue failure and resistant to corrosion. In SAW weld quality is generally decided by selection of wire diameter and composition of the flux together with welding parameters. As per literature survey, the flux composition and selection of electrode decide the strength of welded joint [1]. Important characteristics such as better slag detachability, stability of arc and good penetration increases with the increase of percentage of SiO₂ in the flux. [2]. Manganese fluxes and calcium silicate fluxes give lower residuals of sulphur and remove phosphorous from the weld pool respectively [3]. SiO₂ and TiO₂ based flux increases heat input, and decreases the mechanical properties of the weld for 1.25Cr-.05Mo steel. [4]. In TIG welding high arc voltage is necessary when using SiO₂ based flux [5]. Acicular ferrite in microstructure of weld is controlled by CaO which is responsible for good mechanical properties such as ductility and impact strength [6]. Chemical transfer in slag and weld metal was due to the wire/flux combination and chemical composition of the flux, the same was investigated and interpreted for better tensile strength and impact strength of weld metal [7]. FeO content of the slag is responsible for the oxygen level in basic flux whereas low level of oxygen is desired in the weld metal for good impact strength, due to SiO₂ decomposition in acidic flux [8].
Commercial available fluxes were compared with the chemical composition of some flux along with microstructure and tensile strength in submerged arc welding [9]. The effect of the chemical composition of fluxes for submerged arc welding is well explained by using X-RD and DTA technology [10]. In gas metal arc welding three kinds of oxides fluxes were used to study the effect of activating flux on mechanical properties in AISI 1020 carbon steel [11]. A study of SiO₂ based flux shows that mechanical properties of the weld are good for this type of flux. [12]. Varying MnO, MnO and Fe-Cr content in the flux lead to achieve the desired hardness limit in the weld metal [13]. Increase in MnO, MgO, and Fe-Cr content improves a ductility of weld metal[14]. Weld bead properties such as weld bead width and penetration can be optimized using rutile based flux constituents by Taguchi analysis in submerged arc welding[15]. Silica based flux can be used to optimize the Vickers hardness and Impact strength in submerged arc welding by Taguchi analysis[16]. Fuzzy logic and ANOVA analysis can be used to optimize the Vickers hardness and Impact Strength of Submerged arc welding based on the flux constituents such as NiO, MnO and MgO[17]. Hybrid Grey, Fuzzy and Taguchi analysis can be effectively used to optimize the Vickers hardness, Impact strength and Ultimate tensile strength in submerged arc welding [18].

The bead geometry as shown in figure.1 consists of weld bead width (W), penetration (P), reinforcement(R) etc., that judges the quality of the weld and responsible for overall stress carrying capacity of welded joint. The most important feature is the weld dilution among many of these features of weld bead geometry.

By definition it is the ratio between the areas of reinforcement to the total area of weldment also known as percentage dilution? The weld bead geometry which determines the dilution plays an important role in determining the mechanical properties of the weld. To obtain the desired dilution, it is necessary to have a control on the process control parameters. Controlling of dilution is one of the major requirements for a successful welding process as the composition and properties of the weld deposit have a very strong relationship with the dilution. The purpose of this paper is to develop relationship between the process control parameters and composition of the flux on dilution of weld bead made by submerged arc welding (SAW) using Taguchi’s principle.

2. DESIGN OF FLUX

Taguchi method is used in experimental design to reduce the number of experiments to an optimum level. In the present research work SiO₂ is considered as the base of flux. NiO, MnO and MgO were varied at three different levels. Degree of freedom is the base for proper selection of orthogonal array in experimental design. The degree of freedom for each flux constituents is one less than the level of constituents. So in the present situation, the total degree of freedom for all three factors is 6. Because 2 degrees of freedom is assigned for each three factor, and 2 degrees of freedom is assigned to error terms, so total of freedom becomes 8. Number of experiments can never be less than the total degree of freedom. L9 orthogonal array was selected which has nine (9) numbers of runs in the present situation. Two different voltage conditions were decided for nine experimental run for SiO₂ based flux by varying alloying elements NiO, MnO and MgO in different combinations as per the design.

3. EXPERIMENTAL CONDITION

Total 18 experiments, with all SiO₂ based flux constituents were conducted, because as per our design 9 experiment for each voltage condition were supposed to be performed. A bead on plate
arrangement as shown in Figure 1. was used on a constant voltage DC Submerged Arc welding machine for mild steel plate of dimensions 300x150x22 mm$^3$ with 3.15 mm wire diameter having a grade of EL 8 DIN 8557:SI. Before performing the welding operation the plates were cleaned mechanically with the brush to remove the dust from the plates. The open circuit voltage was kept 32V and 34V constant for all the experiments. Speed of trolley was kept at 20 cm/min. Electrode and plate distance was 2.5 mm. Other welding conditions are shown in Table 1.

| Welding Parameters       | Unit | Value   |
|--------------------------|------|---------|
| Voltage (OC)             | V    | 32,34   |
| Speed of trolley         | cm/min. | 20     |
| Electrode to plate distance | mm   | 2.5     |
| Flux                     |      | SiO$_2$ Based |

4. METHOD OF ANALYSIS

After the experimental runs the slag was removed from the plates. Transverse section was taken from the center of the plate; this portion was polished with different grades of emery papers and finally etched with 2% of natal solution to get the bead geometry parameters as shown in “Figure. 1,” The results of measurements so obtained are presented in Table 2.

So many factors are involved in the process some of them are controlled and others are uncontrolled. The uncontrolled factors can affect the output of the process so these factors are termed as noise factors, where as our responses are called as signal. The ratio of signal to noise is called as variation of index. This is of three types such as lower is better, higher is better and nominal is better. In our case only two types of S/N ratio is used. The variation present in the response leads to information about control factors that decrease the variation and this only can enhance the quality of the process. In the present experiments the percentage dilution is the measured response.
For smaller is better $\frac{S}{N} = -10 \log_{10} \left\{ \frac{\sum_{i=1}^{n} y_i^2}{n} \right\}$ (1)

For higher is better $\frac{S}{N} = -10 \log_{10} \left\{ \frac{n}{\sum_{i=1}^{n} \left( \frac{1}{y_i^2} \right)} \right\}$ (2)

In this experimental study higher is the better S/N is used for % dilution as shown by equation no. 2. Where $Y_i =$ Result of experimental observation; $m =$ target value; and $n =$ Number of experiments. The Figure 1 shown above represents the weld bead cross section. The various dimension measured are weld bead width, penetration and reinforcement for both types of flux. The analysis has been performed for percentage dilution and the results are tabulated in Table no 2. The total area of weld bead is the sum of area of penetration and area of reinforcement. Dilution can be calculated by these areas, as given by the equation 3.

$$\text{% Dilution} = \left( \frac{\text{Area of Penetration}}{\text{Total Area}} \right) \times 100$$ (3)

The three flux constituents were varied in SiO$_2$ types of flux the effect of all the three flux constituents on percentage dilution was the objective of the study. In the Table 2, data related to percentage dilution of SiO$_2$ flux along with S/N ratio is shown at two different voltage conditions. Design matrix along with the quantity of flux constituents used in the experimental work is also shown in the Table 2.

| S.No | Design matrix | 32V | 34V |
|------|---------------|-----|-----|
|      | NiO | MnO | MgO | % Dilution | S/N Ratio | % Dilution | S/N Ratio |
| 1    | 60  | 50  | 85  | 32.59       | 30.26169  | 50.30      | 34.03136  |
| 2    | 60  | 70  | 95  | 36.72       | 31.29805  | 49.59      | 33.90788  |
| 3    | 60  | 90  | 105 | 34.25       | 30.69321  | 63.76      | 36.09097  |
| 4    | 80  | 50  | 95  | 54.95       | 34.79935  | 45.03      | 33.07004  |
| 5    | 80  | 70  | 105 | 47.98       | 33.6212   | 52.80      | 34.45268  |
| 6    | 80  | 90  | 85  | 44.55       | 32.97695  | 53.89      | 34.63016  |
| 7    | 100 | 50  | 105 | 49.61       | 33.91138  | 54.95      | 34.79935  |
| 8    | 100 | 70  | 85  | 48.09       | 33.6411   | 46.53      | 33.35466  |
| 9    | 100 | 90  | 95  | 51.96       | 34.31338  | 52.34      | 34.37667  |

5. RESULT AND DISCUSSION
A. Effect of NiO, MnO and MgO on percentage dilution of SiO$_2$ Flux at 32V
Table 3 represents the analysis of variance for percentage dilution at 32V in case of SiO$_2$ flux at 95% confidence level. The value of F i.e variance value to be compared with $F_{cr}$ that can be found from the Table as Annexure A as follows:

$$F_{cr} = F_{c.l,n1,n2} = F_{0.05,2,8} = 4.46$$

| Source   | DF | Seq SS  | Adj SS  | Adj MS  | F    | P     | % Contribution |
|----------|----|---------|---------|---------|------|-------|----------------|
| NiO      | 2  | 450.992 | 450.992 | 225.496 | 61.07| 0.016 | 86.16          |
| MnO      | 2  | 7.107   | 7.107   | 3.553   | 0.96 | 0.51  | 1.35           |
| MgO      | 2  | 57.917  | 57.917  | 28.959  | 7.84 | 0.113 | 11.06          |
| Residual | 2  | 7.385   | 7.385   | 3.693   |      |       |                |
| Total    | 8  | 523.402 | 7.385   | 3.693   |      |       | 100            |

From the ANOVA, it can be concluded that NiO and MgO are the significant factors affecting the percentage dilution at 32V in case of SiO$_2$ flux. Since the F value of these factors are higher than the $F_{cr}$, MnO is not significant as its F-value is less than $F_{cr}$ value. The analysis is correct since the corresponding p values are higher. Contribution of the error term, in this case, is 1.41%. The % percentage contribution of NiO is the highest followed by the MgO and MnO.

Main effect plot for S/N ratio of percentage dilution at 32V in the case of SiO$_2$ flux is shown in Figure 2. It is desirable to maximize the dilution so larger the better for S/N ratio option was selected.

Figure 2 Main effect plots for SN ratio percentage dilution (32V, SiO$_2$)
Table 4 Signal to noise ratios for percentage dilution taking it as “Larger is better”

| Level | NiO | MnO | MgO |
|-------|-----|-----|-----|
| 1     | 30.75 | 32.99 | 32.29 |
| 2     | 33.8 | 32.85 | 33.47 |
| 3     | 33.96 | 32.66 | 32.74 |
| Delta | 3.2 | 0.33 | 1.18 |
| Rank  | 1 | 3 | 2 |

Table 4 shows response Table for signal to noise ratio for percentage dilution at 32V in case of SiO$_2$ flux. It clearly indicates the effect of various input factors on percentage dilution in the sequence of its effect are NiO, MgO, and MnO. That means NiO affects the percentage dilution at the most.

B. Effect of NiO, MnO and MgO on percentage dilution of SiO$_2$ Flux at 34V

Table 5 represents the analysis of variance for percentage dilution at 34V in case of SiO$_2$ flux at 95% confidence level. The value of F i.e variance value to be compared with F$_{cr}$ that can be found from the Table as Annexure A as follows;

\[ F_{cr} = F_{c.l.n1,n2} = F_{0.05,2,8} = 4.46 \]

Table 5 Analysis of Variance for Means for percentage dilution for SiO$_2$ flux at 34V

| Source   | DF | Seq SS | Adj SS | Adj MS | F    | P   | % Contribution |
|----------|----|--------|--------|--------|------|-----|----------------|
| NiO      | 2  | 27.04  | 27.04  | 13.52  | 13.07| 0.071| 11.34          |
| MnO      | 2  | 92.7   | 92.698 | 46.349 | 44.79| 0.022| 38.88          |
| MgO      | 2  | 116.6  | 116.56 | 58.281 | 56.32| 0.017| 48.899         |
| Residual Error | 2  | 2.07  | 2.07   | 1.035  |      |     | 0.86           |
| Total    | 8  | 238.4  |        |        |      |     |                |

From the ANOVA, it can be concluded that NiO, MnO and MgO are the significant factors affecting the percentage dilution at 34V in case of SiO$_2$ flux. Since the F value of these factors are higher than the F$_{cr}$, The analysis is correct since the corresponding p-values are higher. Contribution of the error term, in this case, is 0.86 %. The % percentage contribution of MgO is the highest followed by the MnO and NiO.

Figure 3 Main Effect plot for SN ratio percentage dilution (34V, SiO$_2$)
Main effect plot for S/N ratio of percentage dilution at 34V in the case of SiO$_2$ flux is shown in Figure 3. It is desirable to maximize the dilution so larger the better for S/N ratio option is selected. The highest level of MnO, MgO and the lowest level of NiO are the optimized value at 34V for SiO$_2$ flux.

Table 6 Signal to Noise Ratios for Dilution taking it as “Larger is better”

| Level | NiO   | MnO   | MgO   |
|-------|-------|-------|-------|
| 1     | 34.68 | 33.97 | 34.01 |
| 2     | 34.05 | 33.91 | 33.78 |
| 3     | 34.18 | 35.03 | 35.11 |

Delta: 0.63  
Rank: 3  

Table 6 shows response Table for signal to noise ratio for percentage dilution at 34V in case of SiO$_2$ flux. It clearly indicates the effect of various input factors on percentage dilution in the sequence of its effect are MgO, MnO and NiO. The rank in the Table indicates the order of level of influences of factors.

6. VERIFICATION OF TAGUCHI RESULTS

Based on the ANOVA and S/N graph level of flux constituents are determined. These optimal findings need verification. The equation used for the calculation of optimal result is

$$\eta_{opt} = \eta_m + \sum_{i=1}^{a} (\eta_i - \eta_m)$$

Where $\eta_m$ = Total means of S/N ratio  
$\eta_i$ = Means S/N Ratio at optimal level  
a = number of design parameter that effect quality characteristics

Comparison between the predicated and observed experimental value for % dilution are tabulated in table no 7.

TABLE 7 Result of confirmatory test for % Dilution

| Voltage | Initial welding parameter | Optimal welding parameter | % increase in % Dilution |
|---------|---------------------------|----------------------------|--------------------------|
| 32V     | LEVEL % Dilution A2B2C2  | A3B1C2                     | A2B3C3                   |
|         | 46.53                     | 55.00                      | 57.21                    |
|         | 2.21 %                    |                            |                          |
| 34V     | LEVEL % Dilution A2B2C2  | A1B3C3                     | A2B1C1                   |
|         | 50.4                      | 63.99                      | 65.20                    |
|         | 1.21%                     |                            |                          |

7. CONCLUSION

For SAW, the effect of NiO,MnO and MgO as alloying elements in SiO$_2$ based flux was revealed experimentally. Result of study shows that NiO is most influential elements at 32V,
with % contribution of 86.16 % where as it is least significant at 34V for % dilution of the weld. At 34V MgO has played dominant role with a contribution of 48.89 % in deciding % dilution of the weld.

For both voltage levels optimal values of NiO,MnO and MgO were selected by S/N analysis. Verification of optimal results obtained for VHN and impact strength at selected optimal levels has shown a remarkable improvement when compared with the predicted as well as initial welding parameters.

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