Experimental investigation and optimization of weld bead shape factor and form factor using recycled steel slag as a flux in submerged arc welding process

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Abstract. The quality and productivity of welds produced depend upon the weld bead profile which is represented by weld penetration shape factor (WPSF) and weld reinforcement form factor (WRFF). The weld profile is further dependent upon welding parameters used hence optimization of welding parameters is essential. In this research work, the steel slag has been recycled to act as a flux in submerged arc welding. The effect of process parameters on WPSF and WRFF using recycled slag has been evaluated. The mathematical models have been developed from the data created. It was found that the weld deposited with recycled steel slag performs well as the WPSF and WRFF are comparable with that deposited with fresh flux. The welding parameters have been optimized using the desirability approach and genetic algorithm. The genetic algorithm yielded more accurate results as compared to the desirability approach.

Keywords: Recycling, steel slag, welding, bead geometry

1. Introduction

Steel slag is normally thrown as a waste which creates soil and air pollution apart from the need for landfill space for dumping. The chemicals, oxides, and minerals present in it are also wasted. There is a need for a methodology to trap these oxides, minerals going waste along with slag and convert them into a useful product. It will not only mitigate the dumping of slag but also save non-renewable resources. In present research work, a methodology was developed to convert steel slag into useful flux required for submerged arc welding process. The performance of flux produced in terms of WPSF and WRFF has been evaluated and presented in this paper. The chemistry of weld metal deposited with recycled has already been evaluated and published by the authors [1].

The load-bearing capacity of the welds produced depends upon the bead profile [2]. The bead profile can be represented by penetration, weld width and reinforcement. The weld penetration shape factor (WPSF) is well-defined as the ratio of bead width to weld penetration. Similarly, bead width to weld reinforcement is termed as weld reinforcement form factor (WRFF). The elements representing bead profile have been shown in Figure 1. The welds produced having WPSF less than one are prone to centerline solidification crack which is termed as ingotism. The problem of ingotism can be tackled by changing the welding procedure to obtain columnar grain structure [3]. Reference [4] found that welds produced having shape factor in the range of 1.3 to 2.0 provided improved mechanical properties due to freedom from ingotism defect. To avoid centerline cracking, it is necessary to keep the weld penetration shape factor from 1.0 to 1.4 [5]. The smoothness of the weld improves with an increase in the weld reinforcement form factor. This is due to fact that an increase in form factor, angle of convexity (α) decreases. For better mechanical properties, the value of the weld
reinforcement form factor should vary between 2.0 to 7.0. The properties of the molten pool, slag and the gaseous phases under the arc have a pronounced effect on the weld form factor. Researcher obtained the form factor value of 2.0 at 800 amperes and 35 volts using a 5.0 mm diameter electrode [4]. The lower form factor is undesirable because it causes stress concentration at the weld toe where reinforcement merges with the top surface of the workpiece [6]. The mechanical properties of welded joints depend upon welding parameters [7]. The weld shape factor and form factor affect the performance of weld during service particularly the fatigue strength, hence optimization of welding parameters is essential.

\[ WPSF = \frac{w}{p} \]
\[ WRFF = \frac{w}{r} \]

where,
- \( p \) = Penetration
- \( r \) = Reinforcement
- \( w \) = weld width
- \( \alpha \) = Angle of convexity
- \( \beta \) = Angle of entry

2. Methodology

The following steps were adopted to complete the research work:

2.1. Recycling of steel slag

The slag generated by the steel plant was collected from their dumping yard free of cost as it is a waste for them. The collected slag was crushed in a mechanical crusher and milled in a ball mill to convert it into powdered form (30 mesh size). Then the necessary alloying elements and deoxidizers in powdered form were added and dry mixed for 30 minutes to get a homogeneous mixture. Then liquid potassium silicate was added as a binder to get the wet mixture [13]. Then, this wet mixture was passed through the 10-mesh size sieve to obtain pellets. These pellets of the wet mixture were air-dried for 24 hours followed by baking in a muffle furnace at 800°C for 4 hours. After baking the baked mass was passed through a sieve of 10 mesh size to get granular flux known as “Recycled slag”. Then the recycled slag in combination with EH 14 filler wire having a diameter of 3.14 mm was used to deposit beads on plates.

2.2. Identification of welding parameters and their working range:

To determine the welding parameters and their working range, extensive test runs were carried out, which are listed in Table 1.
Table 1. Input process parameters having lower and higher values

| Parameter          | Units | Symbols | -2 | -1 | 0  | +1 | +2 |
|--------------------|-------|---------|----|----|----|----|----|
| Welding current    | A     | I       | 250| 350| 450| 550| 650|
| Welding speed      | m/h   | S       | 16 | 20 | 24 | 28 | 32 |
| Arc voltage        | V     | V       | 20 | 23 | 26 | 29 | 32 |
| Nozzle to Plate    | mm    | N       | 20 | 22 | 24 | 26 | 28 |

2.3. Development of design matrix:

The central composite rotatable design has been adopted for this study. As dictated by this technique, the design matrix developed is indicated in Table 2.

Table 2. Design matrix along with responses

| S.N  | Factors | Responses |
|------|---------|-----------|
|     | I (A)   | S(m/h)    | V(V) | N (mm) | p (mm) | w (mm) | r(mm) | WPSF | WRFF |
| 1    | 350     | 20       | 22   | 22     | 5.67   | 6.77   | 6.23  | 1.194| 1.086|
| 2    | 550     | 20       | 22   | 22     | 8.85   | 9.68   | 4.96  | 1.093| 1.951|
| 3    | 350     | 28       | 22   | 22     | 6.00   | 8.5    | 4.56  | 1.416| 1.864|
| 4    | 550     | 28       | 22   | 22     | 6.97   | 6.62   | 5.00  | 0.949| 1.324|
| 5    | 350     | 20       | 22   | 22     | 6.28   | 15.11  | 3.78  | 2.406| 3.997|
| 6    | 550     | 20       | 22   | 22     | 10.95  | 13.25  | 4.37  | 1.210| 3.032|
| 7    | 350     | 28       | 22   | 22     | 5.20   | 11.82  | 2.99  | 2.273| 3.953|
| 8    | 550     | 28       | 22   | 22     | 9.49   | 7.26   | 5.06  | 0.765| 1.434|
| 9    | 350     | 20       | 26   | 26     | 5.97   | 6.95   | 6.11  | 1.164| 1.137|
| 10   | 550     | 20       | 26   | 26     | 7.21   | 7.31   | 6.5   | 1.013| 1.124|
| 11   | 350     | 28       | 26   | 26     | 6.33   | 10.71  | 4.05  | 1.691| 2.644|
| 12   | 550     | 28       | 26   | 26     | 6.29   | 8.31   | 6.57  | 1.321| 1.264|
| 13   | 350     | 20       | 26   | 26     | 5.32   | 14.57  | 3.04  | 2.738| 4.792|
| 14   | 550     | 20       | 26   | 26     | 9.37   | 9.56   | 5.51  | 1.022| 1.735|
| 15   | 350     | 28       | 26   | 26     | 4.73   | 13.21  | 2.67  | 2.792| 4.947|
| 16   | 550     | 28       | 26   | 26     | 7.66   | 8.89   | 6.7   | 1.160| 1.326|
| 17   | 250     | 24       | 26   | 24     | 4.21   | 11.19  | 2.52  | 2.657| 4.440|
| 18   | 650     | 24       | 26   | 24     | 9.77   | 7.78   | 5.92  | 0.796| 1.314|
| 19   | 450     | 16       | 26   | 24     | 7.67   | 11.23  | 6.84  | 1.464| 1.641|
| 20   | 450     | 32       | 26   | 24     | 6.43   | 9.09   | 5.23  | 1.413| 1.738|
| 21   | 450     | 24       | 20   | 24     | 4.43   | 8.85   | 6.05  | 1.997| 1.462|
| 22   | 450     | 24       | 32   | 24     | 6.04   | 17.11  | 4.12  | 2.832| 4.152|
| 23   | 450     | 24       | 26   | 20     | 7.91   | 10.12  | 2.85  | 1.279| 3.550|
| 24   | 450     | 24       | 26   | 28     | 7.87   | 9.22   | 5.11  | 1.171| 1.804|
| 25   | 450     | 24       | 26   | 24     | 8.33   | 8.36   | 5.95  | 1.003| 1.405|
| 26   | 450     | 24       | 26   | 24     | 8.04   | 7.13   | 6.01  | 0.886| 1.186|
| 27   | 450     | 24       | 26   | 24     | 8.48   | 6.48   | 6.46  | 0.764| 1.003|
| 28   | 450     | 24       | 26   | 24     | 7.87   | 7.05   | 6.11  | 0.895| 1.153|
| 29   | 450     | 24       | 26   | 24     | 8.33   | 6.55   | 6.35  | 0.786| 1.031|
| 30   | 450     | 24       | 26   | 24     | 9.55   | 7.35   | 6.56  | 0.769| 1.120|
| 31   | 450     | 24       | 26   | 24     | 7.34   | 7.55   | 6.23  | 1.028| 1.211|

2.4. Conducting the experiments:

A total no. of 31 beads on plates were deposited as dictated by the design matrix using Ador Fontech make submerged arc welding machine. The SA 516 grade 70 with a thickness of 12 mm was used as the base
material. This material is extensively used for the fabrication of boilers, pressure vessels and heat exchangers [8]. The filler wire EH-14 was used in combination with flux manufactured using steel slag as raw material. The chemical composition of base material and filler wire is given in Table 3.

Table 3. Chemical composition of base metal and filler wire

| Material used       | C     | Mn    | Si    | P    | S    |
|---------------------|-------|-------|-------|------|------|
| SA 516 grade 70     | 0.10  | 1.17  | 0.6   | 0.03 | 0.03 |
| EH 14 filler wire    | 0.14  | 1.70  | 0.10  | 0.03 | 0.03 |

2.5. Recording the responses:
A specimen of 20 mm width (Figure 2) was removed from the middle of the weld bead, which was polished, lapped and etched with 2% NITAL etchant. The beads dimensions such as weld penetration, weld width and reinforcement were measured and then WPSF and WRFF were calculated and presented in Table 2.

2.6. Developing models:
The mathematical models were developed from data generated using Design Expert-11 software. The developed models after dropping insignificant coefficients have been presented in Equations 1 & 2.

2.7. Checking the adequacy:
The ‘F’ test was applied to check the adequacy of developed models. It has been found that developed models are adequate at a 95% confidence level. The lack of fit test was used to evaluate the goodness of fit of the fitted quadratic models.

3. Results And Discussion

3.1. Effect of welding parameters on WPSF
The influence of welding parameters on WPSF has been presented in Figure 3 graphically. From the figure and Eq. 1, it is very clear that WPSF decreases exponentially with increasing welding current. This is due to the fact that the heat input increases with increasing welding current, which causes deep penetration resulting in decreased WPSF [9,12]. It is further observed that WPSF slightly decreases initially and then suddenly rises with an increment in arc voltage. The arc length increases with increasing arc voltage, which means that the arc hits a larger surface area of the workpiece. A larger spread of arc leads to the increased width of weld. Thus, increased width is responsible for increased WPSF. No significant effect of NPD and welding speed on WPSF has been observed.

3.2. Effect of welding parameters on WRFF
From Figure 4 and Eq. 2, it can be seen that the WRFF decreases exponentially with increasing welding current; the reason behind this is that increased welding current increases the melting rate of filler wire leading to increased reinforcement. Moreover, increased current provides digging arc and reduced width. Increased reinforcement is responsible for the decrease in WRFF. It was further noticed from Figure 4 that the WRFF increases with increasing arc voltage since the arc voltage increases the bead width as discussed earlier. The equivalent volume of molten filler metal is distributed over a larger surface area, hence reinforcement.
decreases. Due to which WRFF increased. These results agree well with the results of [10]. The effect of NPD and welding speed on WRFF is insignificant.

WPSF = 0.87 - 0.45A + 0.017B + 0.257C + 0.057D - 0.310AC - 0.037AD - 0.081BD + 0.032CD + 0.181A² + 0.109B² + 0.353C² + 0.055D²  

WRFF = 1.158 - 0.728A + 0.004B + 0.758C - 0.131D - 0.305AB - 0.568AC - 0.307AD - 0.230BC + 0.180BD + 0.027CD + 0.402A² + 0.105B² + 0.385C² + 0.352D²  

Figure 3. Direct effect of parameters on WPSF
3.3. Interactive effects of welding parameters on WPSF and WRFF

The interactive effects of several parameters on WPSF and WRFF have been presented in Figure 5. Figure 5 (a) indicates that WPSF decreases with increasing welding current at the lower and upper levels of welding speed. The reason behind this trend is that as the welding current increases, the size of the weld pool increases as a result of deeper penetration. This increase in penetration is responsible for the decrease in WPSF. Figure 5 (b) shows that the WPSF increases abruptly with increasing welding voltage at a lower level of welding current. Since the welding voltage increases the weld width, and low current decreases the penetration which reflects the increasing trend of WPSF. At a higher level of arc voltage, the WPSF decreases with increasing welding current due to the intense heat input which results in higher penetration. From Figure 5 (c), it can be seen that the WRFF increases with decreasing the welding current at a higher welding speed. The reason behind this is the same as discussed above.

The WRFF also increases with decreasing welding current at a higher level of voltage since at higher voltage the arc length is larger which deposited a wider bead that’s why an increase in WRFF was observed as shown in Figure 5 (d).

3.4. Optimization of welding parameters

The welds produced must be sound and free from flaws as well as economical. The quality and productivity depend upon welding parameters. Therefore, the optimization of process parameters is the need of the hour. In the present study, the optimization was done by using the desirability approach and genetic algorithm (GA) optimization. The desirability approach is widely employed in industries and research for the optimization of process parameters. It is quite simple as compared to other optimization techniques since it does not require any complicated algorithm or programming [11]. The desirability approach was done in Design Expert 11 software and the genetic algorithm was carried out in MATLAB 2020 software. The correct tuning of GA parameters influences the performance of optimization.
The optimum results given by both approaches are different and shown in Table 4. By comparing the percentage error given by these techniques, it was observed that the genetic algorithm gives better optimum results as compared to the desirability approach.

Table 4. Validation of models

| Method       | I (A) | S (m/h) | V (V) | NPD (mm) | WPSF   | WRFF   |
|--------------|-------|---------|-------|----------|--------|--------|
| Desirability | 415   | 21      | 28    | 23       | Predicted 1.66 | 2.80  |
|              |       |         |       |          | Confirmation 1.72 | 2.68  |
|              |       |         |       |          | % error      3.48  | 4.47  |
| Genetic      | 442   | 20      | 30    | 26       | Predicted 1.82  | 3.12  |
|              |       |         |       |          | Confirmation 1.78 | 3.05  |
|              |       |         |       |          | % error      2.24  | 2.29  |

Figure 5. Contour plots of WPSF (a, b) and WRFF (c, d)
For comparison of the WPSF and WRFF of welds deposited using recycled slag and fresh flux. A bead was deposited using fresh flux with optimized parameters obtained from the genetic algorithm technique as indicated in Table 5.

| Method        | I (A) | S (m/h) | V (V) | NPD (mm) | WPSF | WRFF |
|---------------|-------|---------|-------|----------|------|------|
| Recycled slag | 442   | 20      | 30    | 26       | 1.78 | 3.05 |
| Fresh flux    | 442   | 20      | 30    | 26       | 1.66 | 3.25 |

From the above Table 5, it can be concluded that the WPSF and WRFF of the welds deposited with fresh commercial flux are comparable to those of weld deposited with recycled steel slag.

4. Conclusions

- The behaviour demonstrated by recycled slag in terms of weld shape factor and form factor is similar to that of fresh flux.
- The minimum and maximum WPSF attained with recycled slag are 0.764 and 2.83 respectively.
- The desirable WPSF (1.78) was provided by recycled slag to have good mechanical properties.
- The desirable WRFF (3.05) was achieved with recycled slag to get improved mechanical properties of weld produced.
- The welding parameters have been optimized to achieve desired shape factor and form factor using recycled slag and fresh flux.
- The optimized parameters obtained using the desirability approach are welding current 415 A, welding speed 21 m/hr, Arc voltage 28 V and nozzle-to-plate distance 23 mm.
- The optimized parameters obtained using the Genetic Algorithm approach are welding current 442 A, welding speed 20 m/hr, Arc voltage 30 V, and nozzle-to-plate distance 26 mm.
- The Genetic Algorithm has provided better optimization results having low percentage error as compared to the Desirability Approach.

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