Effect of Welding Parameters on the Weld Bead Profile of Submerged Arc Welded Low Carbon Steel Plates.

Charu Singh Chaudhary\textsuperscript{a}, Kashish\textsuperscript{b}, Pradeep Khanna\textsuperscript{c}

\textsuperscript{a, b} Students, \textsuperscript{c} Associate Professor, Department of Mechanical Engineering, NSUT, New Delhi, India. kashishbadwal@gmail.com

Abstract: Welding of thick and long steel sections with minimal requirements of etch preparation has posed a challenge to the fabricators to have a reliable and good quality joint. Such requirements are successfully catered to by the submerged arc welding process which was developed in early 40\textsuperscript{s} to weld thick hull sections of naval ships. The process has since been used extensively in heavy fabrication industries like ship building, pressure vessel and rail industries. The strength and quality of weld produced is decided by its bead parameters like depth of penetration, bead width and reinforcement height. It has been found that weld parameters like wire feed rate, voltage welding speed nozzle to plate distance, torch angle and flux composition have influence on bead parameters. Present work is an attempt to develop a mathematical relation between bead parameters and input parameters so that an empirical relation can be developed between them. Full factorial approach with 2 levels and 3 factors is used and graphical depictions are used to analyse the result.

Keywords: Submerged arc welding, Bead parameters, Input parameters, mathematical modeling, Factorial approach

1. Introduction

Submerged arc welding is a widely used welding operation that finds its utility in heavy fabrication industries [1]. The process can join plates up to a thickness of 16 mm without the need of any specific edge preparation because of deep penetration capability and high deposition rates [2]. It also facilitates higher utilization of the electrode wire and has gained popularity due to its ability to get automated and its potential to generate a uniform spatter-free finished weld. The process involves the emergence of an electrical arc between a constantly fed electrode and metal pieces to be joined. This arc is covered by a layer of granular flux in order to ensure shielding of the molten metal from atmospheric contamination [3]. The inherent advantages associated with the process has made it one of the major fabrication processes in industry. All these features have made SAW a chief metal joining process employed in the industry to manufacture a reliable, acceptable and defect-free weld component [4]. The quality, acceptability and reliability of the weldment rely upon the geometric design of the weld bead produced which in turn depends upon the different process parameters that are involved in the metal joining process [5].

Depth of penetration, height of reinforcement and bead width (fig.1) of a welded joint are important weld bead parameters. in determining the quality, operation efficiency, and strength of welded structure. These parameters should be selected according to the shape of the base materials to provide necessary strength [6]. Welding parameters like arc voltage, arc welding speed and wire feed rate are the major variables that influence the characteristics of the bead that are mentioned above. The mechanical and metallurgical properties of the welded joints are influenced because of the above listed parameters. Since the solidification of liquid metal results in weld bead, the surface tension is an important contributing factor in deciding the final bead geometry [7]. The total shrinkage is affected by the bead cross-sectional area, its height and width which to a great extent determines the residual stresses and distortion [7]. Therefore, the input parameters should be precisely chosen so as to obtain the desired geometrical design of the bead [8].
These input parameters, if not carefully controlled, might result in the formation of an inappropriate bead design/outline leading to failure of welded component [9]. Therefore, the study of weld bead geometry is of significant importance as it decides the stress carrying capacity of a weld, controls and predicts the weld quality, maintains the overall efficiency of a weldment and helps establish a relation of the weld bead geometry with the input process variables [10].

The aim of this paper is to relate the process parameters of welding and the bead characteristics using a mathematical model obtained from experimental results to anticipate the bead geometry parameters accurately. Graphical depictions have been used to analyze the results obtained for drawing constructive and logical conclusions.

2. Experimental Setup and Experimentation

The setup used to carry out the present investigative work is shown in fig. 2. It consists of a weld power source with flat V-I characteristics with ampere rating of 800 amps, 100 % duty cycle, 440 volts, three phase.
The weld carriage is mounted on the guide rail with the facility of having different welding speeds. The system ensures a constant welding speed in all the runs to ensure the repeatability. A total of eight butt welds were made with mild steel plates of thickness 10 mm. The range of input parameters with respective codes is shown in Table 1. The lower and upper limits of the input variables are represented by (-1) and (+1) respectively.

### Table-1 Input parameters and their values

| S no. | Input parameter  | Symbol | Unit  | Levels  |
|-------|------------------|--------|-------|---------|
|       | Welding speed    | A      | cm/min| (-1) 10 | (+1) 20 |
| 2.    | Voltage          | B      | V     | (+1) 40 |
| 3.    | Wire feed rate   | C      | m/min | (-1) 5  | (+1) 7  |

A total of eight experiments were conducted with two replicates. The combination of input parameters used for each run according to the design matrix is shown in Table-2.

### Table-2 Design matrix

| S. No. | Welding speed | Voltage | Wire feed rate |
|--------|---------------|---------|---------------|
| 1.     | -1            | -1      | -1            |
| 2.     | +1            | +1      | +1            |
| 3.     | +1            | +1      | -1            |
| 4.     | +1            | +1      | +1            |
| 5.     | -1            | +1      | -1            |
| 6.     | -1            | -1      | +1            |
| 7.     | +1            | -1      | +1            |
| 8.     | +1            | -1      | -1            |

Weld specimens were cut from each of the weldments with the help of a band saw cutting machine. These specimens were then polished by using rough to fine grade emery papers followed by fine polishing on a disc polishing machine with diamond paste. Nital was used as an etchant to observe the bead profile which can be seen in Fig 3. The bead profiles were projected on the screen of a profile projector and were measured by using a DRO System with a resolution of 0.01 mm. The results so obtained in respect of depth of penetration, bead width and reinforcement are recorded in Table 3.
Table 3 The values of bead width, reinforcement height and depth of penetration as per design matrix.

| S. No. | Weld Speed | Voltage | Wire Feed | Bead Width | Reinforcement Height | Depth of Penetration |
|--------|------------|---------|-----------|-------------|----------------------|---------------------|
| 1.     | -1         | -1      | -1        | 9.38        | 2.47                 | 3.50                |
| 2.     | -1         | +1      | +1        | 19.87       | 3.19                 | 6.18                |
| 3.     | +1         | +1      | +1        | 14.61       | 1.28                 | 5.89                |
| 4.     | +1         | -1      | -1        | 9.14        | 1.82                 | 1.76                |
| 5.     | +1         | +1      | -1        | 11.09       | 0.61                 | 4.76                |
| 6.     | -1         | -1      | +1        | 12.56       | 3.56                 | 3.09                |
| 7.     | -1         | +1      | -1        | 14.49       | 2.46                 | 2.32                |
| 8.     | +1         | -1      | +1        | 8.66        | 1.86                 | 3.37                |

3. Development of mathematical models

Minitab 19 software was used to develop mathematical models for the response parameters depth of penetration, width and reinforcement respectively as given in eq 1-3.

Results-

The following section explains the result obtained with respect to bead width, reinforcement height and depth of penetration.

Depth of penetration = 3.93 + 0.01A + 0.85B + 0.84C + 0.52AB - 0.16AC + 0.4BC

Reinforcement height = 2.16 - 0.76A - 0.27B + 0.31C - 0.17AB - 0.13AC + 0.03 BC

Bead width = 12.48 - 1.6A + 0.54B + 0.45C - 0.56AB - 0.69AC + 0.77BC
The above equations can be used to estimate the values of different response parameters for different values of input variables A, B and C. The above mathematical models include the main as well as the interaction effects of input parameters.

4. Results and discussions

The results obtained after performing the analysis through Minitab software are presented in the graphical form under two categories-

1. Direct effects
2. Two factor interaction effects

4.1 Direct effects of input parameters

Direct or main effects refer to the influence of a particular parameter on the response when taken alone. Though such trends may not be realistic because of the possibility of interaction among the input parameters but still such trends provide broader idea of individual effects of the parameters.

4.1.1 Direct effects of input parameters on depth of penetration: Fig. 4 clearly depicts that with an increase in wire feed rate and voltage, the depth of penetration strongly increases. The probable cause could be that with an increase in wire feed rate the heat input into the base metal increases and the digging force of arc also increases resulting in increase in depth of penetration. With the increase in voltage, the overall heat input into the weld increases which results in increase in depth of penetration. Welding speed however was found to have negligible effect on the depth of penetration for the present selected range of speed.

![Fig. 4 Direct effects of parameters on depth of penetration](image)

4.1.2 Direct effects of input parameters on bead width: It can be observed from fig. 5 that voltage and wire feed rate have a positive effect on bead width while welding speed has a strong negative effect. An increase in voltage is associated with increase in arc length which results in more spread of the arc spreading the molten metal over a wider area thereby increasing the bead width. An increase in wire feed rate results in the increase in welding current which increases the bead width because of high heat input. When welding speed increases, the heat input per unit length decreases sharply which results in reduced bead width.
4.1.3 Direct effects of input parameters on reinforcement height: Fig. 6 depicts that reinforcement height strongly decreases with an increase in welding speed because less molten filler metal gets an opportunity to deposit into the surface of the workpiece. Height of reinforcement decreases with an increase in voltage due to associated increase in arc length which distributes the molten metal over a wider area thereby flattening the bead. There is an increase on reinforcement height with an increased wire feed rate because current increases which results in deposition of more melting of filler metal thereby increasing the reinforcement.

4.2 Interaction effects of input parameters

Interaction effects refer to more realistic situations during experimentations as there is always a strong possibility of interaction among the input parameters which may lead to unpredictable effects on the response parameter. Therefore, consideration of interaction effects is of practical importance in any statistical investigation of experiments.

4.2.1 Interaction effects of input parameters on depth of penetration: It is evident from fig. 7 that both voltage and wire feed rate have a positive effect on depth of penetration. Therefore, minimum depth of penetration is obtained at a point where voltage and wire feed rate are minimum and maximum penetration are obtained where wire feed rate and voltage are maximum.
Fig. 7 Interaction effects of wire feed rate and voltage on depth of penetration.

Fig. 8 shows that voltage is found to have a positive effect on penetration while welding speed is having a negative effect on penetration. Also, depth of penetration is minimum for maximum welding speed and minimum voltage while depth of penetration reaches its maximum value at a point where both voltage and welding speed attain a maximum value. No significant change in depth of penetration when voltage increases for least magnitude of welding speed.

Fig. 8. Interaction effect of voltage and welding speed on depth of penetration

Fig. 9 shows that when welding speed is minimum and wire feed rate is maximum, depth of penetration is maximum. Also, minor deviation is observed in the magnitude of depth of penetration when welding speed increases for maximum value of wire feed rate.
4.2.2 Interaction effects of input parameters on bead width: It can be seen from Fig. 10 that both voltage and wire feed rate have a positive effect on bead width. It can be inferred that bead width is minimum for minimum values of both parameters. Whereas, bead width is maximum for maximum values of both input parameters.

It can be concluded from fig.11 that at low welding speed and high value of wire feed rate, bead width increases. While, at maximum welding speed and minimum wire feed rate, bead width is minimum. This concludes that wire feed rate has positive and welding speed has negative effect on bead width.
It can be concluded from fig. 12 that at low welding speed and high voltage, bead width increases. Whereas, at maximum welding speed and minimum voltage, bead width is minimum. This concludes that voltage has positive and welding speed has negative effect on bead width.

![Fig. 12 Interaction effect of voltage and welding speed on bead width](image1)

4.2.3 Interaction effects of input parameters on Reinforcement height: Fig. 13 depicts that for the given ranges of voltage and wire feed rate, the reinforcement height does not show significant changes. Although, the reinforcement is found to increase moderately with an increase in wire feed rate and is seen to have slight decrease with an increase in voltage.

![Fig. 13 Interaction effect of voltage and wire feed rate on reinforcement height](image2)

It can be seen from fig. 14 that welding speed has a strong negative effect on reinforcement height while voltage has a weak negative effect on reinforcement height.

![Fig. 14 Interaction effect of welding speed and voltage on reinforcement height](image3)
Fig. 14 Interaction effect of voltage and welding speed on reinforcement height

Fig. 15 shows that welding speed has a strong negative effect on reinforcement height whereas wire feed rate has a strong positive effect on reinforcement height.

Conclusions

Following are the conclusions on the basis of investigative work carried out so far-

1. Full factorial technique was found to be satisfactory in bringing out the relationships between input and output parameters.
2. The graphical results produced by the software are convenient to interpret and assist in making logical predictions.
3. The mathematical models in respect of depth of penetration, bead width and reinforcement height have been developed incorporating the direct and interactive effects of the input parameters.
4. Depth of penetration is found to increase with wire feed rate and voltage and decrease with wire feed rate.
5. Bead width is found to have increased strongly with voltage and wire feed rate whereas decrease with increase in welding speed.
6. Reinforcement height is found to reduce strongly with welding speed and moderately with voltage whereas wire feed rate has a strong positive effect on reinforcement.
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