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Optimizing submerged arc welding using response surface methodology, regression analysis, and genetic algorithm

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A B S T R A C T

The weld quality is significantly affected by the weld parameters (arc voltage, welding current, nozzle to plate distance and welding speed) in the submerged arc welding (SAW). Bead-on-plate welds were performed on stainless steel plates by automated SAW machine. The experimental data were collected in accordance with the response surface methodology (RSM). In addition to RSM, the regression analysis was performed to set up input–output relationships in the SAW process. It was found that weld parameters define the geometry of weld bead and determine the mechanical properties of the joint. The influence of the input variables on weld bead geometry is represented as graphs. It was found that an increment in voltage increases the bead width but decreases the bead height, whereas the current increment result-in an increment in bead height and no change in bead width. The bead width and height decrease with the increment in the welding speed. With an increment in the nozzle-to-plate distance, bead width decrease, but bead height increases. The value of bead hardness increases with the increment in current but the increment in voltage and travel speed does not have a significant influence on the bead hardness. The predictions from the mathematical model developed and the corresponding experimental results are having a fair agreement. Further, the genetic algorithm (GA) is also used for predicting the weld bead geometry.

1. Introduction

Automation of the welding process for higher production rate requires the established relationship of the weld bead geometry and process parameters for predicting and controlling the quality of weld bead [1]. The design of the experiment and various statistical methods (Response surface methodology, Taguchi Approach, Factorial design etc.) can be used for developing the relationships between weld bead geometry and process parameters [2]. The SAW is having high productivity so it is preferred for many welding applications [3]. The SAW is used in the fabrication of offshore structures, pipelines, marine vessel, and pressure vessel as an excellent surface appearance and the high deposition rate is achieved [4]. A good number of authors [5–10] used statistical techniques for optimization of the process parameters in the SAW process.

The variable polarity can be adopted for controlling the composition of the weld bead during SAW [11]. The heat input during SAW can be reduced by using the bypass electrode [12]. Double electrode SAW can be utilized for achieving the same metal deposition rate for lesser heat input [13]. The optimum combination of travel speed and root opening also reduces the heat input which avoids distortion in fillet welding [14]. The monitoring and controlling the weld bead penetration in SAW can be performed using control system based on base metal current [15]. The SAW is an automated welding process which achieves high deposition rate. SAW includes a solid incessant bare electrode wire and a blanket of powdered flux. The flux accumulated is of enough depth to submerge the arc column entirely so that there is no smoke or spatter and the weld is also protected from the atmospheric gases. The load carrying capability and weld bead geometry depends on the flux used in the welding [16,17]. The flux also influences the mechanical properties and microstructure of the weld metal [18–20]. A few authors have used GA for welding process optimization [21–23].

RSM establishes the cause and effect relationship among the

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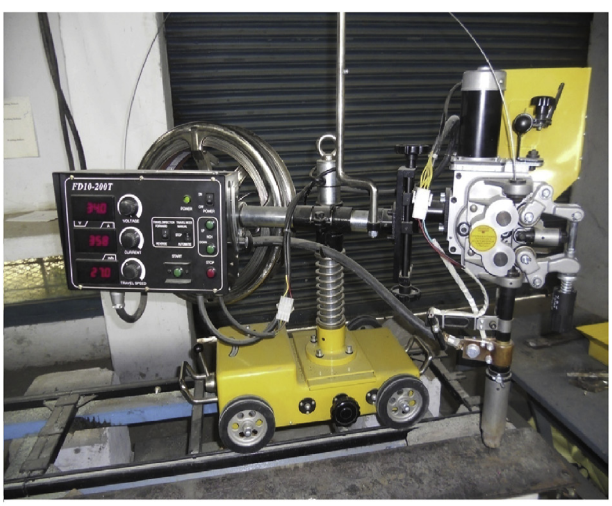
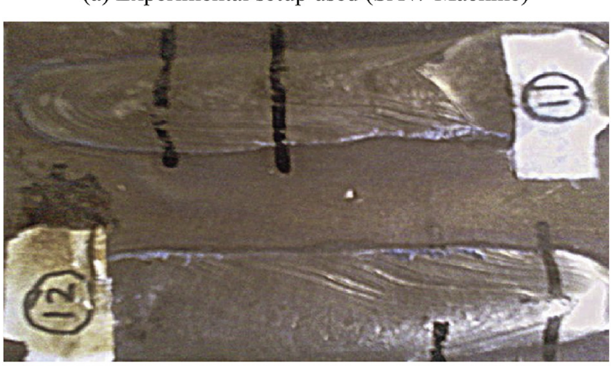
input variables and true mean responses as a two/three-dimensional hyper-surfaces [2]. The input variables can be optimized for good quality of weld by developing the mathematical models through the execution of experimentation following the RSM. RSM is used in the present work for designing the experimentation and also for developing relationships for predicting the hardness and geometry of the weld bead. The effects of variation in open circuit voltage, current, welding speed, and nozzle-to-plate distance on bead width, bead height, and hardness were investigated and analyzed. Later, analysis of variance (ANOVA) is also performed for further analysis and validation of experimentation. The results may be used for predicting the weld bead quality, selecting optimum process parameters quality and optimizing the welding process.

2. Materials and methods

A constant voltage fully automatic SAW machine (TORNADO SAW M – 800) of 800 A, 3-phase, 50 Hz rectifier type power source, and 3.2 mm stainless steel electrode was used for the welding. Fig. 1(a) and Fig. 1 (b) show the experimental set-up and a welded sample respectively. Weld beads were deposited using wire reel of 3.2 mm as per the design matrix on the stainless steel samples of 101.6 × 76.2 × 10 mm. The samples were cleaned manually using the brush to make them dust and rust free before clamping them to the welding bed having the required earth connection. The welded samples were cleaned to make them free from slag. A vernier caliper is used to measure bead height and bead width. Every experimental run (for same inputs) was performed three times and the average bead width and height were considered as final reading to minimize the error. Hardness was measured with the Rockwell hardness tester.



(a) Experimental setup used (SAW Machine)



(b) Photograph of the welded sample

Fig. 1. **(a)** Experimental setup used (SAW Machine) and **(b)** Photograph of the welded sample.

Table 1 shows the welding parameters with their ranges selected for the experimentation. The minimum and maximum values of all the inputs were coded as reflected in Table 1. The experiments were designed according to the parametric approach used in the central composite design of the RSM. The response curves of the process parameters for the data are plotted. The main effects (response curves) are used for evaluating the effects of parametric variation on the response characteristics. The RSM and regression analysis were performed using MINITAB 17.

3. Results and discussion

Table 2 shows the observations recorded during experimentation as per the design matrix. The results of experiment provide insight into the influence of the process parameters on the responses. The value of bead width varies from 17.8 mm to 22.6 mm, bead height varies from 2.88 mm to 4.1 mm. The maximum hardness was 44 measured on Rockwell hardness C scale. The final proposed mathematical model equations for bead height, bead width and hardness terms of coded factors are given by equations (1)–(3) respectively.

$$\textbf{Bead height} = +3.38 - 0.11 \times A + 0.11 \times B - 0.13 \times C + 0.12 \times D - 9.583E - 003 \times A^2 + 0.023 \times B^2 + 0.15 \times C^2 + 0.095 \times D^2 + 0.075 \times A \times B - 0.049 \times A \times C + 0.017 \times A \times D + 0.071 \times B \times C - 0.025 \times B \times D + 0.019 \times C \times D \tag{1}$$

$$\textbf{Bead width} = +20.44 + 0.61 \times A + 0.063 \times B - 0.37 \times C - 0.17 \times D + 0.064 \times A \times B - 1.875E - 003 \times A \times C - 0.25 \times A \times D - 0.54 \times B \times C + 0.12 \times B \times D - 0.42 \times C \times D \tag{2}$$

$$\textbf{Hardness} = +41.00 + 1.01 \times A + 0.30 \times B + 0.22 \times C + 0.47 \times D - 0.92 \times A^2 + 0.013 \times B^2 - 0.050 \times C^2 - 0.050 \times D^2 - 0.36 \times A \times B - 0.16 \times A \times C - 0.037 \times A \times D + 0.088 \times B \times C + 0.21 \times B \times D + 0.5 \times C \times D \tag{3}$$

Here A = voltage, B = current, C = travel speed, D = nozzle to plate

Table 1
Welding parameters and their range.

Parameter	Designation	Range			
		Lower value		Higher value	
		Actual	Coded	Actual	Coded
Open circuit voltage/V	V	33	−2	37	+2
Current/A	A	345	−2	365	+2
Travel speed/$(m \cdot h^{-1})$	S	25	−2	27	+2
Nozzle to plate distance/mm	D	28	−2	36	+2