Parametric Optimization of Submerged Arc Welding Using Taguchi Method

S. Vinodh, S. Karthik Bharathi and N. Gopi

Abstract Submerged Arc Welding (SAW) process has tremendous applications in industrial sectors. The quality of weld joint depends on optimal process parameters. This chapter presents the optimization study for materials with application in valves. Input parameters are voltage, current, and speed of welding; output parameters are penetration and bead width. Taguchi L_9 orthogonal array has been constructed. Signal-to-noise ratio and ANOVA have been used to analyze welding characteristics so as to generate optimal welding parameters. Also, confirmation analyzis has been done.

1 Introduction

Welding is one of the significant metal fabrication processes. Submerged Arc Welding (SAW) has tremendous applications in valves manufacturing [1]. The quality of welded joint typically depends on the input parameters, namely welding current, welding voltage, and welding speed [2]. In order to attain optimum results, the influence of parameters on welding process as well the varying conditions must be understood. The influence of welding input parameters on output parameters, namely penetration depth and bead width are essential and are analyzed [3]. Experimental design approach proposed by Taguchi has been used in this study.

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Orthogonal Array and ANOVA are used to analyze the welding characteristics as well as to perform the welding parameters optimization. Also, confirmation tests have been conducted to compare the experimental and predicted values.

2 Literature Review

The literature has been analyzed from the viewpoint of Taguchi methods and welding processes. Sapakal[1] and Telsang [4] applied Taguchi method to determine the optimal process parameters for penetration in MIG welding. In this investigation, they considered welding current, welding voltage, and welding speed as parameters. In order to optimize welding parameters, Taguchi orthogonal array, signal-to-noise ratio, and ANOVA were used. Kumanan et al. [5] applied Taguchi technique and regression analyzis to determine the optimal process parameters of SAW process. The experiment was conducted by varying voltage, welding current, welding speed, and electrode stick-out. Eshwar and Kumar [6] found the most significant parameters that affect mechanical properties of TIG weldments of Al 65032 alloy using S/N analyzis and mean response analyzis. The parametric design is carried out with weld condition and control parameters such as gas pressure, current, groove angle, and preheats. Three levels are considered for the control parameters based on the preliminary tests and analyzis carried out with L9 orthogonal array. Juang and Tarng [7] proposed modified Taguchi approach for selection of TIG welding process parameters of stainless steel with optimal weld pool geometry and four ‘smaller-the-better’ quality characteristics. Pasupathy and Ravishankar [8] performed welding using AA1050 material and studied the influence of welding parameters namely welding current and welding speed on strength of low-carbon steel. The experiments were planned based on Taguchi technique. The welding characteristics of dissimilar joints were investigated using S/N ratio and ANOVA and the welding parameters were optimized. Chauhan and Jadaun [9] optimized process parameters of MIG welding process for dissimilar metal joint for stainless steel (SS-304) and low-carbon steel using Taguchi design method. ANOVA was applied to determine the significance level of parameter. Sarkar et al. [10] reported a new procedure using analytic hierarchy process (AHP)-based Taguchi method for the selection of best welding parameters with reference to fabrication of SAW of plain carbon steel. In the investigation, three process parameters, namely wire-feed rate, stick out, and traverse speed and three response parameters, namely penetration, bead width, and bead reinforcement were considered. Also, ANOVA was applied to investigate the influence of process parameters on penetration, bead width, and reinforcement. Datta et al. [11] applied Taguchi method to obtain optimal parametric combinations to attain desired weld bead geometry and dimensions of Heat Affected Zone (HAZ) in SAW process. Taguchi L9 orthogonal array design was adopted and experiments were conducted using three different levels of traditional process parameters to obtain bead-on-plate weld on mild steel plates. Saha and Mondal [12] presented a different method to optimize SAW process parameters with multi-response characteristics by applying Taguchi's robust design approach. Experiments were performed using welding current, arc voltage, welding speed, and electrode stick-out as input process parameters to assess weld bead width and bead hardness. The optimum values were analyzed using multiobjective Taguchi method to obtain total normalized quality loss and multi-response signal-to-noise ratio. Tarng and Yang [13] applied Taguchi method to optimize welding parameters in SAW process. The factors considered for optimization include arc current, arc voltage, welding speed, electrode protrusion, and preheat temperature. Yousefieh et al. [14] presented Design of Experiment (DOE) technique, Taguchi method, to optimize pulsed current gas tungsten arc welding (PCGTAW) parameters for analyzis of corrosion resistance in the case of super duplex stainless steel (UNS S32760) welds. L9 orthogonal array of Taguchi design was used which involves nine experiments for four parameters (pulse current, background current, % on time, and pulse frequency) with three levels. ANOVA was performed on the measured data and S/N ratio was computed. Tarng and Yang [15] determined welding process parameters to obtain optimum weld bead geometry in gas tungsten arc welding (GTAW) process using Taguchi method of DOEs. They proved through ANOVA that welding speed, welding current, and polarity ratio are the significant parameters to evaluate weld bead geometry.

3 Submerged Arc Welding

SAW involves the concealment of arc using blanket of granular and fusible flux. Heat source is an arc between a bare, solid-metal (or cored) consumable wire, or strip electrode and the work piece. The arc is retained in a cavity of molten flux or slag, which refines weld metal and protects from atmospheric contamination.

Since thick steel sections can be easily joined using SAW, it is primarily used for shipbuilding, pipe fabrication, and pressure vessels [16]. In addition to joining application, it is used to build up parts and overlay with stainless or wear-resistant steel. Procedural variations in SAW include current, voltage, electrical stick-out (distance from last electrical contact to plate), travel speed, and flux depth. Variation in any of these parameters will affect the shape and penetration of weld, as well as the integrity of weld deposit.

4 Taguchi's Design Method

Taguchi approach is a designed experiment that enables the selection of a product or process that provides consistent performance. Taguchi design focus on identification of controllable factors that minimizes the effect of noise factors. During experimentation, noise factors to force variability can be manipulated and determine optimal control factor settings to develop robust process or product. A process designed with this objective will generate more consistent output regardless of the environment in which it is used. Taguchi designs use orthogonal arrays, which determine the effects of factors on the response mean and variation. An orthogonal array emphasizes balanced design with equal weightage to all factors. This enables independent assessment of factors. Time and cost associated with experimentation could be reduced during which fractionated designs are used [3].

5 Process Parameter Levels

The operating variables of SAW considered in this study include welding current, welding voltage, and welding speed. Arc voltage lengthens the arc so that the weld bead width, reinforcement, and flux consumption are increased. For the given wire diameter, on increasing weld current, the deposition rate and depth of penetration both increase. Higher speeds reduce bead width and increase the likelihood of porosity. Bead size is inversely proportional to welding speed at the same current. Though many direct and indirect parameters affect the quality of weld in SAW, the key process parameters influencing bead geometry include welding current, welding voltage, and welding speed. In this study, three levels of process parameters are considered (Table 1).

Work material:

Electrode diameter: 4 mm.
Base material: Carbon steel.
Maximum stick out: 25 mm.
Polarity: Constant current, electrode positive.
Electrode: EG.
Plate size: 300 × 110 × 16 mm.

6 L9 Orthogonal Array

Taguchi conceptualized a new approach of conducting the DOEs which are based on well-defined guidelines. This approach deploys a special set of arrays termed orthogonal arrays. These standard arrays emphasize the way of conducting reduced number of experiments which could generate complete information of all the factors that affect performance parameters. The core aspect of orthogonal arrays rests with

Table 1 Welding parameters

Welding parameters	Level 1	Level 2	Level 3
Welding current	450	550	650
Welding voltage	28	30	32
Welding speed	300	450	600

Table 2 L9 orthogonal array

Expt. No.	Process parameters		
	Welding current	Welding Voltage	Welding speed
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

selecting the level combinations of the input design variables for each experiment. In this chapter, an experiment has been conducted to understand the influence of three different independent variables (each variable has three level values). In this case, L_9 orthogonal array forms appropriate choice. This array assumes that there is no interaction between any two factors (Table 2).

7 Signal-to-Noise Ratio

The product of ideal quality should reciprocate appropriately in the same way to the signals provided by the control factors. According to Taguchi, variability in product performance with reference to noise factors should be minimized while variability with reference to signal factors must be maximized. Signal factors include those factors that are controlled by operator of the product to obtain final response. Noise factors are those which the operator does not have control over. The goal of Taguchi's DOEs is to determine the best settings of control factors that are involved in the production process, in order to maximize S/N ratio.

There are three Signal-to-Noise ratios of common interest for optimization

(1) Smaller-the-Better:
In cases where the occurrence of some undesirable product characteristics should be minimized

$$n = -10\,\mathrm{Log}_{10}[\text{mean of sum of squares pertaining to measured data}] \tag{1}$$

(2) Larger-the-Better:
In cases where the occurrence of certain product characteristics should be maximized.

$$n = -10\,\mathrm{Log}_{10}[\text{mean of sum squares of reciprocal pertaining to measured data}] \tag{2}$$

(3) Nominal-the-Best:
There is a fixed signal value and the variance around this value can be recognized as the result of noise factors

$$n = 10\,\mathrm{Log}_{10}\frac{\text{square of mean}}{\text{variance}} \tag{3}$$

In any welding process, the amount of penetration of the weld bead is directly related to the quality of weld bead. Hence, to calculate S/N ratio, it is considered to be 'larger-the-better'. The S/N ratios corresponding to penetration is presented in Table 3.

Similarly, to obtain optimum welding characteristics, smaller-the-better characteristics for bead width should be considered. The calculated S/N ratio for bead width is presented in Table 4.

The main objective of Taguchi's process is to maximize S/N ratio irrespective of the category of quality whether it is higher-the-better or lower-the-better. The mean

Table 3 Results of experimentation for penetration and S/N ratio

Expt. No.	Welding current	Welding voltage	Welding speed	Penetration mm	S/N ratio
1	450	28	300	3.416	10.6704
2	450	30	450	2.923	9.3166
3	450	32	600	3.485	10.8441
4	550	28	450	4.614	13.2816
5	550	30	600	4.304	12.6774
6	550	32	300	7.800	17.8419
7	650	28	600	5.945	15.4830
8	650	30	300	7.694	17.7230
9	650	32	450	4.747	13.5284

Table 4 Results of experimentation for bead width and S/N ratio

Expt. No.	Welding current	Welding voltage	Welding speed	Bead width	S/N ratio
1	450	28	300	22.560	−27.0668
2	450	30	450	17.122	−24.6711
3	450	32	600	14.992	−23.5172
4	550	28	450	17.439	−24.8304
5	550	30	600	16.297	−24.2422
6	550	32	300	29.500	−29.3964
7	650	28	600	15.128	−23.5956
8	650	30	300	20.735	−26.3341
9	650	32	450	26.162	−28.3534

Table 5 Table depicting response for signal-to-noise ratios for penetration

Level	Welding current	Welding voltage	Welding speed
1	10.28	13.14	15.41
2	14.60	13.24	12.04
3	15.58	14.07	13.00
Delta	5.30	0.93	3.37
Rank	1	3	2

Table 6 Table depicting response for signal-to-noise ratios for bead width

Level	Welding current	Welding voltage	Welding speed
1	−25.09	−25.16	−27.60
2	−26.16	−25.08	−25.95
3	−26.09	−27.09	−23.78
Delta	1.07	2.01	3.81
Rank	3	2	1

of multi-response signal-to-noise ratio for each level of welding parameters for penetration is consolidated and shown in Table 5.

Similarly, the multi-response S/N ratio for bead width is shown in Table 6.

Figures 1 and 2 show the multi-response signal-to-noise graph for penetration and bead width, respectively, and dashed line represented in Figs. 1 and 2 indicate

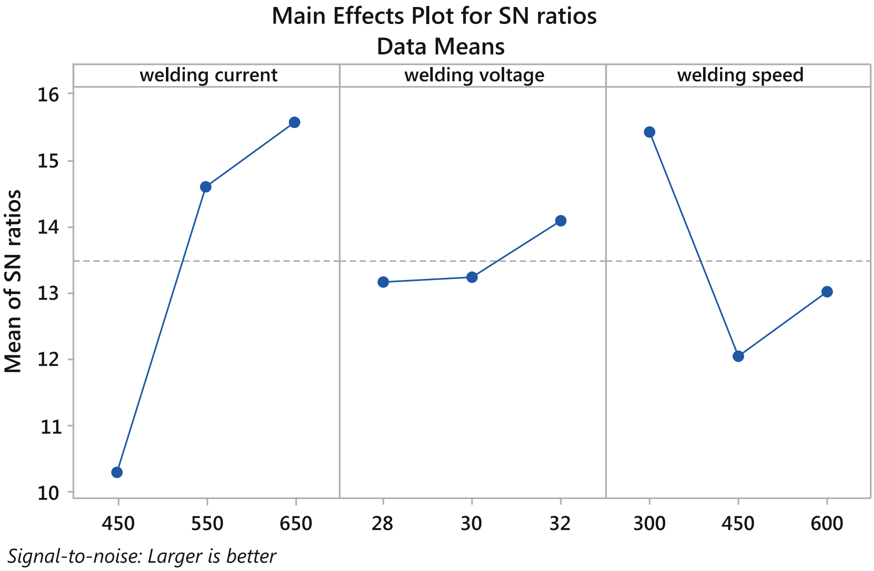

Fig. 1 Main effect plot for S/N ratio of penetration

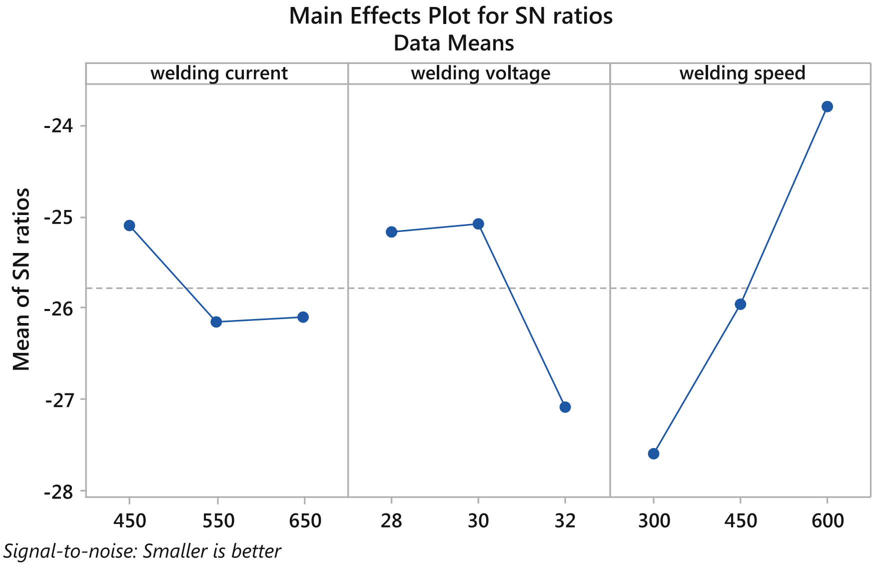

Fig. 2 Main effect plot for S/N ratio of bead width

the value of total mean of the multi-response signal-to-noise ratio. Multi-response signal-to-noise ratio is inversely proportional to the variance of quality characteristics around desired value.

8 ANOVA

ANOVA is used to depict the importance of all process parameters on weld penetration and bead width. ANOVA is a statistics-oriented objective decision making tool used to detect any differences in mean performance of the group of items analyzed taking variation into account rather than using pure judgment. In ANOVA table, sum of squares represents total variability in S/N ratios, which is computed by the sum of squared deviations from total mean S/N ratio. It is given as

$$\mathrm{SSD} = \sum (x_i - x_n)^2 \tag{4}$$

The Degrees of Freedom (DF) refer to terms in sum of squares (SS), which can be assigned arbitrarily. For instance, the sum of deviations from mean in a sample of n observations

$$(x_1 - x)^2 + (x_2 - x)^2 + (x_3 - x)^2 + \cdots + (x_n - x)^2$$

has $(n-1)$ degree of freedom because when $(n-1)$ deviations are known, the nth deviation can be computed from the identity

$$(x_1 - x) + (x_2 - x) + (x_3 - x) + \cdots + (x_n - x) = 0$$

The mean sum of squares can be calculated as

$$\text{Mean sum of squares (MS)} = \frac{\text{Sum of square}}{\text{Degrees of freedom (DF)}} \tag{5}$$

F is called variance ratio.

$$F = \frac{\text{MS}}{\text{MS (error)}} \tag{6}$$

F, thus obtained, is to be compared with F0.05 and F0.01 (from standard *F* tables) to analyze whether the term (main effect or interactive effect) enforces a significant effect on selected response with 95 % confidence level. A factor is said to have significant effect on a response if *F* value obtained from table is found to be less than the computed or calculated *F* value. ANOVA is done using statistical package MINITAB.

The results of ANOVA pertaining to penetration and bead width are presented in Tables 7 and 8, respectively.

From Table 7, it can be seen that welding current possess the highest influence over penetration as it has the highest *F* value at 95 % confidence level.

From Table 8, it can be seen that welding speed possess the highest influence over bead width as it has the highest *F* value at 95 % confidence level.

Table 7 Analyzs of variance for S/N ratios for penetration

Source	Degrees of freedom	Sum of squares	Mean sum of squares	*F*	*P*
Welding current	2	47.749	23.8747	7.33	0.120
Welding voltage	2	1.560	0.7801	0.24	0.807
Welding speed	2	18.084	9.0419	2.78	0.265
Residual error	2	6.510	3.2552		
Total	8	73.904			

Table 8 Analyzis of variance for S/N ratios for bead width

Source	Degrees of freedom	Sum of squares	Mean sum of squares	*F*	*P*
Welding current	2	2.170	1.085	0.52	0.659
Welding voltage	2	7.738	3.869	1.85	0.351
Welding speed	2	21.956	10.978	5.24	0.160
Residual error	2	4.188	2.094		
Total	8	36.052			

Table 9 Results of the confirmation experiment

	Initial welding parameters	Optimal welding parameters	
		Prediction	Experiment
Level	A1B1C1	A3B3C1	A3B3C1
Penetration	3.416	8.027	7.852
S/N ratio	10.6704	18.0911	17.899
Level	A1B1C1	A2B3C1	A2B3C1
Bead width	22.560	13.175	14.54
S/N ratio	−27.0668	−22.3953	−23.251

9 Confirmation Test

This is the last step in Taguchi's design method. From the main effects plot of S/N ratio shown in Figs. 1 and 2, optimum values of welding parameters corresponding to maximum S/N ratio are predicted. In this study for maximum penetration, the optimum level of welding parameters for penetration is predicted to be

Welding current	650
Welding voltage	32
Welding speed	300

Similarly, the optimum values for the least bead width is predicted to be

Welding current	550
Welding voltage	32
Welding speed	300

Now, experiments are conducted having the above values for welding parameters and value of penetration and bead width are noted. The predicted values of penetration and bead width are compared with reference to actual values and a good agreement is attained between predicted and experimented values as shown in Table 9.

10 Conclusion

This chapter reports the study on optimization of process parameters of SAW using Taguchi method. Material used in valves has been considered. Appropriate input and output parameters have been considered. L_9 orthogonal array has been devised. Signal-to-noise (S/N) ratio and ANOVA are used for welding process parameters optimization. From the study, the optimal penetration is found to be 8.027 mm and S/N ratio is 18.0911.

Generally, the results are similar to those obtained by Karaoglu and Secgin [17]. Bead width is more sensitive to voltage and speed variations when compared to bead height and penetration. Current is the most significant parameter with reference to penetration. Penetration is almost nonsensitive to voltage and speed [17]. Karaoglu concluded that at maximum heat input level (maximum current and voltage levels and minimum level of welding speed), current sensitivity of penetration, and speed sensitivity of bead width attain maximum values. Sarkar et al. [10] concluded that the effect of wire-feed rate on weld geometry is more significant than other welding parameters in SAW process. However, in the present study, it has been inferred that welding current has significant effect on weld bead characteristics than other parameters.

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