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ORIGINAL ARTICLE

Application of Taguchi philosophy for parametric optimization of bead geometry and HAZ width in submerged arc welding using a mixture of fresh flux and fused flux

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Abstract Taguchi philosophy has been applied for obtaining optimal parametric combinations to achieve desired weld bead geometry and dimensions related to the heat-affected zone (HAZ), such as HAZ width in the present case, in submerged arc welding. The philosophy and methodology proposed by Dr. Genichi Taguchi can be used for continuous improvement in products that are produced by submerged arc welding. This approach highlights the causes of poor quality, which can be eliminated by self-adjustment among the values of the process variables if they tend to change during the process. Depending on functional requirements of the welded joint, an acceptable weldment should confirm maximum penetration, minimum reinforcement, minimum bead width, minimum HAZ width, minimum bead volume, etc. to suit its area of application. Hence, there exists an increasing demand to evaluate an optimal parameter setting that would fetch the desired yield. This could be achieved by optimization of welding variables. Based on Taguchi's approach, the present study has been aimed at integrating statistical techniques into the engineering process. Taguchi's L9 (3**3) orthogonal array design has been adopted and experiments have been accordingly conducted with three different levels of conventional process parameters using welding current and flux basicity index to obtain bead-on-plate weld on mild steel plates. Features of bead geometry and HAZ in terms of bead width, reinforcement, depth of penetration and HAZ width have been measured for each experimental run. The slag, generated during welding, has been consumed in further runs by mixing it with fresh unmelted flux. The percentage of slag in the mixture of fused flux (slag) and fresh flux has been defined as slag-mix%. Welding has been performed by using varying slag-mix%, treated as another process variable, in order to obtain the optimum amount of slag-mix that can be used without any alarming adverse effect on features of bead geometry and HAZ. This would lead to 'waste to wealth'.

Keywords Taguchi philosophy ·
Design of experiment · 'Waste to wealth'

Nomenclature

W	Bead width (mm)
R	Reinforcement (mm)
P	Depth of penetration (mm)
Hw	HAZ width (mm)

1 Introduction

The submerged arc welding (SAW) process utilizes a granulated fusible flux blanket, which covers the weld pool during operation. This typical arrangement facilitates a slower cooling rate, which, in turn, improves both mechanical properties, and metallurgical characteristics of weld bead as well as the heat affected zone (HAZ). Both slow cooling and rapid cooling have their merits and

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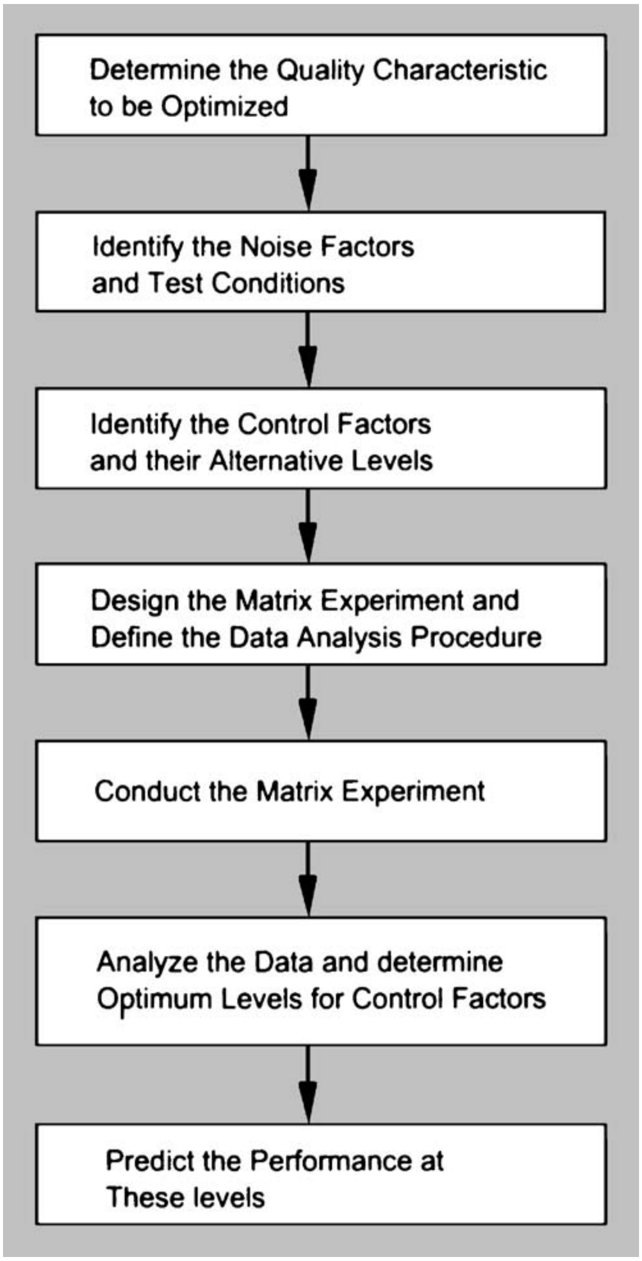

Fig. 1 Flowchart of the Taguchi method [11]

demerits on mechanical and metallurgical properties. Faster cooling, in general, may cause distortion, induce internal stresses, initiate internal cracking and increase hardness and brittleness. However, tensile strength may improve. Slower cooling will protect the weldment from the possibility of cracks, distortion, and brittleness thereby safeguarding the related properties of the joint. Slow cooling generally promotes larger grain size while faster cooling leads to the reverse. Though slower cooling may improve strength, on one hand, on the other hand the above-mentioned adverse effects will be obtained. In welding considerable caution is always needed so that the chances of cracking, brittleness, etc. are avoided. Thus, an optimal cooling rate is desirable, which should generally not be too fast. During SAW welding, a portion of flux melts and the molten flux is termed as fused flux. After welding, slag is separated from weld bead and generally discarded. It is no longer used and therefore appears as waste. Thus, slag produced during the SAW process needs landfill space for storage and results in an increase of disposal cost.

Table 1 Process parameters and their limits

Serial no.	Parameter	Notation	Unit	Level 1	Level 2	Level 3
1	Current	C	Ampere	200	250	300
2	% of slag-mix	S	–	10	15	20
3	Basicity index	F	–	1.0	1.2	1.6

Table 2 Taguchi's orthogonal array L9 (3**3) design

Serial no.	Current, C	Slag-mix%, S	Flux basicity, F
Factors in coded form			
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
Factors in natural values			
1	200	10	1.0
2	200	15	1.2
3	200	20	1.6
4	250	10	1.2
5	250	15	1.6
6	250	20	1.0
7	300	10	1.6
8	300	15	1.0
9	300	20	1.2

In the present work, the aim was to investigate whether slag can be reconsumed in SAW during subsequent runs without imposing any detrimental or adverse effects on features of bead geometry such that this new concept could be recommended in practical applications to yield 'waste to wealth'.

The influence (direct and interaction) of various process control parameters on features of bead geometry and bead quality, as well as performance[1] has been investigated by previous researchers [1–6]. But the idea of consuming slag-

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[1] The term performance has been used here to refer to the performance of the welded joint, which is generally evaluated by various destructive and non-destructive tests. Performance can be judged by ultimate tensile strength, yield strength, hardness, impact value, etc. obtained through these tests.

Table 3 Chemical composition of fluxes used

Flux	Character	Type of manufacture	Chemical composition (%)				Basicity index
			Al_2O_3+MnO_2	CaO+MgO	SiO_2+TiO_2	CaF_2	
F_1	Neutral	Fused					1.0
F_2	Basic	Agglomerated	25	35	35	–	1.2
F_3	Basic	Agglomerated	35	25	20	15	1.6

mix in the conventional SAW process or utilization of recycled slag has been found very challenging to researchers [7]. An acceptable welded joint should satisfy all functional requirements to suit its area of application. Previous investigations revealed that weld metal characteristics play an important role on joint properties. Property and performance depends on structure. The load carrying capacity of the weldment depends upon weld bead geometry and shape, their dimensions and relationship between them [8]. Desirable mechanical properties of the weldment depend on parameters of bead geometry and HAZ. An optimum weld bead should provide maximum penetration, minimum reinforcement, minimum bead width, etc. To reduce weld metal consumption and thereby lower fabrication cost, bead volume should be minimum. All these requirements can be achieved through optimization of welding phenomena.

In the present study, the optimization technique proposed by Dr. Taguchi has been selected to obtain optimal welding process parameters that would provide favorable quality weld bead geometry in the SAW process. The Taguchi method is a process/product optimization technique that is based on several steps including planning, executing and evaluating results of matrix experiments, in order to determine the best levels of control factors. The primary goal is to keep the variance in the output very low even in the presence of noise. Thus the process/products are made robust against all variations. During the study, the selected welding process parameters were welding current, slag-mix % and flux basicity index. The responses measured associated with bead geometry and HAZ were reinforcement, depth of penetration, bead width and HAZ width. Parametric optimization has been performed based on maximization of Taguchi's objective function signal-to-noise ratios.

Table 4 Constant parameters in the experiment

Parameters
Travel speed: 20 cm/min
Nozzle angle: 90°
Voltage: 28 V
Electrode wire: 3.14 mm diameter copper coated mild steel wire (AWS A/S 5.17:EH14)
Thickness of flux layer: fairly constant

2 Technique based on Taguchi's philosophy

Taguchi's philosophy is an efficient tool for the design of high quality manufacturing systems. Dr. Genichi Taguchi, a Japanese quality management consultant, has developed a method based on orthogonal array experiments, which provide much-reduced variance for the experiment with optimum setting of process control parameters. Thus the integration of design of experiments (DOE) with parametric optimization of process is achieved in the Taguchi method. This will provide desired results. The desired results refer to the acceptable quality parameters of the product. For welded joint, this will mean desired mechanical properties of the joint, which-in turn-depend on bead geometry. Again, control of the process parameters will lead to optimal bead.

An orthogonal array (OA) provides a set of well-balanced (minimum experimental runs) experiments and Taguchi's signal-to-noise ratios (S/N), which are logarithmic functions of desired output, serve as objective functions for optimization. This helps in data analysis and prediction of optimum results. The steps involved in the Taguchi method are as follows [8–13]:

Step 1 Formulation of the problem: the success of an experiment depends on complete understanding of the nature of the problem. This involves identification of the performance characteristic of the process output which is most important to the process.

Step 2 Identification of control factors, noise factors and signal factors. A controlled factor is a characteristic that can be controlled in the product or process

Table 5 Experimental data

Serial no.	Bead width (mm)	Reinforcement (mm)	Penetration (mm)	Width of HAZ (mm)
1	12.36	4.04	2.43	2.71
2	12.76	4.09	2.13	3.50
3	14.45	4.40	2.52	3.27
4	13.95	4.52	2.67	3.70
5	15.75	4.67	2.45	3.47
6	15.36	4.06	3.40	4.02
7	17.35	4.85	2.85	4.40
8	15.73	4.50	3.90	4.02
9	17.16	4.93	2.79	4.02

Table 6 S/N ratios (dB) for features of bead geometry and HAZ

Experiment no.	S/N ratio for bead width	S/N ratio for reinforcement	S/N ratio for penetration	S/N ratio for HAZ width
1	−21.8404	−12.128	7.712	−8.659
2	−22.117	−12.234	6.568	−10.881
3	−23.197	−12.869	8.028	−10.291
4	−22.891	−13.103	8.530	−11.364
5	−23.946	−13.386	7.783	−10.807
6	−24.728	−12.171	10.629	−12.084
7	−24.786	−13.715	9.0969	−12.869
8	−23.935	−13.064	11.821	−12.085
9	−24.690	−13.857	8.912	−12.085

subjected to designing. Noise factors are those that cannot be easily controlled in the manufacture or use of a product. In the experimental setting, the levels of noise factors are to be controlled for simulating the sources of variation the product will be subjected to in actual use. The goal of robust parameter design is to find levels of the control factors that will minimize the sensitivity of the product to changes in the noise factors. A signal factor is an input to the experimental system that is supposed to affect the output. Taguchi's dynamic experiment measures the response variable at different levels of a signal factor.

Step 3 Selection of factor levels, possible interactions and degrees of freedom associated with each factor and the interaction effects.

Step 4 Design of an appropriate orthogonal array (OA): Taguchi's orthogonal arrays are experimental designs that usually require only a fraction of the full factorial combinations. The arrays are designed to handle as many factors as possible in a certain number of runs compared to those dictated by full factorial design. The columns of the arrays are balanced and orthogonal. This means that in each pair of columns, all factor combinations occur the same number of times. Orthogonal designs allow estimating the effect of each factor on the response independently of all other factors.

Step 5 Experimentation and data collection.

Step 6 Statistical analysis and interpretation of experimental results.

Step 7 Conducting confirmatory test.

The aforesaid steps involved in the Taguchi method are presented in the form of a flowchart in Fig. 1.

3 Signal-to-noise ratio (S/N ratio)

In order to evaluate optimal parameter settings, the Taguchi method uses a statistical measure of performance called signal-to-noise ratio. The S/N ratio developed by Dr. Taguchi is a performance measure to select control levels that best cope with noise. The S/N ratio takes both the mean and the variability into account. The S/N ratio is the ratio of the mean (signal) to the standard deviation (noise). The ratio depends on the quality characteristics of the product/process to be optimized [12]. The standard S/N ratios generally used are as follows: nominal-is-best (NB), lower-the-better (LB), and higher-the-better (HB). In this paper, the characteristic values are selected by the bead width, reinforcement, depth of penetration and HAZ width, since a good result is obtained by the smaller bead width, reinforcement, HAZ width and deeper depth of penetration. Hence for bead width, reinforcement and HAZ width LB is preferred. For depth of penetration the HB criterion has been selected. The S/N ratio for LB and HB can be calculated by:

$$SN(Lower - the - better) = -10\log\left[\frac{1}{n}\sum_{i=0}^{n} y_i^2\right] \tag{1}$$

$$SN(Larger - the - better) = -10\log\left[\frac{1}{n}\sum\nolimits_{i=1}^{n}\frac{1}{y_i^2}\right] \tag{2}$$

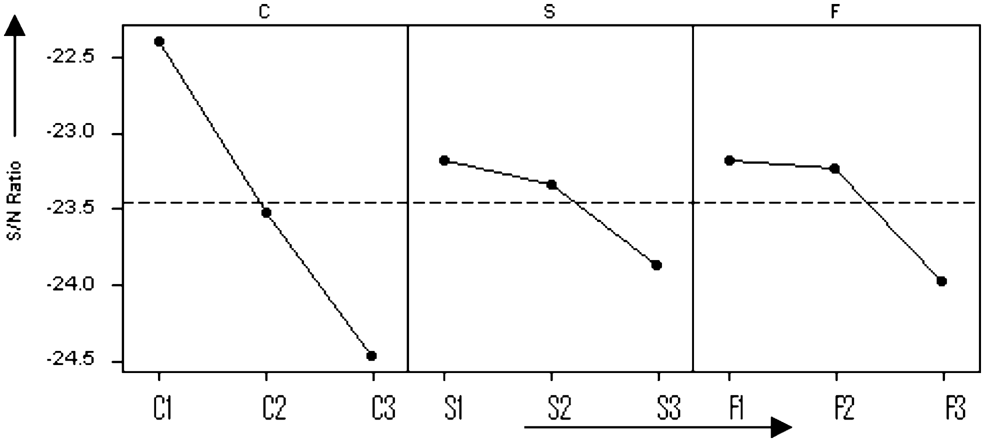


Fig. 2 Main effect plot of S/N ratio for bead width

Fig. 3 Main effect plot of S/N ratio for reinforcement

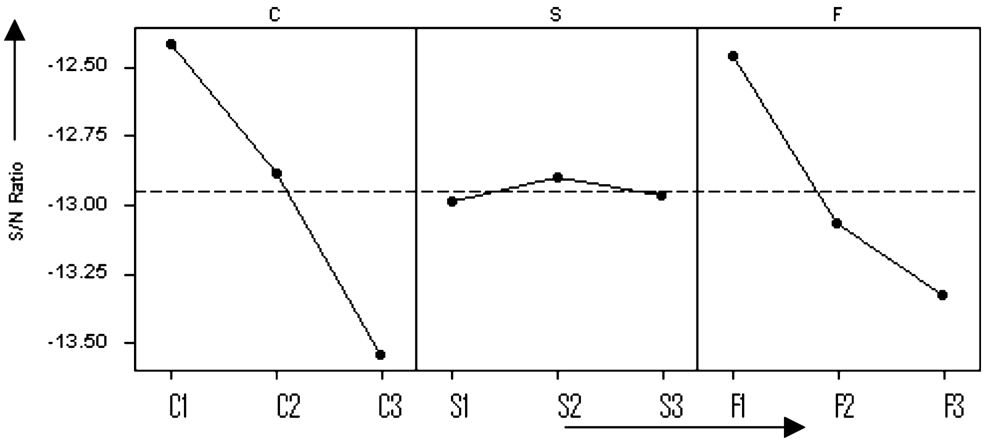


Fig. 4 Main effect plot of S/N ratio for depth of penetration

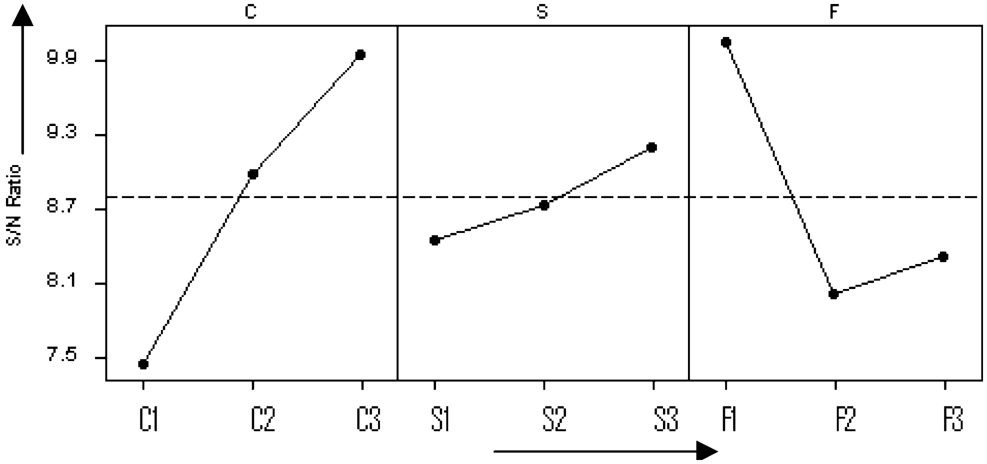


Fig. 5 Main effect plot of S/N ratio for HAZ width

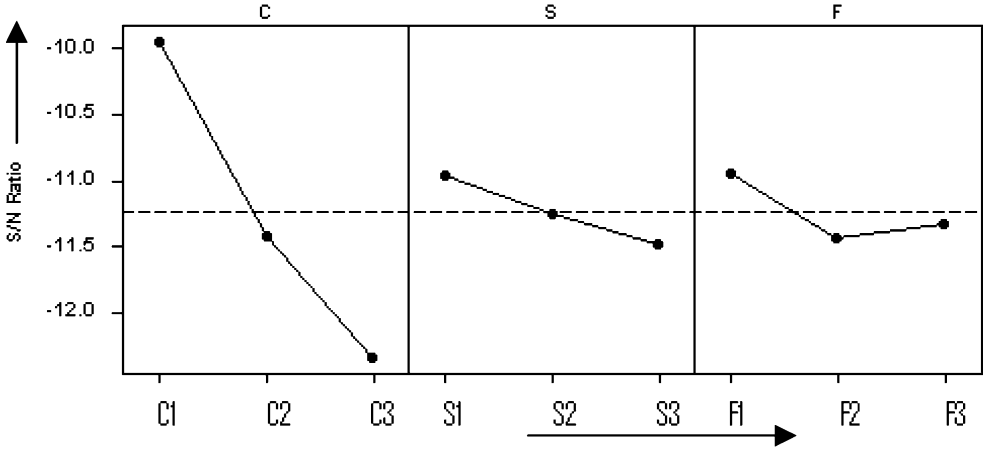


Table 7 Results of ANOVA for bead width

Source	DF	Seq SS	Adj SS	Adj MS	F	P
C	2	18.9802	18.9802	9.4901	54.49	0.018
S	2	2.0828	2.0828	1.0414	5.98	0.143
F	2	3.3921	3.3921	1.6960	9.74	0.093
Error	2	0.3484	0.3484	0.1742		
Total	8	24.8034				

Table 9 Results of ANOVA for depth of penetration

Source	DF	Seq SS	Adj SS	Adj MS	F	P
C	2	1.0184	1.0184	0.5092	3.03	0.248
S	2	0.1013	0.1013	0.0506	0.30	0.768
F	2	0.9201	0.9201	0.4600	2.74	0.268
Error	2	0.3361	0.3361	0.1680		
Total	8	2.3758				

where n is the number of measurements and y_i is the measured characteristic value.

4 Experimentation and data collection

Based on Taguchi's orthogonal array design, experiments have been conducted with three different levels of process parameters: welding current, flux basicity index (type of flux) and percentage of fused flux mixed with fresh flux (slag-mix%) to obtain bead-on-plate weldment on mild steel plates (100×40×12). Process parameters with their notations, unit and values at different levels are listed in Table 1. The design matrix has been selected based on Taguchi's orthogonal array design of L9 (3**3) consisting of nine sets of coded conditions [14] (Table 2). The experiments were performed using the submerged arc welding machine: INDARC Autoweld Major (IOL Ltd., India). The chemical composition of three fluxes along with basicity indices is shown in Table 3.

A sufficient amount of welding has been done to collect fused slag in desired quantities (volumes) for each of the above fluxes. The slag was then broken and finally crushed into a granular size almost to that of the original flux(es). The crushed slag in granular form was allowed to pass through a sieve, through which fresh flux had passed easily. Thus average grain size of the slag has been kept approximately equal to that of fresh flux. Then fused slag of three varieties was kept ready for subsequent welding. The parameters, which were kept invariant during experimentation, are listed in Table 4.

For each of the bead-on-plate specimens, the dimensions of the weld bead geometry have been measured by an optical Trinacular Metallurgical Microscope (Leica, Germany) (Table 5).

5 Data analysis using the Taguchi method

Utilizing the experimental data of Table 5, the S/N ratios for each of the features of bead geometry and HAZ (responses) have been calculated (Table 6). The objective is to obtain the factor combination that would optimize S/N ratio, i.e. maximize S/N ratio (higher-the-better for penetration) or minimize S/N ratio (lower-the-better for bead width, reinforcement and HAZ width). To evaluate quantitatively the degree of significance of process parameters on selected response(s), the ANOVA technique has been adopted. Based on statistical analysis of the collected data, this method can infer which factor is the most significant in influencing output features associated with bead geometry and HAZ obtained by submerged arc welding.

Irrespective of the quality characteristic chosen for a particular response, a greater S/N ratio corresponds to better quality characteristics. Therefore, the optimal level of the process parameters is the level which ensures greatest S/N ratio. Moreover, ANOVA is applied to evaluate which factor(s) impose significant effect on the selected response. With the S/N optimization, the optimal parametric combination can be predicted. Finally a confirmation run is to be performed to verify the optimal process condition dictated by Taguchi analysis.

In the Taguchi method, the term 'signal' represents the desirable value (mean) for the response characteristic and the term 'noise' represents the undesirable value, i.e. standard deviation. Table 6 represents the S/N ratios corresponding to experimental results for all the features of bead geometry and HAZ. For the orthogonal experimental design, it is possible to separate out the effect of each welding parameter at different levels. For example, the mean S/N ratio for the current at levels 1, 2 and 3 can be calculated by averaging

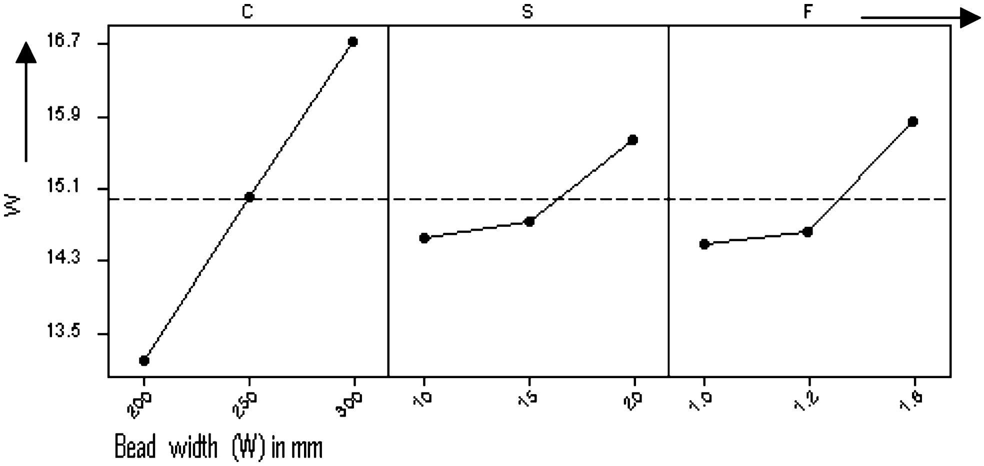
Table 8 Results of ANOVA for reinforcement

Source	DF	Seq SS	Adj SS	Adj MS	F	P
C	2	0.51576	0.51576	0.25788	7.32	0.120
S	2	0.00442	0.00442	0.00221	0.06	0.941
F	2	0.30782	0.30782	0.15391	4.37	0.186
Error	2	0.07049	0.07049	0.03524		
Total	8	0.89849				

Table 10 Results of ANOVA for HAZ width

Source	DF	Seq SS	Adj SS	Adj MS	F	P
C	2	1.4720	1.4720	0.7360	2.98	0.251
S	2	0.0428	0.0428	0.0214	0.09	0.920
F	2	0.0422	0.0422	0.0211	0.09	0.921
Error	2	0.4942	0.4942	0.2471		
Total	8	2.0511				

Fig. 6 Main effect plot of process parameters on bead width



the S/N ratios for the experiments 1–3, 4–6 and 7–9, respectively. The mean S/N ratio for each level of the other parameters can be computed in a similar manner. Figure 2 reveals the S/N response plot for bead width. The higher the S/N ratio is, the smaller is the variance of bead width around the desired target (lower-the-better). The S/N response graph for reinforcement, depth of penetration and HAZ width are shown in Figs. 3, 4 and 5, respectively. For all categories of quality performance criteria (LB or HB), the higher S/N ratio provided smaller variance of the output characteristics above the desired target. Results of ANOVA are shown in Tables 7, 8, 9 and 10. In the ANOVA tables here, degrees of freedom (DF) correspond to terms in a sum of squares (SS), which can be assigned arbitrarily. For example, the sum of deviations from the mean in a sample of n observations: $\sum (x-\overline{x})^2 = (x_1-\overline{x})^2 + (x_2-\overline{x})^2 + \ldots\ldots\ldots..(x_n-\overline{x})^2$ has n−1 degrees of freedom, because when (n−1) deviations are known, the nth deviation can be obtained from the identity $(x_1-\overline{x}) + (x_2-\overline{x}) + \ldots\ldots..(x_n-\overline{x}) = 0$.

Then n−1 degrees of freedom thus correspond to the n−1 independent comparisons, which can be made with the n observations [14]. Similar to factorial experiments, which are designed to enable comparisons to be made between the responses to the different treatment combinations, these comparisons can be associated with the degrees of freedom occurring in the analysis of variance.

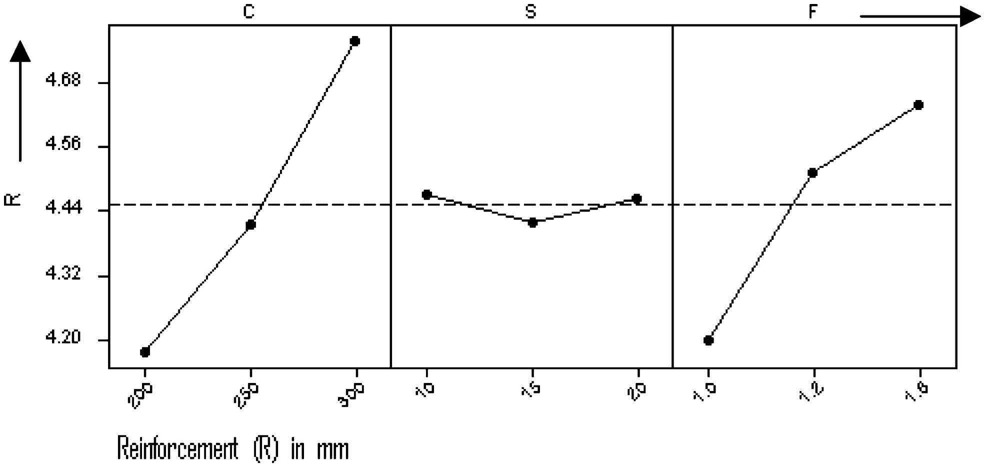
$$Mean\ square\ (MS) = \frac{Sum\ of\ square\ (SS)}{Degrees\ of\ freedom\ (DF)} \tag{3}$$

F is called the variance ratio. $F_{\text{calculated}}$ is defined as:

$$F_{\text{calculated}} = \frac{MS\ for\ any\ term\ (main\ or\ combined\ effect\ )}{MS\ for\ error\ term} \tag{4}$$

$F_{\text{calculated}}$, thus obtained, has to be compared with $F_{0.05}$ and $F_{0.01}$ (from standard F tables) for investigating whether the term (main effect or interactive effect) imposes a significant effect on selected response at 95% and 99% confidence levels, respectively [14, 15]. A factor is said to have significant effect on a response if the tabulated F value becomes less than the calculated F value. ANOVA has been performed in the statistical software package MINITAB. It uses the P-value, termed as probability of significance. P-value is calculated based on calculated F-value. P-value thus obtained is then compared with the Alpha-level. The

Fig. 7 Main effect plot of process parameters on reinforcement



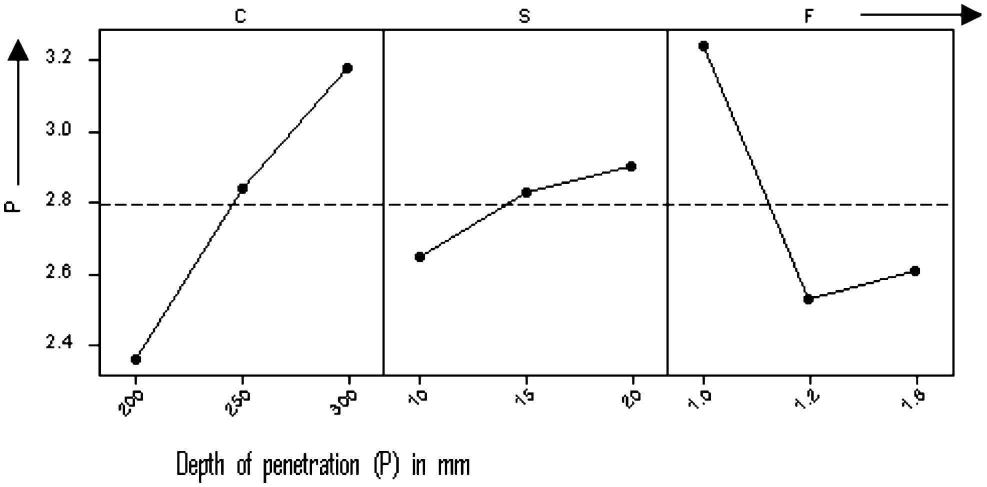


Fig. 8 Main effect plot of process parameters on depth of penetration

presumed Alpha level depends on the confidence level chosen. If the P-value appears less than 0.05, then it can be concluded that the corresponding factor has remarkable influence on the selected response, at 95% confidence level. In this paper interaction of factors has been neglected. If an interaction effect had been considered, then the Taguchi orthogonal array design would likely be changed, and a new experiment is to be performed. Moreover, literature depicted in the Reference list shows that in all cases the interaction effect was neglected while solving optimization problems using the Taguchi method.

ANOVA for the responses are shown in Tables 7, 8, 9 and 10. Figures 6, 7, 8 and 9 represent the main/direct effect plots for the factors welding current, slag-mix% and flux basicity on parameters of bead geometry and HAZ obtained using the statistical software package MINITAB release 13.1. Based on S/N analysis the optimal welding process condition has been determined. The optimal parametric combination for bead width becomes $C_1S_1F_1$. For bead width, reinforcement, depth of penetration and width of HAZ, the optimal parameter setting thus obtained $C_1S_1F_1$, $C_1S_2F_1$, $C_3S_3F_1$ and $C_1S_1F_1$, respectively. (Suffix represents factor level).

From the F distribution tables [14], in relation to the present case, $F_{0.01}$, $F_{0.05}$ and $F_{0.1}$ are 99, 19 and 9, respectively, at 90%, 95% and 99% confidence level. It is evident from Table 7 that the effect of welding current on bead width becomes significant at both 95% and 99% confidence levels (P-value less than 0.05). The effect of flux basicity index on bead width is significant at 99% confidence level only.

The effect of welding current, slag-mix% and flux basicity on reinforcement, depth of penetration and HAZ width appears insignificant (Tables 8, 9 and 10). However, it is clear from the main effect plots (Figs. 6, 7, 8 and 9) that the most influencing factor is current; with its positive effect on selected features of bead geometry and HAZ. With increase in slag-mix%, bead width, penetration and HAZ width increase (other parameters kept at constant level). Figure 7 shows that with an increase in slag-mix%, reinforcement first decreases then assumes an increasing trend. Flux basicity imposes a positive effect on bead width and reinforcement (Figs. 6 and 7). Figure 8 reveals that with increase in flux basicity, penetration first decreases and then tends to increase, while HAZ width first increases with increase in flux basicity and then follows a decreasing trend

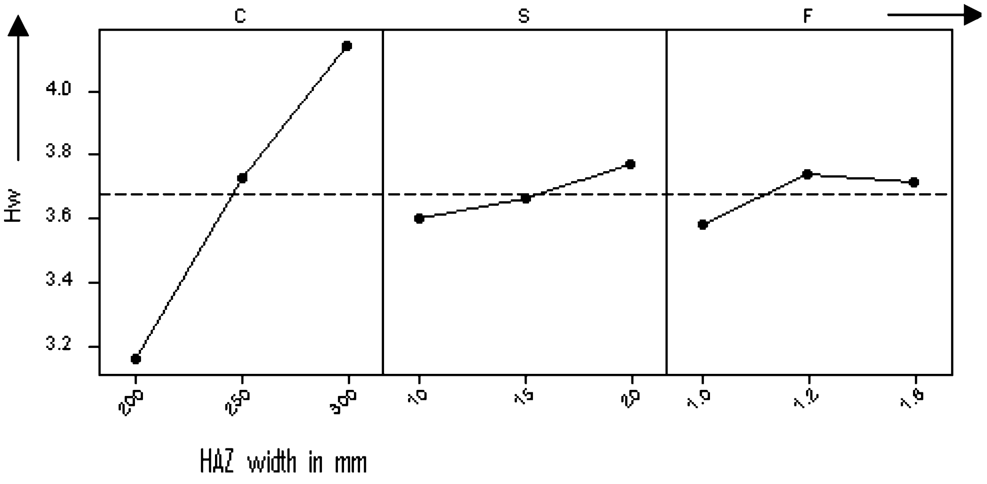


Fig. 9 Main effect plot of process parameters on HAZ width

Table 11 Results of the confirmatory test for bead width

	Initial welding parameters	Optimal welding parameters	
		Prediction	Experiment
Level	$C_2S_2F_2$	$C_1S_1F_1$	$C_1S_1F_1$
Bead width	14.41	12.32	12.36
S/N ratio (dB)	−23.17	−21.81	−21.84
Improvement in S/N ratio=1.33			

(Fig. 9). The figures reveal that all parameters affect/influence, to some extent, bead geometry and HAZ. But ANOVA in the present case does not strongly support this. This may be due to the fact that within a narrow experimental domain it was not possible to detect the variations in the process environment (parameter combination). A fairly broad experimental limit should be used to conduct experiments in order to fetch desirable results. There may be some interactive effect of factors present which have been ignored in the present case.

6 Verification of Taguchi's optimal result

After evaluating the optimal parameter settings, the next step of the Taguchi approach is to predict and verify the enhancement of quality characteristics using the optimal parametric combination. The estimated S/N ratio $\widehat{\eta}$ using the optimal level of the design parameters can be calculated as [13]:

$$\widehat{\eta} = \eta_m + \sum_{i=1}^{o} \left(\overline{\eta_i} - \eta_m \right) \tag{5}$$

where η_m is the total mean S/N ratio, $\overline{\eta_i}$ is the mean S/N ratio at the optimal level, and o is the number of the main design parameters that affect the quality characteristic. Tables 11, 12, 13 and 14 represent the comparison of the predicted bead geometry parameters with the actual parameters by using the optimal welding conditions; good agreement between the two has been observed. This proves the utility of the Taguchi approach in relation to product/process optimization.

Table 12 Results of the confirmatory test for reinforcement

	Initial welding parameters	Optimal welding parameters	
		Prediction	Experiment
Level	$C_2S_2F_2$	$C_1S_2F_1$	$C_1S_2F_1$
Reinforcement	4.6	3.92	4.01
S/N ratio (dB)	−13.26	−11.86	−12.06
Improvement in S/N ratio=1.2			

Table 13 Results of the confirmatory test for penetration

	Initial welding parameters	Optimal welding parameters	
		Prediction	Experiment
Level	$C_2S_2F_2$	$C_3S_3F_1$	$C_3S_3F_1$
Penetration	3.1	3.81	3.6
S/N ratio (dB)	9.83	11.61	11.13
Improvement in S/N ratio=1.3			

7 Conclusions

In the present study a detailed methodology of the Taguchi optimization technique has been reported and applied for evaluating optimal parametric combinations to achieve acceptable features of weld bead geometry and HAZ in submerged arc welding. The Taguchi method is very efficient for process/product optimization that can be performed in a limited number of experimental runs. It is always suggested to apply this technique in a large experimental domain. Apart from process optimization the study has introduced a new concept of slag consumption during subsequent runs of the SAW process. It has been shown that 10% slag-mix can be used to obtain optimum bead width and depth of HAZ, whereas 15% and 20% would yield optimal reinforcement and depth of penetration, respectively. The effect of varying control parameters on responses has also been shown in the paper as main effect plots. The aim of the study was to check the statistical significance of using fused slag in the conventional SAW process. The physics/physical interpretation behind the influence of slag-mix on bead geometry parameters has not been reported in the present paper. Regarding current and flux basicity index, the effect of these two conventional process parameters on features of bead geometry has been found to be consistent with the results of investigations performed by previous researchers. One of the next attempts by the present authors would be to investigate and analyze the physical interpretation on the effect of using slag-mix% on bead geometry, quality and performance of submerged arc welding. The study also focuses on 'interaction of factors' as a new consideration in

Table 14 Results of the confirmatory test for HAZ width

	Initial welding parameters	Optimal welding parameters	
		Prediction	Experiment
Level	$C_2S_2F_2$	$C_1S_1F_1$	$C_1S_1F_1$
HAZ width	4.04	2.94	2.71
S/N ratio (dB)	−12.13	−9.38	−8.66
Improvement in S/N ratio=3.47			

continuation of the present work. It is intended to be applied on the Taguchi method in future work.

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