Determination of submerged arc welding process parameters using Taguchi method and regression analysis

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This paper details the application of Taguchi technique and regression analysis to determine the optimal process parameters for submerged arc welding (SAW). The planned experiments are conducted in the semiautomatic submerged arc welding machine and the signal-to-noise ratios are computed to determine the optimum parameters. The percentage contribution of each factor is validated by analysis of variance (ANOVA) technique. Multiple regression analysis (MRA) is conducted using statistical package for social science (SPSS) software and the mathematical model is build to predict the bead geometry for any given welding conditions.

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Welding is a process of joining different materials. It is more economical and is a much faster process compared to both casting and riveting. SAW is one of the oldest automatic welding processes introduced in 1930s to provide high quality of weld\(^{1,2}\). The quality of weld in SAW is mainly influenced by independent variables such as welding current, arc voltage, welding speed and electrode stick out. The prediction of process parameters involved in SAW is a very complex process. Researchers have made many attempts to predict the process parameters of SAW to get a smooth quality of weld. Weimann elaborates the study of welding procedure generation for the submerged-arc welding process\(^3\). The structure of the dissimilar welds by SAW process was studied by McPherson\(^4\). The effect of increasing deposition rate on the bead geometry of submerged arc welds was studied by Chandel \(et\al\)\(^5\). Yang \(et\al\)\(^6\) studied the effects of SAW process variables on the weld deposit area. Prediction and optimization of weld bead volume for the SAW using mathematical models was carried out by Gunaraj \(et\al\)\(^7,8\). Prediction and control of weld bead geometry and shape relationships in submerged arc welding of pipes was studied by Murugan \(et\al\)\(^9\).

The quality engineering methods of Taguchi, employing design of experiments provide an efficient and systematic way to optimize designs for performance, quality and cost. It is one of the most important statistical tools for designing high quality systems at reduced cost\(^{10-12}\). The use of Taguchi method simplifies the optimization procedure for determining the optimal welding parameters in the SAW process. Unal and Dean\(^13\) explain the approach of Taguchi to obtain design optimization in the manufacturing process. Abdul Ghani Khan \(et\al\)\(^14\) explores the friction welding parameters that influence the output, namely tensile strength such as friction pressure, forging pressure, friction time and forging time using Taguchi method. Fujimoto Ryoichi\(^15\) proposed Taguchi method for the optimization of vibratory drill machining conditions for hard-to-cut-materials applied for aero-engine engineering development. Syrcos\(^16\) used Taguchi methods to optimize die-casting process. Chen \(et\al\)\(^17\) applied Taguchi method in the optimization of laser micro engraving of photo masks. Tarng \(et\al\)\(^18\) used grey-based Taguchi methods to determine submerged arc welding process parameters in hardfacing. Tang \(et\al\)\(^19\) used fuzzy logic in the Taguchi method for the optimization of the submerged arc welding process. The finite element analysis of SAW process using finite element package ABACUS was done by Wen \(et\al\)\(^20\). Yang \(et\al\)\(^21\) used linear-regression techniques to establish mathematical models for the prediction of SAW process parameters. Luke \(et\al\)\(^22\) developed multiple regression model to predict the surface roughness in turning operation via accelerometer. This paper focuses on Taguchi method, on design of

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experiments to build the mathematical model by multiple regression techniques for the prediction of weld geometry and weld bead hardness.

Submerged Arc Welding

The schematic diagram of the SAW process is shown in Fig. 1. Submerged arc welding involves formation of an arc between a continuously-fed bare wire electrode and the work-piece. The process uses a flux to generate protective gas and slag, and also helps to control the composition of the deposited metal by providing alloying elements to the weld pool. Prior to welding a thin layer of flux powder is placed on the work-piece surface. The arc moves along the joint line with the arc fully submerged in flux. As the arc is completely covered by the flux layer, heat loss is minimum. This provides a thermal efficiency as high as 95%. It produces no visible arc light, welding is spatter free and there is no need for fume extraction. The flux, apart from shielding the arc and the molten pool from atmospheric contamination, plays the following roles:

- The stability of the arc is dependent on the flux.
- Chemical and thus the mechanical properties of the weld metal can be controlled by flux.
- The quality of the weld may be affected by the quality and quantity of the flux used over the arc.

Taguchi method

The quality engineering methods of Taguchi, employing design of experiments (DOE), is one of the most important statistical tools for designing high quality systems at reduced cost. Taguchi methods provide an efficient and systematic way to optimize designs for performance, quality, and cost. Optimization of process parameters is the key step in the Taguchi method to achieving high quality without increasing cost. This is because optimization of process parameters can improve quality characteristics and the optimal process parameters obtained from the Taguchi method are insensitive to the variation of environmental conditions and other noise factors. Classical process parameter design is complex and not an easy task. To solve this task, the Taguchi method uses a special design of orthogonal arrays to study the entire process parameter space with a small number of experiments only. Furthermore, Taguchi has created a transformation of the repetition data to another value, which is a measure of the variation present. The transformation is known as signal-to-noise (S/N) ratio. The S/N ratio consolidates several repetitions (at least two data points are required) into one value, which reflects the amount of variation present. There are several S/N ratios available depending on the type of characteristic; lower is better (LB), nominal is best (NB), or higher is better (HB). The S/N ratio for each level of process parameters is computed-based on the S/N analysis. Regardless of the quality of the quality characteristic, a large S/N ratio corresponds to a better quality characteristic. Therefore, the optimal level of the process parameters is the level with the highest S/N ratio. A statistical analysis of variance (ANOVA) is performed to see which process parameters are statistically significant.

Experimental design and set-up

The experiment was conducted at M/s. Ind Auto Products, Tiruchirapalli, India, with the following set-up. SURARC semiautomatic SAW equipment with a constant-voltage, rectifier type power source with a 1200 A capacity was used to join the mild steel plates of size 500 mm (length) × 50 mm (width) × 6 mm (height). Copper coated electrodes AWS ER70S-6, 3.15 mm diameter, of coil form (ESAB brand) and basic-fluoride-type (equivalent to DIN 8557) granular flux was used. A square butt joint with a 1 mm root opening was selected to join the plates in the flat position, keeping the electrode positive and perpendicular to the plate. Samples of 10 mm width were cut from the test piece and were polished, etched and the bead geometries were measured. The hardness was tested by Rockwell hardness-testing machine.
with ‘C’ scale. Photographic view of typical welded sample is shown in Fig. 2.

**Process parameters levels**

The operating variables of SAW are welding current, arc voltage, welding speed, electrode diameter, electrode extension (length of stick out), type of flux, width and depth of flux layer and polarity and current type (AC or DC). Welding current directly influences the depth of penetration and the extend of base metal fusion. The welding arc voltage has a direct influence on the shape of weld bead and external bead appearance. The welding speed has a pronounced effect on the weld size and penetration for a given combination of welding current and welding voltage. At a given current the weld bead shape and the depth of penetration are affected by electrode diameter. The electrode stick out affects the deposition rate and the depth of penetration. Careful attention is necessary to select the welding process parameters to obtain a desirable weld quality. Though many direct and indirect parameters affect the quality of weld in SAW the major key process parameters affecting the bead geometry are arc voltage, welding current, welding speed and electrode stick out. In the present study, two-levels of the four process parameters, i.e., arc voltage, welding current, welding speed and electrode stick out was considered. The values of the welding process parameter at different levels are listed in Table 1.

There are 7 degrees of freedom owing to the four sets of two-level welding process parameters. In this study, an $L_8$ ($4^2$) orthogonal array, which has 7 degrees of freedom, was used. The experimental layout for the welding process parameters using the $L_8$ orthogonal array and the experimental results for the weld bead geometry using the $L_8$ orthogonal array are shown in Table 2.

**Orthogonal array experiment**

To select an appropriate orthogonal array for experiments, the total degrees of freedom are 7, which is the same as the number of process parameters. Therefore, the $L_8$ orthogonal array is suitable for the present study. The results show that the $S/N$ ratio for weld bead width is highest at level 1 of welding current and level 1 of arc voltage, which is the best combination of welding parameters for good weld quality.

Table 2 — Experimental layout using L8 orthogonal array and S/N ratio for weld bead width

<table>
<thead>
<tr>
<th>Trial Nos.</th>
<th>A Welding current, A</th>
<th>B Arc Voltage, V</th>
<th>C Welding speed, mm/min</th>
<th>D Electrode stick out, mm</th>
<th>Measured bead width, mm</th>
<th>MSD (mean square deviation)</th>
<th>S/N ratio</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>13</td>
<td>169</td>
<td>22.28</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>11</td>
<td>121</td>
<td>20.83</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>12.5</td>
<td>156.25</td>
<td>21.94</td>
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<tr>
<td>4</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>13.5</td>
<td>182.25</td>
<td>22.61</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>14.5</td>
<td>210.25</td>
<td>23.23</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>14.0</td>
<td>196</td>
<td>22.92</td>
</tr>
<tr>
<td>7</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>14.5</td>
<td>210.25</td>
<td>23.23</td>
</tr>
<tr>
<td>8</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>15</td>
<td>225</td>
<td>23.52</td>
</tr>
</tbody>
</table>

| Grand average of performance | 22.57 |

Fig. 2 — Typical photographic view of weld samples
computed. The degrees of freedom are defined as the number of constraints between process parameters that must be made to determine which level is better and, specifically, how much better it is. The degrees of freedom associated with interaction between two process parameters are given by the product of the degrees of freedom for the two process parameters. In the present study, the interaction between the welding parameters is neglected. Therefore, there are five degrees of freedom owing to the five sets of welding parameters in the submerged arc welding process.

Once the degrees of freedom are known, the next step is to select an appropriate orthogonal array to fit the specific task. The degrees of freedom for the orthogonal array should be greater than or at least equal to those for the process parameters. In this study, an $L_8$ orthogonal array with five columns and eight rows was used. This array has seven degrees of freedom and it can handle two-level process parameters. Each welding parameter is assigned to a column and eight welding parameter combinations are available. Therefore, only eight experiments are required to study the entire welding parameter space using the $L_8$ orthogonal array.

**Overall loss function and signal-to-noise ratio**

The control factors that may contribute to reduce variation (improved quality) can be quickly identified by looking at the amount of variation present as a response. The bead width, weld reinforcement, depth of penetration of the weld bead geometries and weld bead hardness belong to higher-the-better quality characteristic. The loss function of the higher-the-better quality characteristic can be expressed as:

$$L_{ij} = \left( \frac{1}{r} \sum_{i=1}^{r} \frac{1}{y_{ijk}} \right)^2$$  \hspace{1cm} (1)

where $L_{ij}$ is the loss function of the $i^{th}$ quality characteristic in the $j^{th}$ experiment, $r$ is the number of test, and $y_{ijk}$ the experimental value of the $i^{th}$ quality characteristic in the $j^{th}$ experiment at the $k^{th}$ test. As a result, four quality characteristics corresponding to the bead width, reinforcement, penetration of the weld bead geometry and hardness are obtained using Eq. (1).

The overall loss function is further transformed into the signal-to-noise (S/N) ratio. In the Taguchi method, the S/N ratio is used to determine the deviation of the quality characteristic from the desired value. The S/N ratio $\eta_j$ in the $j^{th}$ experiment can be expressed as:

$$\eta_j = -10 \log (L_{ij})$$  \hspace{1cm} (2)

The S/N ratio corresponding to the overall loss function is shown in Table 2.

Similarly the S/N ratios for weld reinforcement, depth of penetration and weld bead hardness was found separately. The largest signal-to-noise ratio (average) is the optimum level, because a high value of signal-to-noise ratio indicates that the signal is much higher than the random effects of the noise factors. Table 3 shows the calculation of the average S/N ratios for welding current, arc voltage, welding speed and weld bead hardness.

The largest S/Navg for parameter is indicated by (opt) and the effect is shown in the Fig. 3. The dash line shown in Fig. 3 indicates the grand average of performance. The welding process parameter performance levels are shown in Fig. 3. From Table 3 the optimal bead width is obtained by applying

<table>
<thead>
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<th>Table 3 — Average S/N ratio for bead width</th>
</tr>
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<tbody>
<tr>
<td>Weld parameters</td>
</tr>
<tr>
<td>-------------------</td>
</tr>
<tr>
<td>Welding current, A</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Arc Voltage, V</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Welding Speed, mm/min</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Electrode Stick out, mm</td>
</tr>
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<td></td>
</tr>
</tbody>
</table>

Fig. 3 — Effect of controllable factor (bead width) on S/N ratio
welding current 390 A, arc voltage 26 V, welding speed 420 mm/min, and electrode stickout 19 mm for a plate of 6 mm thickness, i.e., A1-B2-C2-D1. Similarly the results for weld reinforcement, depth of penetration and weld bead hardness and their corresponding optimum levels obtained are A2-B2-C1-D1, A2-B1-C2-D2, and A2-B1-C2-D1.

Analysis of Variance

Analysis of variance is done using SPSS software. The ANOVA table for weld bead width is shown in Table 4. Analysis of bead width through ANOVA shows that welding current and arc voltage are the significant welding process parameters that affect the width of weld bead. Similarly ANOVA is carried out for other weld parameters, which shows that welding current has a major effect on weld bead hardness and the electrode stickout has minor effect on weld bead. Welding current and arc voltage have equal effects on bead reinforcement. Welding speed and welding current have major influence on depth of penetration of bead whereas arc voltage has a little effect on it. Electrode stickout has very little influence on weld parameters. Confirmation of experiment showed that the experimental observations are within 95% confidence level.

Multiple regression analysis

Multiple regressions technique is used to ascertain the relationships among variables. The most frequently used method among social scientists is that of linear equations. The multiple linear regressions take the following form:

\[ Y = a + b_1X_1 + b_2X_2 + b_3X_3 + \ldots + b_kX_k \]  ...(3)

where \( Y \) is the dependent variable, which is to be predicted; \( X_1, X_2, X_3, \ldots, X_k \) are the \( k \) known variables on which the predictions are to be made and \( a, b_1, b_2, b_3, \ldots, b_k \) are the coefficients, the values of which are determined by the method of least squares.

Multiple regression analysis is used to determine the relationship between the dependent variables of bead width, weld reinforcement, depth of penetration and weld bead hardness with welding current, arc voltage, welding speed and electrode stickout. The regression analysis was done by SPSS, a commercial statistical program. The regression analysis of the input parameters is expressed in linear equations as follows:

Bead width = -34.833 + (6.667×10\(^{-2}\) × welding current) + (0.75 × arc voltage) + (1.25×10\(^{-2}\) × welding speed) – (4.17×10\(^{-2}\) × electrode stickout)  ...(4)

Weld reinforcement = -7.25 + (8.33×10\(^{-3}\) × welding current) + (0.25 × arc voltage)  ...(5)

Depth of penetration = 16.25 + (2.5 ×10\(^{-2}\) × welding current) – (0.25 ×arc voltage) – (3.75×10\(^{-2}\) × welding speed)  ...(6)

Weld bead hardness = -69.333 + (0.367 × welding current) - (1.0 × arc voltage) + (2.5 ×10\(^{-2}\) × welding speed)-(0.417 × electrode stickout)    ...(7)

From the above equations, values of bead width, weld reinforcement, depth of penetration and weld bead hardness can be predicted for any given values of process parameters.

<table>
<thead>
<tr>
<th>Weld parameters</th>
<th>Sum of squares</th>
<th>Degrees of freedom</th>
<th>Variance</th>
<th>F-value</th>
<th>Significance</th>
<th>% of contribution</th>
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<tr>
<td>Current</td>
<td>8.0</td>
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<td>8.0</td>
<td>12.0</td>
<td>0.013</td>
<td>66.67</td>
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<tr>
<td>Voltage</td>
<td>1.125</td>
<td>1</td>
<td>1.125</td>
<td>0.621</td>
<td>0.461</td>
<td>9.38</td>
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<tr>
<td>Speed</td>
<td>0.125</td>
<td>1</td>
<td>0.125</td>
<td>0.063</td>
<td>0.810</td>
<td>1.04</td>
</tr>
<tr>
<td>Electrode Stickout</td>
<td>0.125</td>
<td>1</td>
<td>0.125</td>
<td>0.063</td>
<td>0.810</td>
<td>1.04</td>
</tr>
<tr>
<td>Error</td>
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<td>12.0</td>
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</table>
Results and Discussion

Economical layout of welding experiments is optimized by the Taguchi method on design of experiments. The results from ANOVA indicate that welding current and arc voltage are the significant welding process parameters that affect the bead width. The mathematical model is build by SPSS Package for bead width, bead reinforcement, depth of penetration and bead hardness. The output results from the predicted model are calculated for the corresponding input data. Measured values from the experiment and the predicted values from the multiple regression technique are shown in Tables 5 and 6. Comparisons of bead width, weld reinforcement,
depth of penetration and weld bead hardness between
the experimental values and the predicted multiple
regression analysis model are given in Figs 4-7.

Conclusions
This paper has presented the application of Taguchi
technique and regression analysis to determine the
optimal process parameters for SAW process.
Experimentation was done according to the Taguchi’s
design of experiments. Using the signal-to-noise ratio
and the ANOVA technique the influence of each
welding parameters are studied and the prediction of
the bead geometry is done by building a mathematical
model in SPSS. The proposed mathematical model is
used to predict the SAW process parameters for any
given welding conditions.

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The authors express their sincere thanks to the
Ministry of Human Resource Development [MHRD],
Government of India for the sponsorship under its
Research and Development program.

Table 6 — Results from multiple regression analysis

<table>
<thead>
<tr>
<th>Weld bead width, mm</th>
<th>Weld reinforcement, mm</th>
<th>Depth of penetration, mm</th>
<th>Weld bead hardness, HRC</th>
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<tbody>
<tr>
<td>12.3759</td>
<td>1.9988</td>
<td>4</td>
<td>40.364</td>
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