Multi-objective Optimization of Resistance Spot Welding of AISI 409M Ferritic Stainless Steel

A Subrammanian1,*, D B Jabaraj2 and J Jayapракash3

1St Peters University, Avadi, Chennai, 600054, India
2, 3 Dr MGR Educational and Research Institute University, Maduravoyal, Chennai, 600095, India

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Resistance spot welding is a widely used sheet metal joining process in automobile and rail car manufacturing industries. One of the most important quality characteristics of a spot welded joint is its tensile shear strength, as it is crucial in improving the crashworthiness of the vehicle. Amount of indentation made by the electrode on the surface of the sheet during spot welding, is another quality characteristic that needs to be minimized, to improve the surface finish and aesthetic value. Ensuring maximum strength of the spot weld joint, while keeping indentation at the minimum level is one of the major challenges in spot welding. In this work, multi-objective Taguchi method has been applied for optimization of various input parameters in resistance spot welding of AISI 409M ferritic stainless steel sheets, to maximize the tensile shear strength of the weld joint and minimize the surface indentation simultaneously. Furthermore, a linear response surface model has been developed to correlate tensile shear strength and indentation values with process parameters. The optimum values of control parameters were 11.5 KA for current, 14 cycles for weld time and 3.5 KN for electrode force. Current was found to be the most influential parameter affecting tensile shear strength and indentation. Results of the optimization process were validated by confirmation test.

Keywords: Resistance Spot Welding, Optimization, Indentation, AISI 409M, Ferritic Stainless Steel, Tensile Shear Strength

Introduction

Resistance Spot Welding (RSW) is a metal joining process, in which two sheets of metal are joined together, making use of resistance heating which takes place when current is passed through the sheets1. RSW is usually used in fabrication of sheet metal assembly2. There are around 2000 to 5000 spot welds in a modern vehicle3. Major advantages of RSW are simplicity, low cost, high speed and possibility of automation4. Ferritic stainless steels account nearly half of the AISI 400 series stainless steels. They are considered as cheaper substitutes to austenitic stainless steels, because of the lower nickel content5. Off late, ferritic stainless steels (FSS) are increasingly used for the fabrication of rail wagons6. Taguchi method is a simple and efficient approach for optimization of process parameters7. Taguchi approach makes use of a loss function to measure the deviation of the observed value of the quality characteristics, from the desired value. This loss function value is further converted in to a value, known as signal-to-noise ratio (S/N ratio). The level corresponding to the highest S/N ratio is taken as the optimum level. Also, analysis of variance (ANOVA), a statistical tool, can be used to estimate the relative significance of control factors on output quality characteristics8-12. Often, the overall performance of a product is related to more than one quality characteristic. It is quite possible that, optimizing parameters for a single quality characteristic may end up in deteriorating the other quality characteristics. Hence, more often than not, situations arise, wherein it is required to optimize parameters for multiple quality characteristics, rather than for a single quality characteristic13. Multi response optimization approach, based on Taguchi’s loss function, was used in some studies in the past for optimization of multiple quality characteristics simultaneously13-16. In this paper, an attempt is made to optimize the RSW parameters by using multi-objective Taguchi method to achieve maximum weld strength with minimum surface indentation, and also to analyze the influence of various input parameters on the output parameters, with the help of ANOVA, in RSW of AISI 409M ferritic stainless steel. Also, with response surface methodology (RSM), a linear first order surface
response model for prediction of tensile shear strength and indentation values has been developed, using MINITAB software.

**Multi-objective Taguchi method**

In multi-objective Taguchi approach, an overall signal to noise ratio is calculated from the quality loss functions of various control parameters. This overall S/N ratio is known as multi-response S/N ratio (MSNR). In order to calculate the multi response signal to noise ratio, the following steps are used\textsuperscript{13-16}. Quality loss values for different quality characteristics corresponding to each combination of parameters are calculated at first ($L_{ij}$ & $L_{ij}$). Subsequently, the normalized quality loss values for the response parameters are calculated ($N_{ij}$ & $N_{ij}$). Next step is to calculate the total normalized quality loss values ($T_{Lj}$), assigning appropriate weighting to each response parameter. Finally, from the total normalized quality loss value, MSNR is calculated.

**Experimental materials and methods**

**Material**

Cold rolled sheets of 2mm thickness ferritic stainless steel AISI 409M were used in this study. The tensile shear test specimens were prepared according to ISO 14273 standards. Size of the specimen used in this study is as given in Figure 1. Specimens were thoroughly cleaned with acetone before welding, to remove any dirt, oil or grease. Chemical composition of the material was tested with spectrometer, make-BAIRD Spectrovac 2000, model- DV6. Percentage by weight of important alloying elements such as chromium, nickel, carbon and manganese, in the test material were found to be 11.654, 0.276, 0.011 and 0.876 respectively. Tensile strength and hardness values of the material used in the experiment are 460 MPa and 178 Hv respectively. Electrode used for welding was of RWMA class 3, water cooled, truncated cone type with a tip diameter of 8mm.

**Orthogonal array and control parameters**

Based on the reported literatures\textsuperscript{11,12,14} on RSW and preliminary trials, three control parameters, weld current, weld time and electrode force were selected for optimization. Three levels were fixed for each control parameter, based on preliminary trials. Degree of freedom (DOF) of each parameter in this case is 2, making it a total of 6, for all the three parameters together. DOF of the orthogonal array must be more than or equal to the sum of individual DOF of all the control parameters\textsuperscript{10}. Hence L9 orthogonal array was chosen for the experiment, which has a DOF of 8. For weld current, the chosen levels were 10 KA (Kilo Ampere), 11.5 KA and 13 KA for level 1, 2 and 3 respectively. Similarly for weld time, corresponding levels were 10 cycles, 12 cycles and 14 cycles respectively (1 cycle = 20 milli seconds). Also, the three levels for electrode force have been chosen as 2.5 KN (Kilo Newton), 3 KN and 3.5 KN as level 1, level 2 and level 3 respectively.

**Tensile shear test and indentation measurement**

Tensile shear test using test samples was carried out on a universal testing machine, make-TE-JINAN and model- WDW 100. Tensile shear strength (TSS) was recorded for each test sample. Indentation (In) caused by the electrode at each weld spot was measured, using a digital depth gauge of 0.01mm accuracy. Three measurements were taken at each spot and the average was used for subsequent analysis.

**Results and Discussion**

From the observed average values of tensile shear strength and indentation, loss functions/ corresponding normalized loss functions values have been determined. Next step is to calculate the total normalized quality loss values ($T_{Lj}$) corresponding to each combination of control parameters, applying weights to each response values. Weighting factors are to be decided based on priorities among responses to be optimized\textsuperscript{14,17}. In this experiment, a weighting factor (w1) of 0.8 was assigned to tensile shear strength and another weighting factor (w2) of 0.2 was assigned to indentation. Higher weighting factor was assigned to tensile shear strength, as it is the most important attribute in a spot welded joint, directly contributing to the reliability of the product and passenger safety as in the case of a railcar fabricated by RSW, unlike indentation. Furthermore, weighting factors of 0.8 and 0.2 were used in some of the reported works in the past, wherein out of the two responses, one was extremely important compared to the other one\textsuperscript{13,15}. Therefore, total normalized quality loss values ($T_{Lj}$) were
calculated. From the total normalized quality loss values, signal to noise ratio was calculated. All of these values are presented in Table 1. The mean S/N ratio of various levels of each control parameter is calculated and is tabulated as shown in Table 2. The level with the largest S/N ratio is the optimum level for that particular control factor. It can be seen from the table that the optimum levels for current, weld time and electrode force in this experiment are A2, B3 and C3 respectively (Figure 2). Also, the parameter with which, the difference between maximum and minimum S/N ratios (represented by delta in Table 2) is the largest, will have the largest influence on the output parameters. Accordingly, here, current is the largest influencing parameter, followed by weld time and electrode force. ANOVA has been used to determine the level of significance of each of the control parameter in both maximizing the tensile shear strength and minimizing the indentation simultaneously. The results of the ANOVA are given in Table 3. The percentage contribution of each control factor towards maximizing the tensile shear strength and minimizing indentation is given in the ANOVA table. In the present experiment, current has the largest influence (60.86%) on the multiple response parameters of both tensile shear strength and indentation, followed by weld time (19.77%) and electrode force (13.99%). F value is determined, to identify the parameters which have significant effect on the response parameters. For a control parameter with large F value, even a small variation in its value can alter the output response value significantly.

**Response surface modelling (RSM)**

A linear first order surface response model was developed using RSM in MINITAB software, for correlating both tensile shear strength and indentation, with the input parameters, from the experimental data. The following equations were developed.

Tensile shear strength (in KN)

\[ y = -5.440 + 1.1778A + 1.0950B - 0.3133C \]  

… (1)

Indentation (in mm)

\[ y = -0.19611 + 0.01667A + 0.01750B - 0.02333C \]  

… (2)

where, A is welding current, B is welding time and C is electrode force. For tensile shear strength, R-Sq = 80.34% at 95% confidence level. For indentation, R-Sq = 97.3% at 95% confidence level. From the results given above, it can be noticed that the regression coefficient value (R), for tensile shear strength is

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**Table 1 — Calculation of S/N ratio from measured responses**

<table>
<thead>
<tr>
<th>Trial No</th>
<th>Average TSS (KN)</th>
<th>Average In (mm)</th>
<th>Loss functions (TSS) ( L_{ij} )</th>
<th>Loss functions (In) ( L_{ij} )</th>
<th>Normalised loss functions (TSS) ( N_{ij} )</th>
<th>Normalised loss functions (In) ( N_{ij} )</th>
<th>Total loss functions ( TL_{ij} )</th>
<th>Signal to Noise ratio ( \eta_{ij} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15.64</td>
<td>0.09</td>
<td>0.00409</td>
<td>0.0081</td>
<td>1.6015</td>
<td>0.41047</td>
<td>1.36327</td>
<td>-1.34582</td>
</tr>
<tr>
<td>2</td>
<td>18.02</td>
<td>0.11</td>
<td>0.00308</td>
<td>0.0121</td>
<td>1.2064</td>
<td>0.61318</td>
<td>1.08774</td>
<td>-0.36524</td>
</tr>
<tr>
<td>3</td>
<td>19.58</td>
<td>0.13</td>
<td>0.00261</td>
<td>0.0169</td>
<td>1.0218</td>
<td>0.85642</td>
<td>0.98873</td>
<td>0.04924</td>
</tr>
<tr>
<td>4</td>
<td>19.80</td>
<td>0.09</td>
<td>0.00255</td>
<td>0.0081</td>
<td>0.9992</td>
<td>0.41047</td>
<td>0.88147</td>
<td>0.54791</td>
</tr>
<tr>
<td>5</td>
<td>21.92</td>
<td>0.13</td>
<td>0.00208</td>
<td>0.0169</td>
<td>0.8153</td>
<td>0.85642</td>
<td>0.82351</td>
<td>0.84329</td>
</tr>
<tr>
<td>6</td>
<td>23.94</td>
<td>0.19</td>
<td>0.00175</td>
<td>0.0361</td>
<td>0.6835</td>
<td>1.82939</td>
<td>0.91269</td>
<td>0.39679</td>
</tr>
<tr>
<td>7</td>
<td>18.64</td>
<td>0.12</td>
<td>0.00288</td>
<td>0.0144</td>
<td>1.1274</td>
<td>0.72973</td>
<td>1.04791</td>
<td>-0.20325</td>
</tr>
<tr>
<td>8</td>
<td>21.50</td>
<td>0.17</td>
<td>0.00216</td>
<td>0.0289</td>
<td>0.8474</td>
<td>1.46453</td>
<td>0.97087</td>
<td>0.12840</td>
</tr>
<tr>
<td>9</td>
<td>23.70</td>
<td>0.19</td>
<td>0.00178</td>
<td>0.0361</td>
<td>0.6974</td>
<td>1.82939</td>
<td>0.92382</td>
<td>0.34415</td>
</tr>
</tbody>
</table>
moderately high and that of indentation is very high, hence it can be reasonably concluded that the data is in good agreement with the developed models.

**Confirmation test**

After identifying the optimum level of parameters, the final step is to predict and verify the adequacy of the model. A set of confirmation experiments was conducted to validate the conclusions drawn, during the previous phase. Specific combination of optimum parameters already arrived at, has been used for the confirmation experiment. The mean S/N ratio of the experiment at the preferred combination of the levels can be predicted using the formula given below\(^\text{17}\).

\[
\mu_{A_2B_2C_1} = \bar{A_2} + \bar{B_3} + \bar{C_3} - 2\bar{T} \quad \ldots (3)
\]

where \(\bar{A_2}, \bar{B_3}\) and \(\bar{C_3}\) are the average S/N ratios corresponding to the optimum levels and \(\bar{T}\) is the overall mean S/N ratio of all the trials. Here, the predicted S/N ratio, according to the formula given above, is 1.001 dB (decibel). Usually the result of a confirmation experiment is considered satisfactory, when the observed mean result falls within certain limits, above and below the predicted mean. Such a limit for the predicted mean is known as confidence interval (CI), and it is calculated at a confidence level. Confidence interval for the predicted result can be calculated using the equation given below\(^\text{12, 18}\).

\[
CI = \left( F_{\alpha(1, f_e)} V_e \left[ \frac{1}{N_{eff}} + \frac{1}{R} \right] \right)^{\frac{1}{2}} \quad \ldots (4)
\]

where \(F_{\alpha(1, f_e)}\) is the F ratio required for a risk, \(\alpha = 0.05\), \(f_e\) = degree of freedom of error, \(V_e =\) error variance and \(N_{eff}\) = the effective number of repetitions = \(N/[1+\text{Total degrees of freedom associated with the estimate of mean}]\), \(R\) is the number of repetition for the confirmation experiment. In this experiment, \(F_{0.05(1, 12)} = 18.5\), \(V_e = 0.088144\), \(N_{eff} = 45/(1+2+2+2) = 6.428\), and \(R=5\). Hence calculated \(CI = \pm 0.761\). Predicted S/N ratio = (1.001 –CI) < \(\mu\) < (1.001 + CI) = 0.240 < \(\mu < 1.760\). Confirmation of test was carried out with the optimum set of parameters. The observed S/N ratio was found to be 1.120 dB against the predicted S/N ratio 1.001 dB. The prediction error of 0.119 is much less than the calculated CI value and furthermore, the observed S/N ratio is well within the confidence interval of the predicted result, at 95% confidence level. The observed tensile shear strength and indentation values of the confirmation experiment were 24 KN and 0.15 mm respectively.

**Conclusion**

Multi objective Taguchi approach has been used to optimize the parameters for RSW of AISI409M ferritic stainless steel, considering tensile shear strength and indentation as quality characteristics, simultaneously. The following are the results of the study.

- The optimum level of parameters for maximum tensile strength with minimum indentation was found to be as follows. Current 11.5 KA, weld time 14 cycles and electrode force 3.5KN.
- The welding current is the predominant contributor (60.86%) for maximizing tensile strength with minimum indentation, followed by weld time (19.77%) and electrode force (13.99%) respectively.
- The results were verified by confirmation test and S/N ratio was found to be increased. Also, the observed result was within the 95% confidence interval of the predicted optimal result.
- A linear response surface model was developed to predict tensile shear strength and indentation values. The developed model was found to be well fitted.

This study is expected to be helpful in developing welding procedure specification (WPS) for RSW, in fabrication of railcar body of enhanced surface finish without compromising much on weld joint strength.

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Railways, Chennai, India, for extending facilities of Chemical and Metallurgical Testing Laboratory, to carry out this investigation.

References