Effect of Multi-Objective Optimization for Double Pulse Resistance Spot Welded Joints of Ferritic Stainless Steel

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Abstract

In this research work, an attempt is made to optimize the parameters of double pulse resistance spot welding process of AISI 409M ferritic stainless steel sheets by multi objective Taguchi approach. The tensile shear strength of the weld joint and indentation at the weld surface are taken as the response quality characteristics, which are required to be maximized and minimized respectively. Three control parameters, such as second pulse current, second pulse weld time and cooling time were taken for the analysis. Furthermore, a linear response surface model has been developed to correlate tensile shear strength and indentation values with process parameters. The results showed that, the second pulse current value was found to be the most influential parameter affecting tensile shear strength and indentation in double pulse resistance spot welding. Results of the optimization process were also validated by confirmation test.

Keywords: Double pulse, Resistance spot welding, optimization, indentation, ferritic stainless steel, tensile shear strength.

1. Introduction

Resistance Spot Welding (RSW) is extensively being used as a sheet metal joining process, in which sheets are joined by resistance heating which takes place when current is passed through the sheets [1,2]. RSW is a major welding process in automobile and rail car manufacturing. A modern vehicle has around 2000 to 5000 spot welds [3]. Main advantages of RSW are simplicity, low cost, high speed and possibility of automation [4]. Ferritic stainless steels account nearly one half of the AISI 400 series stainless steels. They are considered as cheaper substitutes to austenitic stainless steels, because of the lower nickel content [5]. Off late, ferritic stainless steels (FSS) are increasingly used in structural frameworks and body panelling of buses and rail coaches [6, 7]. Taguchi methods have proved to be successful in the past, in improving product quality and process performance. It emphasizes a mean performance characteristic value close to the target value, rather than a

value within certain specification limits and this loss function value is further converted into signal-to-noise ratio (S/N ratio). The analysis of variance (ANOVA) is a statistical tool, can be used to estimate the relative significance of control factors on output quality characteristics [8-9]. Many researchers attempted optimization of parameters of resistance spot welding in the past [10], The optimized resistance spot welding parameters of low carbon steel sheets of varying thickness and to improve the strength of the weld joint using Taguchi method [11]. Multi response optimization approach based on Taguchi's loss function was used in some studies in the past for optimization of multiple quality characteristics simultaneously One of the prime quality characteristic in resistance spot welding process is the tensile shear strength of the welded joint, as it is crucial in improving the crashworthiness of the vehicle. At the same time, the 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. Achieving maximum weld strength, while keeping indentation at the minimum level is one of the major challenges in spot welding process [12-13]. One of the ways to improve the mechanical performance of a resistance spot welded joint is by adding a second pulse current in addition to single pulse current [14]. A local post heat treatment can be accomplished by introducing a second pulse current just after the primary current pulse [15]. The double pulse spot welding is one of the most efficient methods to modify the microstructure of the weld nugget and thus its mechanical properties [16]. This research work reports optimization the double pulse RSW parameters of AISI 409M ferritic stainless steel, by using multi-objective Taguchi method to maximize 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. Furthermore, with response surface methodology (RSM), a linear first order surface response model for prediction of tensile shear strength and indentation values have 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 [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 (TL_j), assigning appropriate weighting to each response parameter. Finally, from the total normalized quality loss value, MSNR is calculated.

2. 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. The dimension of the specimen used in this study is as given in Fig 1. Specimens were

thoroughly cleaned with acetone before welding, to remove any dirt, oil or grease. Chemical composition and physical properties of the material is as given in Table 1 and Table 2. Electrode used for welding was of RWMA class 3, water cooled, truncated cone type with a tip diameter of 8mm.

Table 1: Chemical composition of test materials (percentage by weight).

Grade	C	Si	Mn	P	S	Cr	Cu	Ni	Nb	Mo	Fe
AISI 409M	0.011	0.561	0.876	0.012	0.012	11.654	0.062	0.276	0.006	0.013	Balance

Table 2: Physical properties of test materials

Material	Yield strength (MPa)	Tensile strength (Mpa)	Elongation %	Hardness (Hv)
Ferritic stainless steel AISI 409M	240	450	22	168

Fig 1-Test specimen size

Orthogonal array and control parameters

Based on the reported literatures^{8, 11, 12, 15} on RSW and preliminary trials, three control parameters, second pulse weld current, second pulse weld time and cooling time, were chosen for optimization. Basic parameters such as, First pulse current value, first pulse weld time value and the corresponding electrode force were kept same for all the experiment trials. The values for the above mentioned parameters were chosen as 13 KA, 12 cycles and 3.5 KN respectively based on preliminary trials and reported literature¹⁵. For experimentation, three levels were fixed for each of the three control parameters, based on preliminary trials as given in Table-3. 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 individual control parameters¹⁰. Hence L9

orthogonal array was chosen for the experiment, which has a DOF of 8. A total of three sets of experiments were conducted and the average values were taken for calculation.

Table 3- Control factors and their levels

Symbol	Factors	Unit	Level 1	Level 2	Level 3
A	Second pulse current	kA	6	9	12
B	Second pulse weld time	Cycles	6	9	12
C	Cooling time	Cycles	10	20	30

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.

3. 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 (TL_j) 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 optimized¹³. In this experiment, a weighing 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 significant attribute in a spot welded joint, directly affecting the safety and reliability of the product, unlike indentation. Furthermore, weighting factors of 0.8 and 0.2 were used in some of the reported works in the past, on similar situations^{8, 12, 15}.

Thereafter, total normalized quality loss values (TL_j) were calculated. From the total normalized quality loss values, signal to noise ratio was calculated. All of these values are presented in Table 4.

Table 4-Calculation of S/N ratio from measured responses

Tra il No.	Average TSS (KN)	Average In (mm)	Loss functions (TSS) L_{ij}	Loss functions (In) L_{ij}	Normalised loss functions (TSS) N_{ij}	Normalised loss functions (In) N_{ij}	Total loss functions TL_j	Signal to Noise ratio η_j
1	25.98	0.1	0.0015	0.0100	1.3318	0.4599	1.1574	-0.6348
2	28.02	0.09	0.0013	0.0081	1.1449	0.3725	0.9904	0.0417
3	29.53	0.16	0.0011	0.0256	1.0308	1.1773	1.0601	-0.2536
4	28.97	0.14	0.0012	0.0196	1.0711	0.9014	1.0371	-0.1583
5	31.25	0.13	0.0010	0.0169	0.9205	0.7772	0.8918	0.4972
6	33.2	0.19	0.0009	0.0361	0.8155	1.6602	0.9845	0.0680
7	29.51	0.12	0.0011	0.0144	1.0322	0.6622	0.9582	0.1853
8	32.45	0.17	0.0009	0.0289	0.8537	1.3291	0.9487	0.2285
9	33.53	0.19	0.0009	0.0361	0.7995	1.6602	0.9717	0.1248

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 second pulse current, second pulse weld time and cooling time in this experiment are A3, B2 and C3 respectively (Fig.2). Also, the parameter with which, the difference between maximum and minimum S/N ratios (represented by delta in Table 5) is the largest, will have the largest influence on the output parameters¹². Accordingly, here, second pulse current is the largest influencing parameter, followed by second pulse weld time and cooling time in succession

Table 5- Mean S/N Ratio

Symbols	Factors	Level 1	Level 2	Level 3	Delta	Rank	Max at level
A	Second pulse welding current	-0.2822	0.1357	0.1795	0.4618	1	A3
B	Second pulse weld time	-0.2026	0.2558	-0.0202	0.4584	2	B2
C	Cooling time	-0.1128	0.0027	0.1430	0.2558	3	C3

Fig. 2- SN ratio graph

ANOVA has been used to determine the level of significance of each of the control parameters in both maximizing the tensile shear strength and minimizing the indentation simultaneously. The results of the ANOVA are given in Table 6. 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 work, second pulse current has the largest influence (46.02%) on the multi-response parameters of both tensile shear strength and indentation, followed by second pulse weld time (37.74%) cooling time (11.62%) and. F value is determined, to identify the control 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 significantly¹¹.

Table 6-ANOVA table

Factors	Degree of Freedom	Sum of squares	Mean squares	F Ratio	Percentage contribution
Second pulse welding current	2	0.3898	0.1949	9.9439	46.01
Second pulse weld time	2	0.3196	0.1598	8.1546	37.74
Cooling time	2	0.0984	0.0492	2.5109	11.62
Error	2	0.0392	0.0196	----	4.63
Total	8	0.8740	----	----	100.00

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.

$$\text{Tensile shear Strength in kN} = 18.3 + 0.664 A + 0.656 B - 0.0215 C \quad (1)$$

$$\text{Indentation (in mm)} = 0.0050 + 0.00722 A + 0.01 B - 0.00083 C \quad (2)$$

where, A is second pulse welding current, B is second pulse welding time and C is cooling time.

For tensile shear strength, R-Sq = 92.43% at 95% confidence level.

For indentation, R-Sq = 79.94% at 95% confidence level.

From the results given above, it can be noticed that the regression coefficient value (R), for tensile shear strength is very high and that of indentation is moderately 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 below¹⁶.

$$\mu_{A_2 B_2 C_1} = \bar{A}_2 + \bar{B}_3 + \bar{C}_3 - 2\bar{T} \quad (3),$$

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 0.5125 dB (decibel).

Usually the result of a confirmation experiment is considered satisfactory, when the observed mean 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^{11, 16}.

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

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 $F_{0.05; (1, 2)} = 18.5$,

$V_e = 0.0196$,

$N_{eff} = 45 / (1 + 2 + 2 + 2) = 6.4285$, and $R = 5$

Hence calculated $CI = \pm 0.3590$

Predicted S/N ratio = $(0.5125 - CI) < \mu < (0.5125 + CI) = 0.1534 < \mu < 0.8715$

Confirmation of test was carried out with the optimum set of parameters. The observed S/N ratio was found to be 0.8506 dB against the predicted S/N ratio 0.5125 dB. The prediction error of 0.3381 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 32 KN and 0.11 mm respectively.

4. Conclusions

The multi objective Taguchi approach was used to optimize the control parameters for double pulse RSW of 2 mm sheets of AISI 409M ferritic stainless steel, considering tensile shear strength and indentation as main quality characteristics, simultaneously. The following outcomes are obtained through this research work:

1. The optimum level of parameters for maximum tensile strength with minimum indentation was found to be as follows. Second pulse current 12 kA, second pulse weld time 9 cycles and cooling time 30 cycles.
2. The second pulse welding current is the predominant contributor (46.01%) for maximizing tensile strength with minimum indentation, followed by second pulse weld time (37.74%) and cooling time (11.62%) respectively.
3. 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.
4. 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 research work is helpful in developing welding procedure specification (WPS) for RSW, in fabrication of railway car body of enhanced surface finish without compromising much on weld joint strength.

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