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Tri-objective Optimization of Carbon Steel Spot-welded Joints

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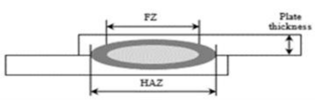
Graphical abstract



Experiment number	WT	EF	WC	TNQL	MSNR (dB)
1	1	1	1	0.8146	0.8904
2	2	1	2	0.9125	0.3977
3	3	1	3	0.8148	0.8897
4	1	2	2	0.9119	0.4006
5	2	2	3	0.8928	0.4926
6	3	2	1	0.7637	1.1709
7	1	3	3	0.7139	1.4636
8	2	3	1	0.7051	1.5175
9	3	3	2	0.7200	1.4264
Mean of MSNR of all experimental runs					0.9610

Abstract

The investigation was intended to optimize tri-objective of the welding parameters on tensile-shear (TS) strength, Fusion Zone (FZ) size and Heat Affected Zone (HAZ) size development in resistance spot welding (RSW) process of similar sheet metals joint. The experimental studies were conducted on varying weld time, electrode force and weld current for 1.2mm thickness of low carbon steel. The experimental tests, conducted according to the settings of process parameters were carried out according the L9 Taguchi orthogonal array in randomized way. The optimum process parameter for tri-objective was obtained using multi signal to noise ratio (MSNR) and further analyzed the significant level using analysis of variance (ANOVA). Response Surface Method (RSM) was employed to developed second order model at optimal welding parameters. The confirmation tests results demonstrate that the tri-objective Taguchi method used to optimize the welding parameters and enhance the welding performance is practical and effective in RSW process.

Keywords: Tri-objective Taguchi method; optimum process parameter; rsw process

1.0 INTRODUCTION

Resistance spot welding (RSW) is the process of contacting two metal surfaces joined by the heat obtained from resistance to electric current. By forcing the large of pressure clamped with copper alloy electrode to concentrate welding current into a small spot. Applying too much energy will melt too much metal, eject molten metal, and make a hole rather than a weld. Once the parameter are not follow the specification and it will be damage the spot weld component then the joining is not appropriate to the requirement in term of strengthens. Furthermore, cost of the process will become high and worst thing ever by making the scrap [1]. Therefore, it is necessary to identify and controls the parameters affecting the quality and mechanical properties of the weld using optimization method.

In order to overcome this problem, there are plentiful literature reports on process optimization to define optimum parameter through developing mathematical models. Some works have been done on single objective optimization in RSW process. Zhao et. al [2] applies response surface methodology (RSM) to explore the effects of process parameters of spot welded titanium alloy on the failure energy. The optimum process parameter maximizing failure energy are captured by the proposed mathematical model. Thakur et.al [3] applies Taguchi method to investigate the effects of pressure, weld time and weld current on tensile shear strength of resistance weld joint by means of performing analysis of variance (ANOVA) to determine predominant process parameter. Esme [4] applies Taguchi experimental method to study the effects of welding parameters on tensile strength using analysis signal-to-noise (S/N) ratio. Hamidinejadet. al [5] developed an accurate relationship between process input parameter and the output tensile-shear strength by utilizing first linear regression model.

However, in practical applications of RSW process involve several objectives to be considered simultaneously. The appropriate objectives for a particular application are often conflicting, which means achieving the optimum for one objective requires compromise on one or more other objectives. Multi-objective optimisation is the determination of the values of decision variables which correspond to and provide the optimum of more than one objective. The majority of the multi-objective optimisation studies in the literature involve two objectives. Muhammad et. al [6] investigated the effect of process parameters on the weld zone development (radius of weld nugget and width of HAZ) of low carbon steel. Simultaneous consideration of multiple responses of RSW process using multi Taguchi method of varying welding current, weld time and hold time on weld nugget development had been explored by Muhammad et. al [7]. Muhammad et. al [8] studied on multi-objective optimization and developed quadratic model for radius of weld nugget and radius of HAZ in RSW process. Experimental confirmation test is then carried out to validate the predicted model is reliable. However, tri-objective optimization on weld quality especially on combination of shear strength, FZ size and HAZ size has not yet been explored yet in the study of RSW process.

In this present paper, a tri-objective Taguchi experimental method and response surface method has been used to optimize welding parameters under simultaneous consideration of tensile-shear strength, FZ size and HAZ size. As the main objective of the manufacturing process is always to enhance the overall quality of a product, it is necessary to optimize multiple quality characteristics simultaneously [9].

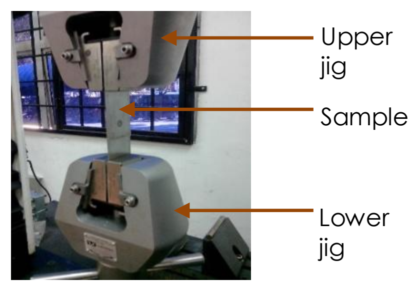
2.0 EXPERIMENTAL SET-UP

Sheet metals of low carbon steel JIS G3141 with 110 mm x 45 mm x 1.2 mm were used as the parent metal to be lap welded in this investigation. The experiment involved joining of two sheet metals using RSW machine model JPC 75-kVA. Welding was carried out using a 45-deg truncated cone Class 2 electrode with a 6 mm face diameter. Three welding parameters such as weld time, electrode force and weld current were selected for experimentation for three levels of factors. The value of welding process parameter at different levels is tabulated in Table 1.

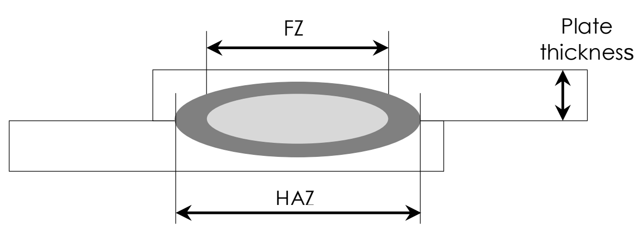
Table 1 Control factors and their levels.

Symbol	Factor	Unit	Level 1	Level 2	Level 3
WT	Weld Time	S	0.20	0.24	0.28
EF	Electrode Force	kN	2.3	2.7	3.1
WC	Weld Current	kA	8	9	10

Samples for tensile-shear testing were prepared using AWS D8.9m standard. The tensile-shear tests were performed at cross-head speed of 2mm/min with a 250-kN testing machine, as shown in Figure 1 (a). The metallographic examination samples were prepared using standard metallography procedure. The welded plates were cut transversely to measure the FZ size and HAZ size. Nital etching reagent was used to reveal the microstructure of the samples. A schematic illustration of FZ size and HAZ size are shown in Figure 1 (b).



(a)



(b)

Figure 1 (a) The 100-kN Instron tensile test machine, (b) Schematic illustration of FZ and HAZ size

2.1 Tri-Objective Taguchi Method

The total number of experiments can be substantially reduced with the help of a well-designed experimental plan without affecting the accuracy during the experimental study of any manufacturing process. Taguchi have suggested that it is better to make the process robust rather than equipment just by nullifying the effects of variations through selection of appropriate parameter level. In this present research work three control factors with three levels of each have been considered and performed by using simplest L_9 OA as shown in Table 2.

Table 2 Experimental layout using L_9 OA.

Experiment number	Factor level		
	WT	EF	WC
1	1	1	1
2	2	1	2
3	3	1	3
4	1	2	2
5	2	2	3
6	3	2	1
7	1	3	3
8	2	3	1
9	3	3	2

The selection of OA is based on the total degree of freedom (DoF) of the process. Mathematically, the DoF can be computed as [7, 9]:

DoF = [((number of levels – 1) for each factor) + ((number of levels – 1) x (number of levels – 1) for each interaction + 1)] (Eq. 1)

In this research, for the shear strength, FZ size and HAZ size, the larger-the-better, nominal-the-better and smaller-the-better were chosen, respectively using the following equations [10]:

Larger-the-better = MSD = $\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}$ (Eq. 2)

Nominal-the-better = MSD= σ^2 (Eq. 3)

Smaller-the-better = MSD= $\frac{1}{n}\sum_{i=1}^{n} y_i^{2}$ (Eq. 4)

where MSD = mean square deviation for the output characteristic and commonly known as quality loss function, *n* is the number of tests, y_i is the value of responses and σ is standard deviation of the *i*th test. Taguchi method also provides the relative effect of the different welding parameters that can be analysed by the analysis of variance (ANOVA). It is a statistical method to estimate quantitatively the relative significance factors on quality characteristics. If the *p*-value is less than significance level (α), the factor is then regarded to be statistically significant [11]. In multi-objective optimization, a single overall S/N ratio for all quality characteristics is computed in place of separate S/N ratios. This overall S/N ratio is known as multiple S/N ratio (MSNR) and mathematically can be computed as [7]:

MSNR = - 10 $\log_{10}(Y_j)$ (Eq. 5)

(Eq. 6)

$$Y_j = \sum_{i=j}^{k} w_i \frac{L_{ij}}{L_{i^*}}$$

where Y_j = total normalised quality loss (TNQL) in *j*th trial, w_i = weighting factor for the *i*th quality characteristic, *k* = total number of quality characteristics and Y_{ij} is the normalised quality loss associated with the *i*th quality characteristic at the*j*th trial condition, and varies from a minimum of zero to a maximum of 1. L_{ij} = MSD for the *i*th quality at the*j*th trial, and L_{i^*} = the maximum quality loss for the *i*th quality characteristic among all the experimental runs.

2.2 Response Surface Method

Response surface methodology (RSM) is a multi-variation analysis technique which is able to simultaneously consider a couple of input variables at different levels, quantify the relationships between the controllable various factors and output variables using polynomial model, study the interactive effects among different input variables, and work out the optimum combination of the process parameters [12]. In RSM, all the input process parameters are assume to be measurable. It is required to find a suitable approximation for the true function relationship between independent variables and the response surface. Usually, a second-order regression model as given below is utilised in RSM.

$$y = b_o + \sum_{i=1}^{p} b_i x_i + \sum_{i=1}^{p} b_{ii} x_i^2 + \sum_i \sum_j b_{ij} x_i x_j \quad \text{(Eq. 7)}$$

where all *b*'s are the regressions coefficients, determined numerically by using least square fit method, x_i are the different control factors changing from *i*=1 to *n*, *n* is the total number of control factors, y_j are the different responses (*j* are the number of responses used).

3.0 RESULTS AND DISCUSSION

3.1 Tri-objective Taguchi optimization

The MSNR and TNQL for multiple quality characteristics TS, FZ and HAZ has been calculated using Eqs. (5-6).These results are shown in Table 3. In calculating total normalized quality loss, three weights i.e. w_1=0.6 for TS, w_2=0.2 for FZ, and w_2=0.2 for HAZ has been assumed. Higher weighting factor has been assigned to the TS strength rather than FZ and HAZ size as it is more important in order to achieve a good joint quality.

The effect of different control factors on MSNR is shown in Table 4. The optimum levels of different control factors for higher tensile-shear strength, nominal weld nugget size and minimum HAZ size are weld time at level 1(0.2 s), electrode force at level 1(2.3 kN) and weld current at level 3 (10 kA).

Table 3 Total Normalized Quality Loss (TNQL) and Multi S/N Ratios (MSNR)

Experiment number	WT	EF	WC	TNQL	MSNR(dB)
1	1	1	1	0.8146	0.8904
2	2	1	2	0.9125	0.3977
3	3	1	3	0.8148	0.8897
4	1	2	2	0.9119	0.4006
5	2	2	3	0.8928	0.4926
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9	3	3	2	0.7200	1.4264
Mean of MSNR of all experimental runs					0.9610

Table 4 Multiple S/N response (average factor at different level)

Factors	Mean of multiple S/N ratios (dB)			Rank
	Level 1	Level 2	Level 3	
WT	1.2784*	1.2449	1.0661	3
EF	1.4947*	0.8021	1.2926	2
WC	0.9416	0.6938	1.9540*	1

The results of ANOVA for the welding responses are presented in Table 5. Larger F value indicates that the variation of the welding parameters produces a big change on the rank. In this study, weld current is the most important welding parameters affecting the responses whereas weld time is less important. For a factor with a high percent of contribution, a small variation will have a great influence on the performance [13]. The most important factor of RSW that influences the TS strength, FZ size and HAZ size is weld current with 68.68% contribution. Only 0.146 of the variance was inducted by experimental errors which prove that the experimental design was very successful.

Table 5 Results of ANOVA for TS strength, FZ size and HAZ size

Factors	DoF	Sum of Squares	Mean of squares	F	P	Contribution (%)
WT	2	4.851	2.4255	12.59	0.006	6.43
EF	2	18.776	9.388	48.72	0.011	24.89
WC	2	51.811	25.9055	134.45	0.042	68.68
Error	2	0.146	0.073			
Total	8	75.854				100

3.2 Response surface modeling

The second-order response surface model for TS strength, FZ size and HAZ size has been developed from the experimental response values obtained using L_9 OA experimental matrix. The model developed is fitted in the following equations:

TS strength (MPa) $= 305.03 + 16X_1 + 9.70X_2 + 8.11X_3 - 7.77X_1^2 - 0.88X_2^2 - 1.05X_3^2 - 7X_1X_2 - 9.5X_1X_3 + 4X_2X_3$ (Eq. 8)

FZ size (mm) $= 3.61 + 0.15X_1 + 0.08X_2 + 0.14X_3 - 0.13X_1^2 + 0.01X_2^2 - 0.04X_1X_2 - 0.07X_1X_3 + 0.02X_2X_3$ (Eq. 9)

HAZ size (mm) $= 4.68 + 0.12X_1 + 0.07X_2 + 0.05X_3 - 0.06X_1^2 + 0.03X_2^2 - 0.02X_3^2 - 0.06X_1X_2 - 0.04X_1X_3 + 0.07X_2X_3$ (Eq. 10)

where X_1 is weld time, X_2 is electrode force, X_3 and weld current.

3.3 Confirmation Test

The final steps are prediction and verification the quality characteristics using the optimal level of the welding parameters. The predicted MSNR ($\hat{\eta}$) at optimal level of the welding parameters can be calculated as:

$$\hat{\eta} = \eta_m + \sum_{i=1}^{k}(\bar{\eta}_i - \eta_m) \quad \text{(Eq. 11)}$$

where η_m is the total mean MSNR, $\bar{\eta}_i$ is the average MSNR at optimal level and, k is the number of the main welding parameters that affect the quality characteristics. Confirmation experimental results will be then compared using Eq. (8)-(10). The comparison of predicted and actual value of MSNR using optimum welding parameters is shown in Table 6. The percentage error between confirmation experiment and prediction is 2.04, 0.58 and 1.29% for TS strength, FZ size and HAZ size, respectively. The percentage errors are within the acceptable range. Good agreement between model equation presents and experimental results are observed.

Table 6 Results of the confirmation tests for TS strength, FZ size and HAZ size

Parameter levels	Optimal welding parameters		Error (%)
	Prediction, $WT_1EF_1EF_3$	Experiment, $WT_1EF_1EF_3$	
TS Strength (MPa)	288	294	2.04
FZ size (mm)	3.46	3.44	0.58
HAZ size (mm)	4.65	4.59	1.29

4.0 CONCLUSION

Tri-objective Taguchi method and response surface approach has been used for optimizing welding process parameters. Based on the modeling and optimization results, the following conclusion can be drawn.

(i) The developed second order response surface model has been found well fitted and can be effectively used for prediction TS strength, FZ size and HAZ size.
(ii) The optimal parameter achieved as weld time (0.2s), electrode force (2.3kN) and weld current (10kA).
(iii) The confirmation test results demonstrate the used of tri-objective Taguchi method for enhancing the welding performance and optimizing the welding parameters in RSW process is practical and effective.

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