A Quality Improvement Approach for Resistance Spot Welding using Multi-objective Taguchi Method and Response Surface Methodology

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Abstract— **This research deals with an approach for optimizing the weld zone developed by the resistance spot welding (RSW). This approach considers simultaneously the multiple quality characteristic (weld nugget and heat affected zone) using Multi-objective Taguchi Method (MTM). The experimental study was conducted under varying welding currents, weld and hold times for joining two sheets of 1.0 mm low carbon steel. The setting of welding parameters was determined using Taguchi experimental design method and L_9 orthogonal array was chosen. The optimum welding parameter for multi-objectives was obtained using multi signal to noise ratio (MSNR) and the significant level of the welding parameters was further analyzed using analysis of variance (ANOVA). Furthermore, the first order model for predicting the weld zone development was developed by using Response Surface Methodology (RSM). Confirmation experiment was conducted at an optimal condition for observing accuracy of the developed response surface model. Based on the confirmation test results, it is found out that the developed model can be effectively used to predict the size of weld zone which can improve the welding quality and performance in RSW.**

Keywords— **resistance spot welding (RSW), multiple quality characteristic, multi-objective Taguchi Method.**

I. INTRODUCTION

Resistance Spot Welding (RSW) is widely utilized for joining purpose especially in automobile industry due to its robustness, speed, flexibility and low cost operation. These advantages are coming from its operating principle which employs the electrical resistance concept. The metal to be joined is placed between two electrodes and then pressure applied and current turned on. The RSW process fundamentally consists of four stages which are squeeze cycle, weld cycle, hold cycle and off cycle. The sequence of the process is shown in Fig. 1 [1]. Squeeze cycle is a time during which the upper electrode is brought in contact with the sheets to be welded and force is exerted at the welding region. While the weld cycle is a time during which current is turned on and resistance to current flow at the sheet interface producing a nugget. The hold cycle is a time during which the current is turned off and the fully grown nugget is allowed to cool slowly and solidify under constant pressure. The off cycle is final time during which the electrode is raised from the welded sheets. Major factors controlling this process are current, time, electrode force, contact resistance and sheet material. The quality is best judged by nugget size and joint strength [2].

Controlling the welding parameters plays an important role on the quality of the weld. Therefore, it is important to select the welding process parameters for obtaining optimal size of weld nugget. Usually, the desired welding process parameters are determined based on experience or from handbook. However, this does not ensure that the selected welding process parameters can produce the optimal weld nugget for that particular welding machine and environment.
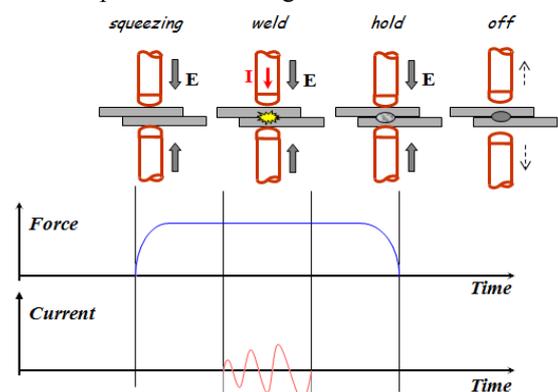

Fig. 1: The sequence of the RSW process

In order to overcome this problem, various optimization methods can be applied to define the desired output variables through developing mathematical models to specify the

relationship between the input parameters and output variables. Some works have been done on various aspects of modelling and process optimization in the RSW process. Ugur Esme [3] reported an investigation on the optimization and effect of welding parameters on the tensile shear strength of spot welded SAE 1010 steel sheet using Taguchi method; A.G.Thakur and V.M.Nandedkar [2] presented a systematic approach to determine effect of process parameters on tensile shear strength of RSW of austenitic stainless steel AISI 3040 using Taguchi Method; S.M.Darwish and S.D.Al-Dekhial [4] proposed response surface methodology (RSM) for the influence of spot welding parameters on the strength of spot welded aluminium sheets; and Hefin Rowlands and Jiju Antony [5] presented the use of Taguchi's loss function analysis and RSM to a spot welding process in order to discover the key process parameters which influence the tensile strength of welded joints.

In the present paper, a Taguchi experimental design method, Multi objective Taguchi Method (MTM) and response surface method (RSM) approach has been used to develop the response models and to optimise the multiple quality characteristics which are radius of weld nugget and width of HAZ. Based on the past researches, most of the investigations focused on modelling and optimizing single quality characteristic which may deteriorate other characteristics. As the main objective of the manufacturing process is always to improve the overall quality of a product, it is necessary to optimize multiple quality characteristics simultaneously [6].

II. EXPERIMENTAL PLANNING METHOD

A. Taguchi and Multi-objective Taguchi Method

The Taguchi design method is a simple and robust technique for optimizing the process parameters. In this method, main parameters which are assumed to have influence on process results are located at different rows in a designed orthogonal array (OA). With such an arrangement, completely randomized experiments can be conducted [7]. An advantage of the Taguchi method is that it emphasizes a mean performance characteristic value close to the target value rather than a value within certain specification limits, thus improving the product quality. It can be used to quickly narrow the scope of a research project or to identify problems in a manufacturing process from data already in existence [8].

In this method, main process parameters or control factors which influence on process results are taken as input parameters and the experiment is performed as per specifically designed OA. The selection of appropriate OA is based on total degree of freedom (dof) which is computed as [6,9]:

dof = {(number of levels – 1) for each factor}
    + {(number of levels – 1)
    x (number of levels – 1) for each interaction + 1}   (1)

In general, signal to noise (S/N) ratio (η, dB) represents quality characteristics for the observed data in the Taguchi design of experiments (DOE) and mathematically can be computed as [6,9]:

$$\eta = -10 \log [MSD] \qquad (2)$$

where MSD = mean square deviation from the desired value and commonly known as quality loss function.

Usually, there are three categories of the quality characteristic in the analysis of the S/N ratio which are lower-the-better, higher-the-better and nominal-the better. In this research for the radius of weld nugget and width of HAZ the nominal-the-better and the lower-the-better was choosen,respectively with following equations:

$$\text{Nominal-is-best} = \eta = -10 \log_{10} \sigma^2 \qquad (3)$$

$$\text{Smaller-is-better} = \eta = -10\log\left[\frac{1}{n}\sum_{i=1}^{n} y_i^2\right] \qquad (4)$$

where y_i (mean) and σ (standard deviation) denote the observe data at ith trial and n is the number of trials. From the S/N ratio, the effective parameters having influence on process results can be obtained and the optimal sets of process parameters can be determined.

Taguchi Method also provide a better feel for the relative effect of the different parameters/factors that can be analysed by the decomposition of the variance (ANOVA). It is a statistical method to estimate quantitatively the relative significance factors on quality characteristics [10, 11]. If the p-value is less than the significance level (α), the factor is then regarded to be statistically significant [5,12]. The relative significance of factors is often represented in terms of F-ratio or in percentage contribution. Greater the F-ratio indicates that the variation of the process parameter makes a big change on the performance, or p-ratio less than 0.05 the more significant will be the factor.

In multi-objective optimization, a single overall S/N ratio for all quality characteristics is computed in place of separate S/N ratios for each of the quality characteristic. This overall S/N ratio is known as multiple S/N ratio (MSNR). The MSNR for jth trial (η_j^e) is computed as [13]:

$$\eta_j^e = -10 \log_{10}\left(Y_j\right) \qquad (5)$$

$$Y_j = \sum_{i=1}^{k} w_i y_{ij} \qquad (6)$$

$$y_{ij} = \frac{L_{ij}}{L_{i*}} \qquad (7)$$

where Y_j is the total normalised quality loss in jth trial, w_i represents the weighting factor for the ith quality characteristic, k is the total number of quality characteristics and y_{ij} is the normalised quality loss associated with the ith quality characteristic at the jth trial condition, and it varies from a minimum of zero to a maximum of 1. L_{ij} is the quality loss or MSD for the ith quality characteristic at the jth trial, and L_{i*} is the maximum quality loss for the ith quality characteristic among all the experimental runs.

B. Response Surface Methodology

Response surface methodology is a collection of statistical and mathematical methods that are useful for the modeling

and analyzing engineering problems. In this technique, the main objective is to optimize the response surface that is influenced by various process parameters. Response surface methodology also quantifies the relationship between the controllable input parameters and the obtained response surfaces. The design procedure of response surface methodology is as follows [6,14]:

i. Designing of a series of experiments for adequate and reliable measurement of the response of interest.
ii. Developing a mathematical model of the second order response surface with the best fittings.
iii. Finding the optimal set of experimental parameters that produce a maximum or minimum value of response.
iv. Representing the direct and interactive effects of process parameters through two and three dimensional plots.

If all variables are assumed to be measurable, the response surface can be expressed as follows:

$$y = f(x_1, x_2, \ldots . x_k) \qquad (8)$$

The goal is to optimize the response variable y, it is assumed that the independent variables are continuous and controllable by experiments with negligible errors. It is required to find a suitable approximation for the true functional relationship between independent variables and the response surface.

III. EXPERIMENTAL SET-UP & PROCEDURES

In this study electrode size, electrode force and squeezing cycle were set to be constant throughout the investigation for welding two sheets layer with a thickness of 1.0 mm low carbon steel.Three welding parameters such as welding current, weld time and hold time were selected for experimentation, each factor has three levels.

The value of the welding process parameter at the different levels is listed in Table 1. The interaction between factors was not considered. Experimental process was conducted using L_9 orthogonal array in Taguchi Method which has nine rows corresponding to the number of experiments as shown in Table 2.The outputs studied were radius of weld nugget and width of HAZ.

To measure the radius of weld nugget and witdth of HAZ, the welded metal was cut transversely from the middle position using a common cutting machine. In order to assure the precision of the specimen dimension, it was etched by 2% Nital solution. The macrograph of weld zone was captured using a metallurgical microscope interfaced with an image analysis system as shown in Fig.2.
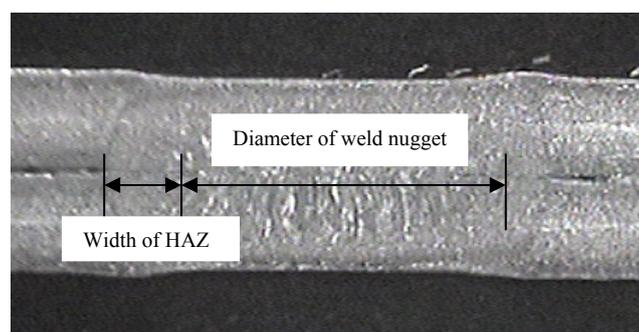

Fig. 2: Magrograph of weld zone

TABLE I
CONTROL FACTORS AND THEIR LEVELS USED IN THE EXPERIMENT

Symbol	Factors	Unit	Level 1	Level 2	Level 3
A	Welding current	kA	4	5	6
B	Weld time	cycle	8	10	12
C	Hold time	cycle	1	2	3

TABLE II
EXPERIMENTAL LAYOUT USING L_9 ORTHOGONAL ARRAY

Experiment number	Factor level		
	A	B	C
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

IV. RESULTS AND DISCUSSION

The values of the observed data for radius of weld nugget and width of HAZ are shown in Table 3. Two or more experimental data are needed because the quality characteristic (nominal is best) for radius of weld nugget, S/N ratio is based on standard devition.

A. *Multi-objective Optimization Results using Taguchi Approach*

From Table 3, quality loss values for different quality characteristics (nominal is best for radius of weld nugget and smaller is better for width of HAZ) in each experimental run are calculated using Eqs (3) and (4).These quality loss values are shown in Table 4. The normalized quality loss values for both quality characteristics (radius of weld nugget and width of HAZ) in each experimental run have been calculated using Eq. (7) that is shown in Table 5. The MSNR for multiple quality characteristics (radius of weld nugget and width of HAZ) and total normalized quality loss values (TNQL) has been calculated using Eqs. (5) and (6). These results are shown in Table 6. In calculating total normalized quality loss values, two unequal weights that is $w_{1=}$ 0.8 for radius of weld nugget and w_2= 0.2 for width of HAZ. Higher weighting factor has been assigned to the weld nugget because it is more important compared to HAZ in order to achieve a good quality of weld in resistance spot welding process.

The effect of different control factors on MSNR is shown in Table 7. The optimum levels of different control factors for nominal radius of weld nugget and minimum width of HAZ obtained are welding current at level 3 (6.0 kA), weld time at level 3 (12 cycles) and hold time at level 2 (2 cycles).

ANOVA technique has been employed to detect significant factors in multi-objective optimization for radius of weld nugget and width of HAZ. The result of ANOVA for the welding outputs are presented in Tables 8. According to this analysis, it shows that weld current was statistically significant since its p-value is less than 0.05 %. Furthermore, it also shows the percentage contribution which indicates the relative power of a factor to reduce variation. For a factor with a high percent contribution, a small variation will have a great influence on the performance [3]. The percentage contribution of different control factors on multiple quality characteristics (radius of weld nugget and width of HAZ) shows that welding current was the major factor (88.65%), it follows by weld time (9.99%) and hold time (0.687%).

B. *Response Surface Modelling*

The first order response surface model for radius of weld nugget and width of HAZ has been developed from the experimental response values obtained using OA experimental matrix. The model developed using RSM in MINITAB software is:

Radius of weld nugget (mm) = 0.046728 + 0.357458 A +
$$0.023063\ B - 0.000750\ C \quad (9)$$
Width of HAZ (mm) = 1.4896 – 0.08204 A– 0.00908 B
$$- 0.01937\ C \quad (10)$$

where A, B and C is welding current, weld time and hold time respectively.

To test whether the data are well fitted in the model or not, the value of S and R^2 are observed. In general, the more appropriate regression model is the higher the values of R^2 (R is correlation coefficient) and the smaller the values of S (standard errors of samples). From the developed models, calculated S value of the regression analysis on radius of weld nugget is 0.120029 and width of HAZ is 0.0589357, which are smaller and R^2 value for both response (radius of weld nugget and width of HAZ) are 91.54 % and 71.98 % respectively, these are moderately high, therefore the data for each response are well fitted in the developed models.

TABLE III
EXPERIMENTAL OBSERVATIONS

Experiment number	Radius weld nugget 1 (mm)	Radius weld nugget 2 (mm)	Width of HAZ 1 (mm)	Width of HAZ 2 (mm)
1	1.6525	1.8900	1.0425	1.2370
2	1.6355	1.8475	0.9405	0.9745
3	1.6780	1.8390	1.0255	1.0510
4	1.8135	1.9405	0.9240	0.8900
5	1.9830	2.1015	0.8050	1.0340
6	1.9070	2.0085	1.0510	0.8350
7	2.3305	2.4235	0.9830	0.8140
8	2.4150	2.4915	0.9910	0.7850
9	2.5595	2.6120	0.8050	0.8475

TABLE IV
QUALITY LOSS VALUES FOR RADIUS WELD NUGGET AND WIDTH OF HAZ

Experiment number	A	B	C	Quality loss values (dB) Radius weld nugget	Width of HAZ
1	1	1	1	0.0282	1.2990
2	1	2	2	0.0224	0.9168
3	1	3	3	0.0129	1.0779
4	2	1	2	0.0081	0.8226
5	2	2	3	0.0070	0.8454
6	2	3	1	0.0052	0.8892
7	3	1	3	0.0043	0.8073
8	3	2	1	0.0029	0.7916
9	3	3	2	0.0014	0.7310

TABLE V
NORMALIZED QUALITY LOSS VALUES FOR RADIUS OF WELD NUGGET AND WIDTH OF HAZ

Experiment number	A	B	C	Normalized Quality loss values Radius weld nugget	Width of HAZ
1	1	1	1	1.0000	1.0000
2	1	2	2	0.7968	0.7057
3	1	3	3	0.4595	0.8298
4	2	1	2	0.2859	0.6332
5	2	2	3	0.2489	0.6508
6	2	3	1	0.1826	0.6845
7	3	1	3	0.1533	0.6214
8	3	2	1	0.1037	0.6094
9	3	3	2	0.0488	0.5627

TABLE VI
TOTAL NORMALIZED QUALITY LOSS VALUES (TNQL) AND MULTIPLE S/N RATIOS (MSNR)

Experiment number	A	B	C	TNQL	MSNR(dB)
1	1	1	1	1.0000	0.0000
2	1	2	2	0.7786	1.0865
3	1	3	3	0.5336	2.7275
4	2	1	2	0.3554	4.4923
5	2	2	3	0.3293	4.8233
6	2	3	1	0.2830	5.4815
7	3	1	3	0.2469	6.0734
8	3	2	1	0.2048	6.8846
9	3	3	2	0.1516	8.1919
Mean of MSNR of all experimental runs					4.4179

TABLE VII
MULTIPLE S/N RESPONSE (AVERAGE FACTOR EFFECT AT DIFFERENT LEVEL)

Symbol	Factors	Mean of multiple S/N ratio (dB)		
		Level 1	Level 2	Level 3
A	Welding current	1.271	4.932	7.050*
B	Weld time	3.522	4.265	5.467*
C	Hold time	4.122	4.590*	4.541

TABLE IX
RESULT OF THE CONFIRMATION EXPERIMENT

	Optimal process parameters		Percentage
	Prediction	Experiment	error (%)
Level	A3B3C2	A3B3C2	
Radius weld nugget (mm)	2.466	2.586	4.64
Width of HAZ (mm)	0.8496	0.7675	10.70

TABLE VIII
RESULTS OF ANOVA

Symbol	Factors	Degrees of Freedom (DOF)	Sum of squares	Mean of squares	F	P	Contribution (%)
A	Welding current	2	51.2807	25.6403	133.13	0.007	88.65
B	Weld time	2	5.7801	2.8900	15.01	0.062	9.99
C	Hold time	2	0.3975	0.1988	1.03	0.492	0.687
Error		2	0.3852	0.1926			
Total		8	57.8435				

C. *Confirmation Test*

The final step is a verification experiment to validate the optimum conditions suggested by the matrix experiment do indeed give the projected improvement. The confirmation experiment is performed by conducting a test with a specific combination of the factors and levels previously evaluated. After determining the optimum conditions, a new experiment was conducted with the optimum levels of the welding parameters. Confirmation experimental results will be then compared with the predicted value for radius of weld nugget and width of HAZ using Eqs (9) and (10) respectively.

Results of confirmation test compared to predicted value and also the percentage error is shown in Table 9. The percentage error between confirmation experiment and prediction is 4.64% for radius of weld nugget and 10.70% for width of HAZ. It shows that the model equation presents good agreement with the experimental result.

V. CONCLUSIONS

A multi-objective Taguchi Method has been applied for simultaneous consideration of multiple response (radius of weld nugget and width of HAZ) to optimize the multiple quality characteristics in RSW process. Based on the modelling and optimization results it can be concluded that:

i. The highly effective parameter for the development of radius weld nugget and width of HAZ is the welding current.

ii. The developed linear response surface model for prediction radius of weld nugget and width of HAZ has been found well fitted and can be effectively used to predict the size of weld zone.

iii. The optimum parameters has been found which is welding current at level 3 (6.0 kA), weld time at level 3 (12 cycles) and hold time at level 2 (2 cycles).

iv. The confirmation test validated the used of multi-objective Taguchi Method for enhancing the welding performance and optimizing the welding parameters in resistance spot welding process.

REFERENCES

[1] Y.H.P.Manurung, N.Muhammad, E.Haruman, S.K.Abas, G.Tham, K.M.Salleh and C.Y.Chau, *Investigation on Weld Nugget and HAZ development of Resistance Spot Welding using SYSWELD's Customized Electrode Meshing and Experimental Verification*, Asian Journal of Industrial Engineering, vol.2, pp. 63-71, 2010.

[2] A.G.Thakur and V.M.Nandedkar, *Application of Taguchi Method to Determine Resistance Spot Welding Conditions of Austenitic Stainless Steel AISI 304*, Journal of Scientific & Industrial Research, vol.69, Sept 2010, pp.680-683.[3] Ugur Esme, *Application of Taguchi Method for the Optimization of Resistance Spot Welding Process*, The Arabian Journal for Science and Engineering, vol.34, pp.519-528, Oct.2009.

[4] S.M.Darwish and S.D.Al-Dekhial, *Statistical Models for Spot Welding of Commercial Aluminium Sheets*, Int Journal of Machine Tools & Manufacture, vol.39, pp.1589-1610, 1999.

[5] Hefin Rowlands and Jiju Antony, *Application of Design of Experiments to a Spot Welding Process*, Assembly Automation, vol.23, pp.273-279, 2003.

[6] Avanish Kumar Dubey and Vinod Yadava, *Multi-objective Optimisation of Laser Beam Cutting Process*, Optics & Laser Technology, vol.40, pp.562-570, 2008.

[7] Jae-Seob Kwak, *Application of Taguchi and Response Surface Methodologies for Geometric Error in Surface Grinding Process*, Int.Journal of Machine Tools & Manufacture, vol.45, pp.327-334, 2005.

[8] S.Fraley, M.Oom, B.Terrien and J.Z.Date, *Design of Experiments via Taguchi Methods:Orthogonal Arrays*, The Michigan Chemical Process Dynamic and Controls Open Text Book, USA, 2006.

[9] Avanish Kumar Dubey and Vinod Yadava, *Multi-objective Optimisation of Nd:YAG Laser Cutting of Nickel-based superalloy Sheet using Orthogonal Array with Principal Component Analysis* Optics & Laser Technology, vol.46, pp.124-132, 2008.

[10] J.S.Son, I.S.Kim, H.H.Kim, I.J.Kim, B.Y.Kang and H.J.Kim, *A Study on the Prediction of Bead Geometry in the Robotic*, Journal of Mechanical Science and Technology, vol.21, pp.1726-1731, 2007.

[11] S.C.Juang and Y.S.Tarng, *Process Parameter Selection for Optimization the Weld Pool Geometry in the Tungsten Inert Gas Welding of Stainless Steel*, Journal of Material Processing Technology, vol.122, pp.33-37, 2002.

[12] V.Gunaraj and N.Murugan, *Application of Response Surface Methodology for Predicting Weld Bead Quality in Submerged Arc Welding of Pipes*, Journal of Mechanical Processing Technology, vol.88, pp.266-275, 1999.

[13] J.Antony, *Simultaneous Optimisation of Multiple Quality Characteristics in Manufacturing Processes using Taguchi's Quality Loss Function*, Int.J.Adv Manuf Technology, vol.17, pp.134-138, 2001.

[14] S.Raissi and R.Eslami Farsani, *Statistical Process Optimization Through Multi-Response Surface Methodology*, World Academy of Science, Engineering and Technology, vol.51, pp.267-271, 2009.