Optimizing the resistance spot-welding process for dissimilar stainless steels

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Abstract. The objective of this study was to identify the ideal welding circumstances to conduct resistance spot-welding in the case of 316 austenite and 425 ferrite stainless steels, which offer the challenge of being dissimilar. The study examines a number of welding variables, including weld current, weld time, hold time, electrode force, and the upper and lower electrode types. Initially, a $2^{6-1}$ fractional factorial design was used for the screening of variables involved in the process. After this stage, the Box-Behnken design was employed for analysis of those variables and in order to specify the multiple response optimizations applicable to the size of nuggets through examination of the desirability function. The experiment was run using a resistance spot-welding machine at 50 kVA, 50 Hz. The quality of welded specimens was determined by their penetration, nugget diameter and nugget area. The optimal welding conditions were found to be 3.3 kN of electrode force, 25 cycles of weld time, 10,000 amperes of weld current, 50 cycles of hold time, and both R30 types of up-low electrodes. The optimal welding conditions provided nugget sizes of quality which were able to pass the specifications of the customer.

1. Introduction
The use of RSW (Resistance Spot Welding) has become commonplace in many industries where sheet metal must be joined. The technique is found in the manufacturing, automotive, and medical sectors due to its simplicity and relatively low cost [1-5]. RSW of stainless steel is an efficient joining process for the assembly of vehicle exhaust parts. Ferritic and austenitic stainless steel grades have been widely used in joint exhaust pipe parts due to its high corrosion resistance, decorative appearance, and excellence welding ability. RSW can be very complex when it involves stainless steel, since a number of factors must interact, most notably the thermal, electrical, mechanical, and metallurgical elements. The pieces of metal which are to be welded together are first placed in between the up-low electrodes prior to pressurization and the introduction of the electric current. Weld strength and quality is directly linked to the size and shape of the weld nuggets, whereby the nuggets of quality size can be produced simply by following the guidance offered with regard to suitable measurements in the manual produced by the Welder Manufacturers’ Association. It is thus vital to choose suitable welding parameters for the welding process in order to achieve the optimal nugget size. However, the chosen welding parameters are not assured of being optimal [6].

Process optimization in RSW has already been studied for resistance spot-welding parameters in terms of nugget size. Muhammad, N et al. presented the use of a multi-objective center composite design and the Taguchi approach tested a design method which put forward the response surface...
method for characteristics with multiple qualities, which in this case would be the weld nugget radius or the HAZ width [7]. On the other hand, some research has shown multi-response optimizations (more than 2 responses). Ruggiero, A et al. investigated the use of the Box-Behnken experiment design method with 3 factors for 5 responses to a laser-welding process. It was necessary to perform this step to establish the main parameters for the process which can affect the weld bead profile for joints which have been welded [8]. Ragavendran, M et al. reported on the investigation of optimized weld parameters on the weldments of a hybrid laser TIG welded 316LN stainless steel sheet using a center composite design method with 4 factors for 3 responses [9].

The objective of this paper was to determine the optimal welding conditions for quality characteristics, which are penetration, nugget diameter and nugget area, on the RSW of dissimilar stainless steel grade 316 and grade 425. The variables used in this study relating to the welding conditions were weld current, weld time, electrode force, hold time, and upper and lower electrode types. $2^{6-1}$ fractional factorial design method and ANOVA were used to screen the RSW parameter factors on the nugget shape of RSW. Then, the Box-Behnken experiment design method for optimization of the experiment using RSM (Response Surface Methodology) and a desirability function were employed as multiple-response optimization tools. The tensile shear load and microstructure of the weld sample, which was welded using the optimal conditions, was evaluated.

2. Experimental procedure

2.1. Materials and Methodologies

The workpiece material used in this study had a thickness of 1.5 mm. The base materials used were austenitic stainless steel 316 (SUS316L) and ferritic stainless steel 425 (SUS425) sheets. Both materials were cut into plates of 125 x 45 x 1.5 mm in size, which were lap joined according to JIS Z3139 standard and spot welded using a 50 kVA, 50 Hz RSW machine [10]. Six welding factors were selected for experimentation. The weld nugget attributes of all the samples were measured to analyze their metallographic cross-sections in the area to be welded, as Figure 1 indicates.

![Figure 1](image.png)

**Figure 1.** (a) Schematic depiction of the welding area; (b) Macrostructure of cross section weld sample.

2.2. Fractional factorial and optimized experiment design

Fractional factorials are widely used in screening experimentation, so in this study the design was of a general $2^{6-1}$ fractional factorial type with an additional 3-center point. Table 1 presents the various levels and factors applied. This experiment was created to identify the key welding factor among those in the response surface study. The data were then subjected to ANOVA analysis using a confidence level of 95%. RSM is a combination of a number of multiple regression methods and experimental designs. It can be applied to analyze the various factors which can stimulate the response [11]. The Box-Behnken design was used to optimize the main factors which can influence the development of the weld quality via the fractional factorial design.
Table 1. Experimental design factors and levels.

| Factors                  | Symbol | 2⁶⁻¹ fractional factorial | Box Behnken. |
|--------------------------|--------|---------------------------|--------------|
|                          |        | Low level (−1) | Up level (+1) | Low level (−1) | Middle level (0) | Up level (+1) |
| Force (kN)               | f      | 2  | 4 | 2  | 4  | 4  |
| Welding current (Amperes)| I      | 7,000 | 10,000 | 7,000 | 8,500 | 10,000 |
| Welding Time (Cycle)     | Tw     | 25 | 50 | 25 | 38 | 50 |
| Holding time (Cycle)     | Th     | 0  | 50 | 0  | 25 | 50 |
| Upper Electrode          | Up ET  | 0  | 30 | 0  | 16 | 30 |
| Lower Electrode          | Low ET | 0  | 30 | 0  | 16 | 30 |

Applying MINITAB statistics software, the experiment data were assessed using RSM in order to optimize the various response variables. The analysis makes it necessary to find a possible approximation for the true relationship linking the response surface and the independent variable. It is common to apply a second order model when analyzing response surfaces.

\[
y = \beta_0 + \sum_{i=1}^{n} \beta_i x_i + \sum_{i=1}^{n} \beta_{ii} x_i^2 + \sum_{i<j} \beta_{ij} x_i x_j + \varepsilon
\]  

(1)

in which \( \beta_0 \) denotes the constant, \( \beta_i \), \( \beta_{ii} \) and \( \beta_{ij} \) are the respective coefficients of the linear, quadratic, and interaction variables; \( y \) denotes the response, or dependent variable; \( x_i \) and \( x_j \) denote the independent variables, while the error term is given by \( \varepsilon \) represents the influence of the parameters which are not included. The coefficient of determination \( R^2 \) indicated the fitting quality for the equation of the polynomial model.

The software can be used to measure the importance of each individual response and give a suitable weighting. The basic method is to begin by changing each of the responses given by \( y_i \) to become a desirability function \( d_i \) which falls somewhere within the range of 0 - 1, in which a greater value for \( d_i \) shows the greater desirability of the response value \( y_i \). In the case when \( d_i = 1 \), this indicates a response which is wholly desirable [12]. In this study, the evaluation of each of the individual desirability responses, \( d_i \), was achieved through using the target for the responses \( y_i \) at the maximum value equation. Equation (2) reveals the overall objective function in conditions, where the changing degree of importance is given to the different response.

\[
D = (d_1^x \cdot d_2^x \cdot d_3^x \cdot \ldots \cdot d_n^x)^{1/n}
\]

(2)

in which \( n \) represents the responses.

3. Results and discussion

3.1. 2⁶⁻¹ Fractional factorial experiment results

The significance of each of the factors was assessed using normal distribution based on the standardized effect with a confidence level of 95%. The normal probability plot of standardize effect for each response observed that the main effect are the most important factors affecting the welding quality (t1, t2, di, Area). The \( R^2 \) values of the model were 99.64%, 99.95%, 99.99%, and 100%, respectively. The adjusted \( R^2 \) values of the model were 93.89%, 99.08%, 99.85%, and 99.99%, respectively. All of the factors were selected for optimization of the experiment.
3.2. Optimized experiment results
MINITAB statistical software was used to create and analyze the experiment data. The data from the experiments were subjected to multiple regression analysis applying a polynomial model of the second order. The significance for each regression coefficient was evaluated using the p-value. In this case the p-value was smaller than the confidence level of 0.05, indicating the statistical significance of the model. The $R^2$ values of this analysis were 88.17%, 86.61%, 91.26% and 93.09%, respectively, while the adjusted $R^2$ values of the model were 75.89%, 72.71%, 82.18% and 85.91%, respectively. These values were relatively moderate to high. For each of the responses, the data fit well to the model developed. The following second-order polynomial equation was used to explain $t_1$, $t_2$, $d_i$, Area removal efficiency, with the final reduced mathematical model in terms of both code and uncode factors determined by MINITAB software. The uncode mathematical model is shown below as Equations 3-6. The equations in terms of uncode factors can be given as:

Penetration 1 ($t_1$) = 1.68926 + 0.00046(Tw) – 0.01132(I) - 0.00963(Th) - 0.02703(UpET) + 0.00454(Low ET) + 0.00006(Th)$^2$ + 0.00055(UpET)$^2$ – 0.00018(Tw*LowET) + 0.00009(I*Th) + 0.00016(f*UpET)

Penetration 2 ($t_2$) = 3.1235 - 0.55063(f) – 0.03245(I) – 0.00607(UpET) - 0.02602(Low ET) + 0.06678(f)$^2$ + 0.00020(I)$^2$ + 0.00010(Th)$^2$ + 0.00052(Low ET)$^2$ + 0.00391(f*UpET) + 0.00018(I*Low ET) - 0.00042(UpET*Low ET)

Nugget Diameter (di) = 12.3727 - 2.7227(f) - 0.1460(Tw) – 0.0149(I) + 0.0321(UpET) + 0.00555(Low ET) + 0.0016(Tw)$^2$ + 0.0021(Low ET)$^2$ + 0.0189(f*Tw) + 0.0199(f*I) – 0.0014(f*Low ET) – 0.0024(UpET*Low ET)

Nugget Area (Area) = 34.4043 - 8.7522(f) – 0.2320(Tw) – 0.2226(I) – 0.1093(Tw) – 0.1626(UpET) – 0.0547(Low ET) + 0.0049(Tw)$^2$ + 0.0008(Th)$^2$ + 0.0045(UpET)$^2$ + 0.0075(Low ET)$^2$ + 0.0411(f*Tw) + 0.0541(f*I) + 0.0025(I*UpET) - 0.0074(UpET*Low ET)

The optimization criteria employed in this study is shown in Table 2. The optimized graphics were carried out by response optimization plot and overlay response contour plot. The optimal values for RSW parameters were 3.3 kN of electrode force, 25 cycles of weld time, 10,000 amperes of weld current, 50 cycles of hold time and both R30 type of up-low electrodes. Response optimization results are for achieving 1.20 mm of penetration 1 ($t_1$), 1.05 mm of penetration 2 ($t_2$), 8.12 mm nugget diameter (di) and 16.80 mm$^2$ nugget area (Area). Optimization desirability was evaluated to be 1, showing that the parameters were all within acceptable working bounds.

| Condition          | Goal     | Lower | Target | Weight | Importance |
|--------------------|----------|-------|--------|--------|------------|
| Penetration1($t_1$)| Maximum  | 0.30  | 0.375  | 1      | 1          |
| Penetration2($t_2$)| Maximum  | 0.30  | 0.375  | 1      | 1          |
| Nugget diameter(di)| Maximum  | 3.674 | 4.899  | 1      | 1          |
| Nugget Area(Area)| Maximum  | 8.877 | 10.435 | 1      | 1          |

3.3. Test for confirmation
The experiment required for confirmation involved testing using a particular mix of factors which had already been assessed earlier. The calculation results of the object parameters based on the optimum design parameters set are listed in Table 3. The percentage error for penetration 1, penetration 2, nugget diameter, and nugget area were 3.33%, 0.95%, 2.59% and 3.87%, respectively. The small percentage error demonstrates the efficiency of the optimization method.

In order to estimate the weldability of RSW, tensile strength was measured by the tensile shear load test. The specimens were prepared according to JIS Z3136 [13]. The tensile shear load for material sheet thickness was 1.5 mm, as recommended by the automotive industry. JIS Z3140 is greater than...
7.65 kN [14]. The results indicated that most combinations were satisfactory with the criterion, assuring the reliability of the RSW of stainless steel. The tensile shear load values for specimens 1, 2, 3 were 14.76kN, 14.81kN and 14.51kN, respectively, meaning they achieved the JIS Z3140 standard.

| Response                  | Predicted | Desirability | Experimental No.1 | Experimental No.2 | Experimental No.3 | Average | Error (%) |
|---------------------------|-----------|--------------|-------------------|-------------------|-------------------|---------|-----------|
| Penetration(t1)           | 1.20      | 1            | 1.17              | 1.15              | 1.15              | 1.16    | 3.33%     |
| Penetration(t2)           | 1.05      | 1            | 1.06              | 1.07              | 1.05              | 1.06    | 0.95%     |
| Nugget diameter(di)       | 8.12      | 1            | 8.33              | 8.48              | 8.18              | 8.33    | 2.59%     |
| Nugget area(Area)         | 16.80     | 1            | 16.14             | 16.26             | 16.05             | 16.15   | 3.87%     |

The cross section microstructure of welded specimens joined at optimal welding parameters was investigated by optical microscopic analysis. The type of microstructure of RSW for stainless steel considers two distinct regions, base metal and HAZ (Heat Affect Zone), as shown in Figure 2. Figures 2a, 2b, 2c, and 2d show the microstructure of weld nuggets and HAZ. The grains sizes are greater than the base metal and elongate parallel to the electrode force direction. Figures 2e and 2f illustrate the fusion zone region and also as the ferritic microstructure with various morphologies.

**Figure 2.** Microstructure of cross section weldment sample (optimal welding parameters).

**4. Conclusions**

In the present paper, multi-response optimizations of RSW process parameters for dissimilar stainless steel grade 316 and grade 425 were successfully implemented to influence the quality of nugget size. Six variables were employed as in experiment. The $2^{6-1}$ fractional factorial design technique was applied in screening the parameter factors for RSW related to the nugget shape. Afterwards, the study used the Box-Behnken design for the investigation, while optimization was sought through the use of the desirability function. The optimal values of RSW parameters were 3.3 kN of electrode force, 25 cycles of weld time, 10,000 amperes of weld current, 50 cycles of hold time and both R30 types of up-low electrodes. Under optimal conditions, the tensile shear load of specimens achieved the JIS Z3140 standard.
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Acknowledgements
The researchers are grateful to Yokoyama Kogyo Thailand Co., Ltd for providing access to the RSW machine. The authors would also like to express their thanks to the Faculty of Engineering of King Mongkut’s Institute of Technology Ladkrabang who offered support in covering the costs incurred in conducting this research.