Optimization of Welding Parameters for Resistance Spot Welding of Trip Steel Using Response Surface Methodology

H. Park, T. Kim, and S. Rhee

Abstract

Because of the environmental problems, automotive companies are trying to reduce the weight of car body. Therefore, TRIP(TRansformation Induced Plasticity) steels, which have high strength and ductility have been developed. Welding process is a complex process; therefore deciding the optimal welding conditions on the basis of experimental data is an effective method. However, trial-and-error method to decide the optimal conditions requires too many experiments. To overcome these problems, response surface methodology was used. Response surface methodology is a collection of mathematical and statistical techniques that are used in the modeling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize this response. This method was applied to the resistance spot welding process of the TRIP steel to optimize the welding parameters.

Key Words : Resistance spot welding, TRIP(TRansformation Induced Plasticity) steel, Response surface methodology, Central composite design, Desirability function, Shear strength, Indentation.

1. Introduction

Resistance spot welding is widely used in thin sheet of steel assembly processes such as automobile body because of its relatively simple principle and cost effective facilities. However, even in a procedure which is as easy to apply as resistance spot welding, the factors which determine weld quality greatly affect each other, making it difficult obtain satisfactory weld quality. Setting the required conditions to obtain the desired weld quality is an inefficient task which requires a great deal of trial and error. Therefore, it is necessary to obtain the optimal conditions under which the desired weld quality can be produced by using a welding process model which can express the weld quality with the least number of experiments.

The development of lightweight car bodies is the most prominent issue in the automotive industry today, in preparation of environmental regulations such as reduction of CO_2 emissions. Also, with the recent implementation of mandatory off-set collision test, many studies have been carried out to enhance the safety of automobiles. Recently, TRIP steel has developed as a prominent alternative due to its high strength and superior elongation. The use of TRIP steel as a high tensile steel is expected to become widespread.

Therefore, in this study, the response surface methodology was used to determine the optimal resistance spot welding conditions for TRIP steel for use in the manufacturing of automotive bodies. Through the response surface methodology, the optimal welding conditions which produce the satisfactory weld quality were determined.

2. Response surface methodology

In the resistance spot welding process, there are many control factors and environmental conditions which can determine the quality of the weld, such as the welding current, welding time, pressure, surface condition, electrode tip wear, and thickness of the workpiece. In this study, the welding current, welding time and pressure were used to analyze the quality of the weld, as these are the factors which have the greatest effect on weld quality. The effect of the above factors on the shear strength, indentation and the generation of expulsion were examined using the response surface methodology [1,2]. Using the data obtained through this experiment, a welding process model was formulated to express the quality of the weld.

The response surface methodology is comprised of an experimental design for a proximity model between the

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input variable and output variable, the statistical modeling which displays the relationship between the of the output variables. The second-order model was selected as the response surface model, as shown in equation (1).

$$y_k = \beta_0 + \sum_{i=1}^{3} \beta_i x_i + \sum_{i=1}^{3} \beta_{ii} x_i^2 + \sum_{j=2}^{3}\sum_{i=1}^{j-1} \beta_{ij} x_i x_j + \varepsilon \qquad (1)$$

where, is the coded unit of the input variables(welding current, welding time and pressure), while is the output variables(shear strength and indentation) which express the quality of resistance spot welding. In order to obtain the second-order model equation (1), the central composite design(CCD) was used in this study as a highly efficient experimental design method.

When using these second-order models to determine the conditions which can optimize the quality of the weld within the region of interest, the desirability function was used as an objective function. The desirability function, which is an effective method of finding the input values through the optimized value of the multiple responses, determines the desirability factor of each response using a regression model induced from the designed experiment or the regression analysis. In this study, the overall desirability function suggested by Derringer & Suich [3] was used to determine the optimal conditions. The overall desirability function defines the desirability function of each response into a single objective function.

3. Experiment

Generally, the quality of the weld in resistance spot welding is determined by shear strength, nugget size and indentation. The shear strength and nugget size are particularly important in determining the quality of the weld. However, this study attempted to determine the optimal conditions which would not generate expulsion. Therefore, the indentation was used to determine whether or not expulsion had been generated instead of nugget size. In resistance spot welding, the shear strength and indentation are determined by welding current, welding time and pressure. Therefore, the experiment was carried out using these factors.

In this study, modifications were made in the existing central composite design. In resistance spot welding, welding defects are frequently produced when expulsion is generated during the welding process. Therefore, the welding process must be carried out within a range that does not produce expulsion. When the existing central composite design was used, excessive expulsion could be generated when the welding current is 9kA, welding time 15cycle, and pressure 3.14kN. Therefore, the central composite design was modified to include a region of interest.

Table 1 Factors and levels for experimental design

Factor	Factor name	-1 level	0 level	1 level
ξ_1	welding pressure [kN]	4.12	3.63	3.14
ξ_2	welding current [kA]	7	8	9
ξ_3	Welding time [cycle]	7	11	15

The following constraints were applied as standards in modifying the central composite design [4,5].

$$\begin{aligned} &-1 \le x_1 \le 1 \\ &-1 \le x_2 \le 1 \\ &-1 \le x_3 \le 1 \\ &x_1 + x_2 + x_3 \le 2 \end{aligned} \qquad (2)$$

The experiment range which satisfies the above three conditions was shown in Fig 1.

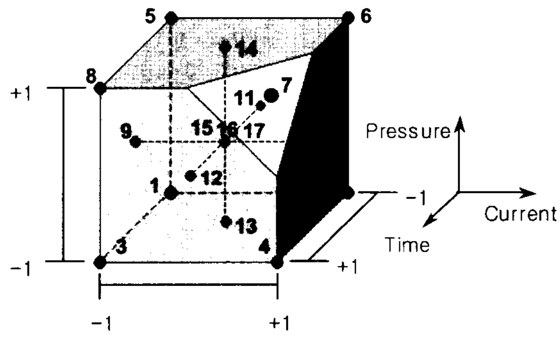


Fig. 1 Modified central composite design

4. Results and discussion

The second-order model was used as a response surface using the results of the experiment within the established experiment range. The regression equations of the output shear strength(S) and indentation (I) according to each input variable of welding current, welding time and welding pressure were shown in the following equations.

$$\begin{aligned} S_{CR} = 13.938 &+ 0.092x_1 + 0.632x_2 + 0.164x_3 \\ &- 0.201x_1^2 - 0.671x_2^2 - 0.363x_3^2 \\ &- 0.003x_1x_2 - 0.029x_1x_3 - 0.287x_2x_3 \end{aligned} \qquad (3)$$

$$I_{CR} = 0.331 - 0.714x_1 + 0.356x_2 + 0.247x_3 - 0.034x_1^2 - 0.109x_2^2 + 0.238x_3^2 + 0.005x_1x_2 - 0.107x_1x_3 - 0.069x_2x_3 \quad (4)$$

The significance of the second-order model obtained through the method of least squares was determined through the F test of the analysis of variance and the coefficient of multiple determination(R^2).

In the analysis of variance, the F_0 is the ratio between the mean of squares due to regression(MSR) and the mean of squares due to residual errors(MSE). If the level of significance(α) of the above the second-order model was selected at 0.05, the critical value was $F(\phi_R,\ \phi_E\ ;\alpha) = F(9, 7\ ; 0.05) = 3.68$.
A comparison of the coefficient of determination showed that the coefficient of multiple determination for each regression equation was 0.955 and 0.893. This meant that the 95.5% of the total variance of the shear strength and 89.3% of the total variance of the indentation could be explained through the regression equation.

Therefore, an examination of the F test and coefficient of determination for each model showed that the model was satisfactory in expressing the resistance spot welding process.

Model equations (3) and (4) estimated the responses of each input variable in the region of interest where the optimal conditions was to be determined. Therefore, these estimations could be used in determining the optimal input variables which produce satisfactory weld in resistance spot welding. In order to find the welding current, welding time and welding pressure which satisfied both output responses used in this study which was the shear strength and indentation, the desirability function was used as a method of determining the optimal input value of multiple output variables. The one-sided desirability function, which is used when the response must be maximized, was applied to the shear strength, while the two-sided desirability function, which is used when the response has an objective value, was applied to the indentation.

For the shear strength standard, 11.9kN was used, as it is the standard strength of automobile company in 1.2mm resistance spot welding. The standard suggested by AWS was used for the indentation. Thus, if the indentation exceeded 25% of the steel thickness, the desirability function was determined at 0 [6].

$$d(\hat{S}(\mathbf{x})) = \begin{cases} 0 & if \quad \hat{S} \le 11.9 \\ \left(\dfrac{\hat{S} - 11.9}{15 - 11.9}\right) & if \ \ 11.9 < \hat{S} < 15 \\ 1 & if \quad \hat{S} \ge 15 \end{cases} \quad (5)$$

$$d(\hat{I}(\mathbf{x})) = \begin{cases} 0 & if \quad \hat{I} < 0 \\ \left(\dfrac{\hat{I} - 0}{0.4 - 0}\right) & if \ \ 0 \le \hat{I} \le 0.4 \\ \left(\dfrac{\hat{I} - 0.6}{0.4 - 0.6}\right) & if \ \ 0.4 \le \hat{I} \le 0.6 \\ 0 & if \quad \hat{I} > 0.6 \end{cases} \quad (6)$$

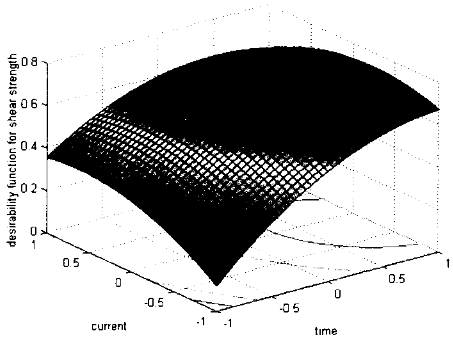
where, $d(\hat{S}(\mathbf{x}))$ is the desirability function of the shear tensile strength and $d(\hat{I}(\mathbf{x}))$ is the desirability function of the indentation. The overall desirability function, which is defined as the geometric mean of the desirability function of each response, is as follows.

$$D(\mathbf{x}) = \left(d(\hat{S}(\mathbf{x}) \cdot d(\hat{I}(\mathbf{x})\right)^{1/2} \quad (7)$$

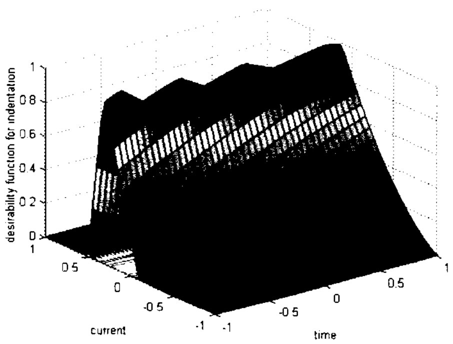
Using equation (7) which was the defined objective function, the input variable which maximizes the objective function within the region of interest was determined. To do this, the region of interest was divided into small squares, and the grid search method was used to determine the objective function value within each square.

The optimal coded values of the input variables obtained through the grid-search method was $(x_1,\ x_2,\ x_3)$ = (0.2, 0.85, 0.15), while the natural values was $(\xi_1,\ \xi_2,\ \xi_3)$ = (3.53, 14, 8.15) and the overall desirability function was 0.8498. The estimated output under the optimal conditions were $(\hat{S},\ \hat{I})$ = (14.14, 0.399), and the actual values obtained through welding experiments were $(S,\ I)$ = (14.30, 0.35). A comparison showed that the two values coincide relatively well.

Fig. 2(a) was the desirability function distribution of the shear strength according to the welding current and time when the pressure was determined at an optimal 3.14kN. Generally, the shear strength was weak when the current was low and time was short, and the shear strength was strong when the welding current was normal and welding time was long. Also, Fig. 2(a) showed that the optimal conditions were where the graph reached its peak. Fig. 2(b) was the desirability function distribution of the indentation. Unlike the shear tensile strength, a two-sided desirability function was used. Therefore, the desirability function reached its maximum value when the coded value of the current was approximately 0.3. As seen in Fig. 3, the overall desirability function showed both output variable responses simultaneously. The indentation reached a value close to 0 in low and high current regions. This was because the indentation is not satisfied due to a shortage in current and generation of expulsion. Therefore, Fig. 3 showed that under an optimal welding current, the desirability function of the indentation reached its peak when the welding time was long. The results showed that when using TRIP steel, optimal welding could be achieved under relatively lower welding currents. This is because the high concentration of Si and Mn which are high in resistivity causes much heat during resistance spot welding.



(a) shear strength



(b) indentation

Fig. 2 Result of desirability function for shear strength and indentation

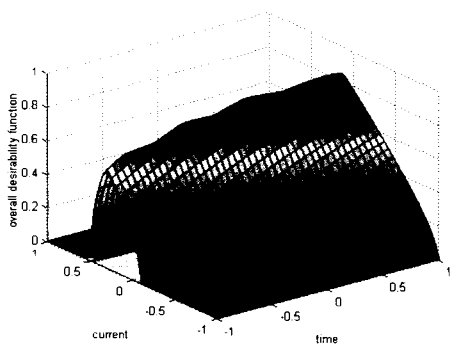


Fig. 3 Result of overall desirability function

5. Conclusion

In order to apply the resistance spot welding process to high tensile TRIP steel, it is necessary to establish the optimal input conditions which produce satisfactory weld quality. In this study, the response surface method was used to determine the optimal conditions. In order to determine the response surface which expresses the relationship between the input variables (welding pressure, welding time and welding current) and the output variables (shear strength and indentation), the welding experiment was carried out after which the obtained data was used to generate a regression model. A modified central composite design was established to formulate an effective regression model which requires a smaller number of experiments. The overall desirability approach was used in determining the optimal welding conditions in order to satisfy both response surface output values. Overall, it was possible to obtain optimal weld quality under relatively lower welding currents by using TRIP steel, and when using galvanized steel, it is important to extent the welding time.

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