



Analysis of Resistance Spot Welding Process Parameters Effect on the Weld Quality of Three-steel Sheets Used in Automotive Industry: Experimental and Finite Element Simulation

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PAPER INFO

Paper history:

Received 17 October 2019

Received in revised form 03 November 2019

Accepted 08 November 2019

Keywords:

Resistance Spot Weld
Spot Welding Process Parameters
Nugget Diameter
Taguchi Approach
Multiple Regression
Response Surface Method

ABSTRACT

In the present research, the effects of spot-welding process parameters on the nugget diameter and electrode penetration depth of spot-welded joints were investigated. To achieve this, a spot-welded joint of three-thin sheet low carbon steels (same thicknesses of 0.8 mm) was simulated as an electrical-thermal-mechanical coupling of 3D finite element model. After validating the finite element simulation presented in this study by comparison with the experimental results for the spot diameter, various cases of spot welds were analyzed based on the design on experiment (i.e., Taguchi method). Six variables including electrode force, electric current, and quadrilateral times (squeeze, up-slope, welding time, and hold) at three different levels were considered as Taguchi algorithm inputs. The results of Taguchi sensitivity analysis showed that the parameters of electrical current (22 %) and welding time (17 %) are the most effective factors on the nugget diameter. Next, Multiple Regression Technique (MRT) was used to present a new equation for calculating spot diameter via the process parameters. The findings of this study showed that the difference between FE results and MRT for predicting spot diameter is less than 13%. Eventually, Response Surface Method (RSM) was utilized to determine the interaction effects of process parameters on the spot weld quality.

doi: 10.5829/ije.2020.33.01a.17

1. INTRODUCTION

One of the most important design parameters in different industries (e. g., automotive industry) is the attention to the geometry of the components and the effort to reduce the weight of the structure. Therefore, resistance spot welding joint method is widely used by artisans compared to other joint methods. However, the reliability and strength of structures are very important and one cannot override the other in order to achieve one of these goals. In spot welding, unlike other welding processes, the filler material is not used to bond two parts. In other words, the electrode does not melt in this method. Rather, electrodes, usually made of high electrical and thermally conductive materials such as copper, are clamped to both

sides of sheets and caused to create contact at the two-sheet surfaces by applying force. Then, the high-amperage electric current passes through one electrode, sheets, contact surfaces, and finally enters the other electrode. Since the sheets and their contact surface with electrodes have electrical resistance, this current generates heat in a small region and melts the two sheets, and by applying force through the two electrodes, the molten portions are joined together, and finally the spot core is formed. Due to the extremely high temperature in the sheets during this process (near the melting point), the metallurgical structure of the materials changes and subsequently affects the mechanical properties of the component including tensile strength, corrosion resistance, and surface hardness. Therefore, various tests

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and inspection processes are designed and used in different industries to control the quality and the strength of spot-welded joints. Also, a large number of studies have been performed in the field of quality assessment of spot weld, effects of process parameters on the nugget diameter, and optimization of process parameters.

Mirzaei et al. [1] have optimized the strength of resistance spot-welded (RSW) joints made of galvanized steel sheets. In this research, the effect of process parameters including electric current, welding time, and the electrode force has been investigated on the nugget diameter. The results showed that the electric current had the greatest effect on the diameter size of spot weld. In addition, they found that as the RSW nugget diameter increases, the bond strength also increases but this is not a permanent relationship. Eshraghi et al. [2] have performed the parametric study on the spot welding process of dual-phase steels. They have used the Design of Experiments (DOE) to investigate the effect of process parameters on the geometric characteristics of weld core and Heat-affected zone (HAZ) including diameter and height. They found that the most important parameters are electric current, sheet thickness, and welding time, respectively. Also, the radius of electrode head cross-section is the most ineffective parameter with respect to the above goals. Butt and Saleem [3] have presented a new formula to evaluate nugget diameter via process parameter of the electric current in the spot-welded low carbon hot rolled sheets using linear first-order regression technique. Moreover, the strength of Cu-Cu spot-welded joint has been predicted utilizing multiple regression and neural network methods [4]. The results showed that the neural networks technique predicts a more accurate response than the results obtained using multiple regression. In addition, Taguchi sensitivity analysis has been used to investigate the effect of spot welding process parameters on the galvanized steel sheet connection [5]. The results of this study indicate that the electric current and welding time have the greatest effect on bond strength, respectively (The effect of electric current is almost twice that of the second parameter influence). Finally, they have reported that the bond strength increases (about 13%) by applying the optimum values for the spot welding process parameters. In this regard, Sun et al. [6] have optimized the welding process parameters using Particle Swarm Optimization (PSO) algorithm and a kernel extreme learning machine model.

In recent years, the spot-welded joint of sheets with different materials and various thicknesses has attracted the attention of researchers. Vignesh et al. [7] have optimized the process parameters of spot-welded joints made of dissimilar materials (AISI 316L austenitic stainless steel and 2205 duplex stainless steel) [7]. The results of Taguchi's analysis revealed that the electric current is the most effective parameter for both bond strength and spot weld quality. Chen et al. [8, 9] have

investigated multi-objective optimization in the spot welding parameters of aluminum-titanium thin foils (thickness of 0.05 mm). They reported that the process parameters of electrode force, upward slope time, and welding time had the least effect on the quality and strength of spot-welded joint, respectively. In this regard, Wan et al. [10, 11] have studied the quality and failure energy of the spot weld using first-order linear regression technique and applying Artificial Neural Network (ANN). They found that the sensitivity of the dynamic resistance and the failure strength of spot weld to the value of electric current exceeded that of the electrode force.

In spite of the research done in the field of sheet metal jointing by RSW and using various methods including experiment, finite element simulation, statistical computational methods, there are different types of problems in the automotive industry. Therefore, the need for further development and research in the field of spot welding process and quality inspection is evident in the industry. In many industries, the spot welding process is also used to connect more than two sheets (three sheets and sometimes four and more). It is clear that in the three-sheet joint, the interaction of the surfaces on each other and the effect of process parameters on the spot weld quality is far more complex than the two-sheet joints. In the present paper, the effect of welding process parameters on the size of the nugget diameter and the depth of electrode penetration was investigated in the three-sheet joint. To achieve this purpose, different techniques including Electrical-Thermal-Mechanical Coupling (ETMC) finite element simulation, Multiple Regression Technique (MRT), Taguchi method (TM), and Response Surface Method (RSM) were used to conduct a comparative study.

2. METHODOLOGY

Firstly, the three-sheet spot-welded joint of low-carbon steel with the same thicknesses was simulated as an ETMC model in the FE software. The validation process of the FE results was performed by comparison with experimental results. Next, various spot weld cases were analyzed by changing the process parameters based on the proposed Taguchi algorithm. Taguchi sensitivity analysis was performed to determine the most and least effective parameters on the spot weld quality. Moreover, the mathematical relationships between the welding process parameters and nugget diameter were presented by applying MRT. Using these equations, the nugget diameter can be predicted via process parameters with good precision at the minimum time and test and computational cost. Finally, RSM was used to obtain the best range of parameter changes for having an arbitrary nugget diameter.

2. 1. Experimental Setup A three-sheet spot-welded joint consisting of DC03A as both middle and bottom sheets and DC04A as a top sheet was considered in this research. The initial phase of the sheets is completely ferrite. The grain size for both low carbon steels is 7 based on the NFA04-102 test method. Also, the thickness of all sheets is equal to 0.8 mm. Sheet length and width are 125 and 45 mm, respectively. The overlap length of RSW joint is considered to be 35 mm. A schematic of the specimen geometry and the spot weld position is shown in Figure 1. Standard F0-16-20-8 electrodes made of 1.1% alumina copper alloy were used to prepare spot-welded specimens. The used values of welding process parameters are reported in Table 1. An electric current is applied alternately at frequency 50 Hz. After that, the specimens were cut transversely through the spot welding. The metallographic analysis was performed to determine the nugget diameter and heat-affected zone (Figure 2).

2. 2. Finite Element Simulation Simufact welding software version 6.0 was used to simulate the 3D process of the RSW as an ETMC model. The geometry and conditions of the spot welding process were considered in accordance with the experimental specimen. Two pairs of clamping supports ($40 \times 40 \times 0.3$ mm) were used on both sides of each sheet (Figure 3).

Moreover, in the finite element simulation, the mechanical, thermal, and electrical properties were defined in terms of temperature for all materials. In addition, phase and metallurgical changes during the process were also considered for sheets by utilizing CCT and TTT diagrams.

Poisson's coefficient was assumed to be equal to 0.3. The simulation algorithm used in this study is illustrated in Figure 4. The tetrahedral element with the ability of

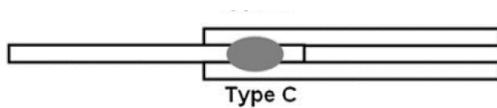


Figure 1. Schematic of the specimen geometry and the spot weld position in the three-sheet joint [12]

TABLE 1. The values of welding process parameters used in this research

Parameters	Unit	Value
Force	N	365
Electric current	KA	11.5
Squeeze time	Cycle	25
Upslope	Cycle	3
Welding time	Cycle	12
Hold time	Cycle	9

electrical-thermal-mechanical coupling characteristics was used to mesh the model. Mesh sensitivity analysis was performed to reduce computational costs considering the highest accuracy of response. To this end, several simulations considering different element sizes (0.25, 0.5, 1, 1.2, and 1.4 mm) were performed and the convergence of mean diameter (diameter between the top and middle sheets and diameter between the middle and bottom sheets) was evaluated. The target was assumed to be less than 1% with a desired change rate. The final FE model of the sheets (element size of 1 mm and two times refinement around the spot weld position) is shown in Figure 5.

2. 3. Statistical Analysis

2. 3. 1. Taguchi Approach Six parameters were considered as input variables in the DOE of the Taguchi method based on the varied history of the parameters used in an automaker company. Also, three levels (A, B, and C) were assumed for each input variable.

In this study, the highest and lowest values are related to the C and A, respectively. The variables and different levels considered as inputs for the Taguchi approach are given in Table 2. It is a static problem by considering the spot weld quality (nugget diameter and depth of electrode penetration) as the output. To use the Taguchi prediction algorithm, the smaller is better and the larger is better

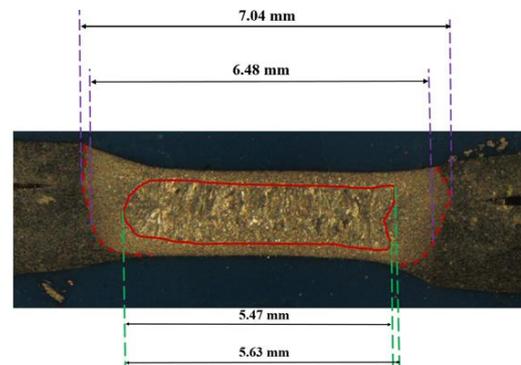


Figure 2. Experimentally measured nugget diameter and heat-affected zone

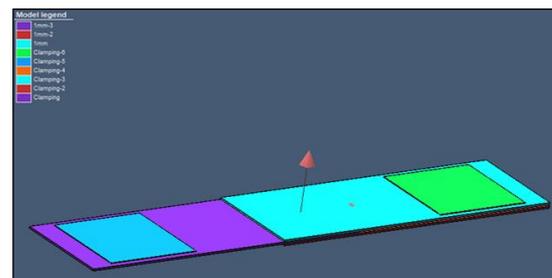


Figure 3. The location of clamping supports and spot weld

viewpoints are considered for the depth of electrode penetration and nugget diameter, respectively. A schematic diagram of the Taguchi design for spot welding process is demonstrated in Figure 6.

The main purpose of this section is to study the effect of the process parameters on the spot weld quality and then provide recommendations for improving the health of the spot-welded joint. The L27 orthogonal matrix was used to perform Taguchi analysis.

2.3.2. Multiple Regression Technique In general, using this technique allows for the study of the linear relationship between a set of independent variables with a dependent variable in a way that the existing relationships among the independent variables are also considered. Its results can be used to predict responses for different states and parameter changes.

In addition, the optimal process and interaction between independent parameters can be achieved by relying on MRT results and applying various techniques of optimal parameter estimation such as the least-squares method, random gradient method, and maximum likelihood estimation. For this purpose, the various cases obtained in the Taguchi design section (27 experiments) were used.

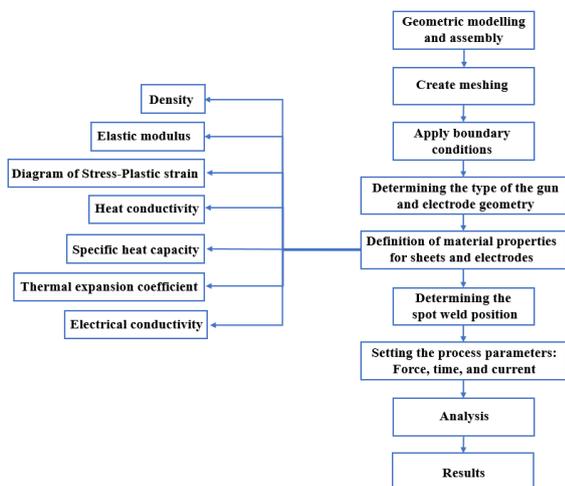


Figure 4. The algorithm used to simulate the spot welding process

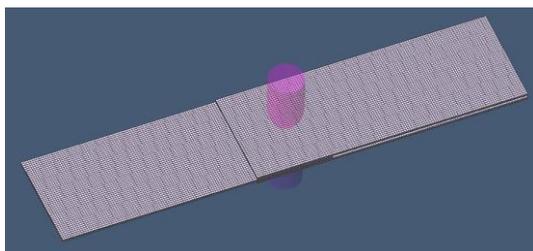


Figure 5. The final finite element model of the sheets

2.3.3. Response Surface Analysis The response surface method is a set of statistical techniques and applied mathematics to construct experimental models. The aim of such schemes is to optimize the response (output variable) that is affected by several independent variables (input variables). Thus, in each experiment, changes the values of input variables are made to determine the causes of changes in the response variable. In order to use this method, at least 53 cases must be evaluated with respect to the number of input parameters and levels studied in this research (it is better to utilize 90 cases for raising the accuracy of the analyzes).

The Taguchi prediction algorithm was used to extract different cases considering the high computational costs of finite element analysis.

3. RESULTS AND DISCUSSION

3.1. Finite Element Simulation Figure 7 shows the spot nugget diameter obtained between the top and middle sheets (5.903 mm) and between the middle and bottom sheets (5.896 mm). The FE results compared with the experimental measurements have a mean difference of 6.35%. After validating the finite element model

TABLE 2. Variables and levels of input parameters used in the Taguchi approach

Type of variable	Parameter	Level		
		A	B	C
Force (N)	Force	320	365	398
Current (KA)	Heat_2	10	11	12
	Squeeze	15	20	25
Time (Cycle)	Upslope	2	3	4
	Weld_2	11	12	13
	Hold	8	9	10

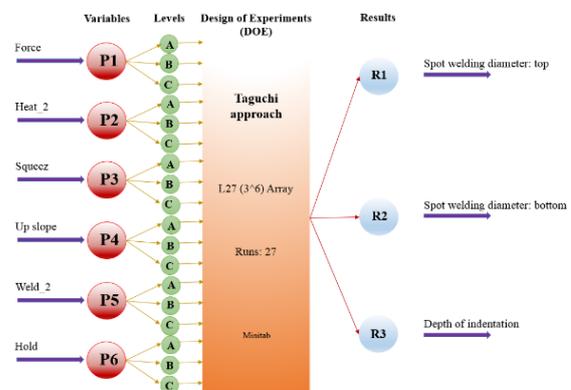


Figure 6. Schematic diagram of the Taguchi design for the spot welding process

presented in this study, the spot welding process for the 27 different cases (proposed by Taguchi design) was analyzed and the results are reported in Table 3.

According to the definition of a health spot weld in the automotive standard (the minimum nugget diameter is 4 mm), all cases studied here caused to create a health spot weld. On the other hand, there is no limitation to the maximum nugget diameter. However, previous research shows that this does not mean that the larger nugget diameter leads to better performance and the higher strength of spot-welded joint. However, the largest nugget diameter between the top and middle sheets and between the bottom and middle sheets are assigned to cases 8 and 9, respectively. It is evident that the deformation of the sheets increases by raising the depth of electrode penetration. And it is possible to result in some defects such as perforation. Therefore, the minimum depth of electrode penetration is optimal (the penetration depth must be such that there is no adhesion defect).

3. 2. Taguchi Approach Since all finite element responses (Table 3) have the same dimension (the unit of all outputs is mm), dimensionless operations are not

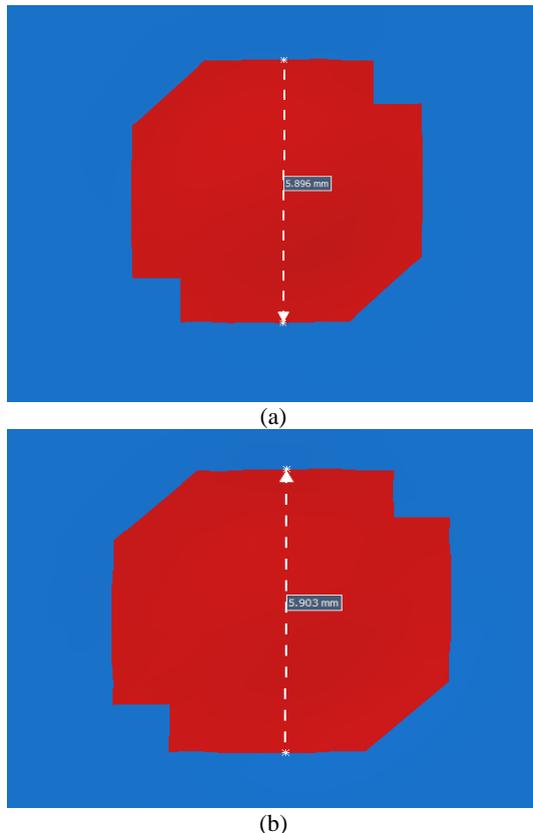


Figure 7. The geometry and size of the welding core in the three-sheet joint: A) between middle and bottom sheets and B) between top and middle sheets

required to equalize output values for providing comparability between them. Taguchi sensitivity analysis was performed for each of the quality parameters (nugget diameter and depth of electrode penetration) using finite element responses. The ranking of the influence of welding process parameters is presented in Table 4.

The results show that the importance of the process parameters on the nugget diameter between the top and middle sheets and the nugget diameter between the middle and bottom sheets is divergent. The main reason for this difference can be the passage of one-way currents and the connection from one electrode to another.

TABLE 3. Finite element results extracted for different Taguchi cases (All dimensions are in millimeters)

Case No.	Nugget diameter		Depth of electrode penetration
	Between the top and middle sheets	Between the middle and bottom sheets	
1	5.78	5.87	0.145
2	5.03	5.89	0.160
3	4.2	5.9	0.190
4	5.85	5.85	0.200
5	5.89	5.86	0.220
6	5.89	5.88	0.160
7	5.86	5.87	0.225
8	6.81	7.79	0.270
9	6.03	7.82	0.360
10	5.88	5.87	0.165
11	5.89	5.03	0.175
12	5.10	5.09	0.210
13	5.91	5.9	0.180
14	5.86	5.89	0.170
15	5.41	5.11	0.200
16	5.88	5.88	0.205
17	5.92	4.05	0.325
18	5.01	5.87	0.230
19	5.87	5.89	0.170
20	5.88	5.88	0.155
21	5.89	5.87	0.170
22	5.90	5.50	0.190
23	5.12	5.13	0.280
24	5.03	5.94	0.245
25	5.91	5.13	0.260
26	4.6	5.16	0.315
27	5.88	5.88	0.200

However, the electric current and welding time have the greatest effect on the depth of electrode penetration and the least effect is related to the squeeze time. In summary, to achieve the maximum nugget diameter and the minimum depth of electrode penetration, the optimal effect can be obtained by changing the parameters of electric current, squeeze time, and welding time. Furthermore, the effect of welding process parameters (quantitatively) on the spot weld quality via their weight percentages are illustrated in Figure 8.

The results of Taguchi's analysis (Figure 8) indicate that if the main objective of the spot weld health is based on both nugget diameter and depth of electrode penetration, the efficiency of electric current and welding time is 22 and 17%, respectively and each of the rest parameters has about 15% efficiency.

3. 3. Multiple Regression The linear relationship between the nugget diameter and spot welding process parameters including electric current, electrode force, and various time steps (squeeze, upslope, weld, and hold times) was presented by applying multiple regression technique.

$$R1 = 1.7 - 0.0362A - 0.75B - 0.07C + 1.67D - 1.78E + 5.14F + 0.000048A^2 + 0.042B^2 + 0.00392C^2 - 0.259D^2 + 0.064E^2 - 0.279F^2 \quad (1)$$

and

$$R2 = -10.5 - 0.0292A + 5.49B - 0.269C + 2.07D + 1.79E - 5.06F + 0.000036A^2 - 0.228B^2 + 0.00646C^2 - 0.362D^2 - 0.068E^2 + 0.29F^2 \quad (2)$$

Equations (1) and (2) represent the nugget diameters between the top and middle sheets and between the middle and bottom sheets, respectively. To measure the error rate of both relationships in comparison with the results of finite element simulations, the comparative diagrams are depicted in Figure 9.

The mean error for nugget diameter prediction between the top and middle sheets and between middle and bottom sheets are 4.9 and 12.8%, respectively.

TABLE 4. The ranking of the influence of spot welding process parameters based on the Taguchi sensitivity analysis

Parameters	Result_1	Result_2	Result_3	Total
Force	6	1	5	6
Heat_2	5	5	1	1
Squeeze	1	2	6	3
Up slope	4	4	3	4
Weld_2	2	6	2	2
Hold	3	3	4	5

Therefore, the error values of the presented equations are acceptable compared to the reduction of computational costs such as simulation time and finite element analysis as well as decrease of experiment costs. Eventually, using these relationships can be very useful in the automotive industry.

3. 4. Response Surface Method RSM was utilized to determine the interaction effects of process parameters on the spot weld quality. The results for the nugget diameters between the top and middle sheets and between the middle and bottom sheets are shown in Figures 10 and 11, respectively.

The most important results extracted from the contours of Figure 10 and Figure 11 are:

1- In order to obtain the maximum nugget diameter on both sides of the spot-welded specimen, it is recommended to consider the minimum force level and the maximum electric current level. Moreover, the nugget diameter decreases by increasing the force level

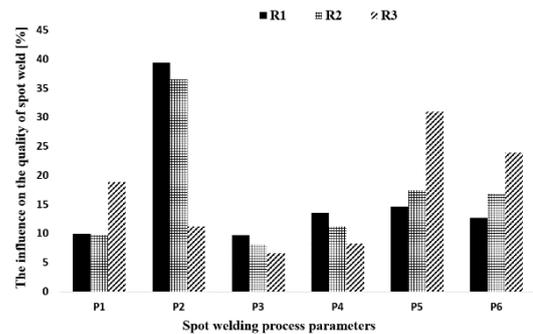


Figure 8. The quantitative effect of welding process parameters on the quality of spot weld

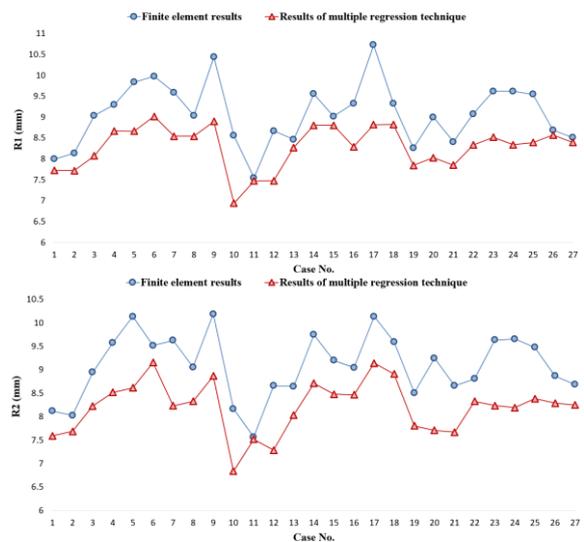


Figure 9. The comparative diagrams between the results of multiple regression method and FE results

so long as the electric current is maximum. In addition, the nugget diameter increases by raising electric current

(while the force parameter has the lowest value in the process).

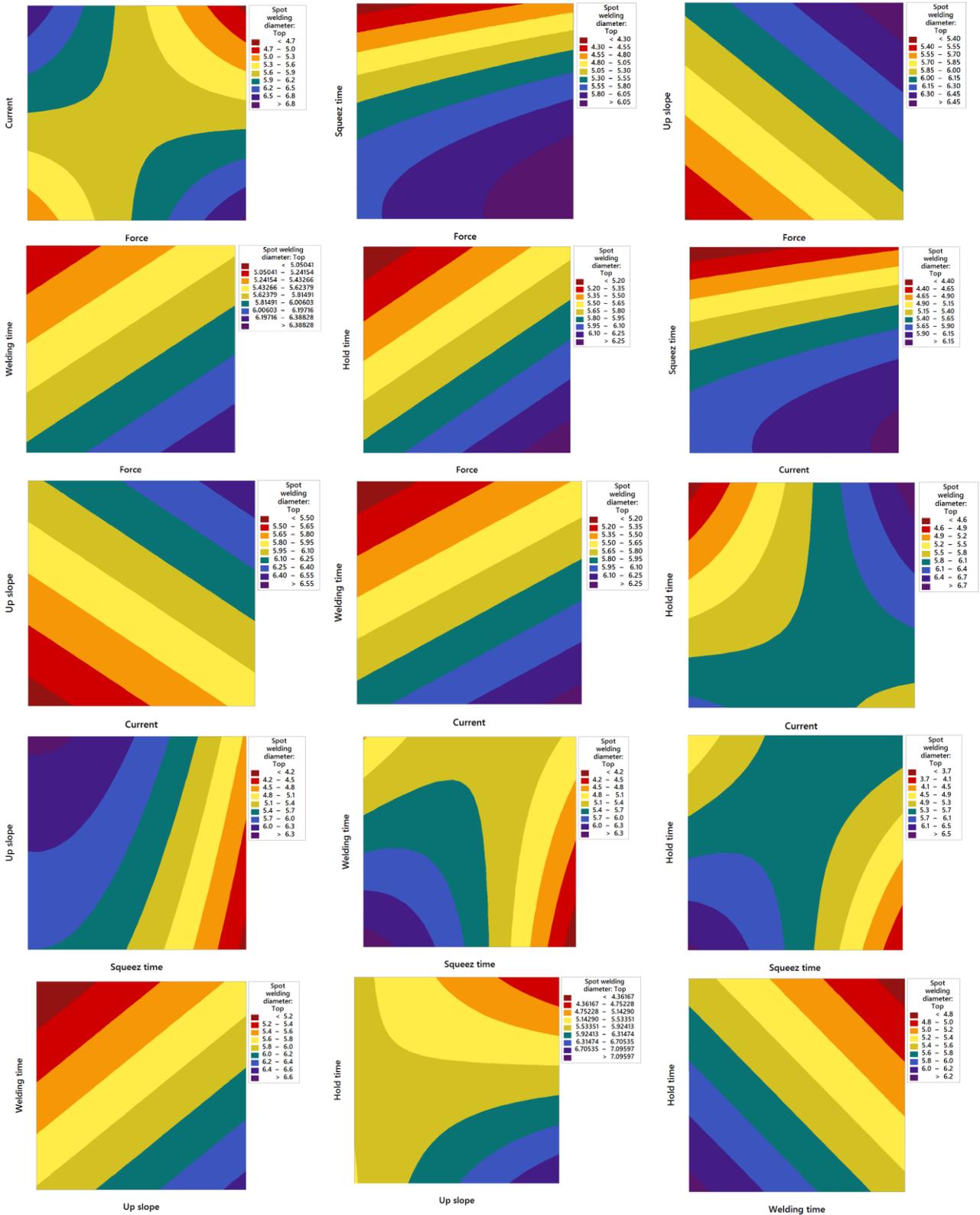


Figure 10. The RSM results for nugget diameter between the top and middle sheets in a three-sheet spot-welded joint

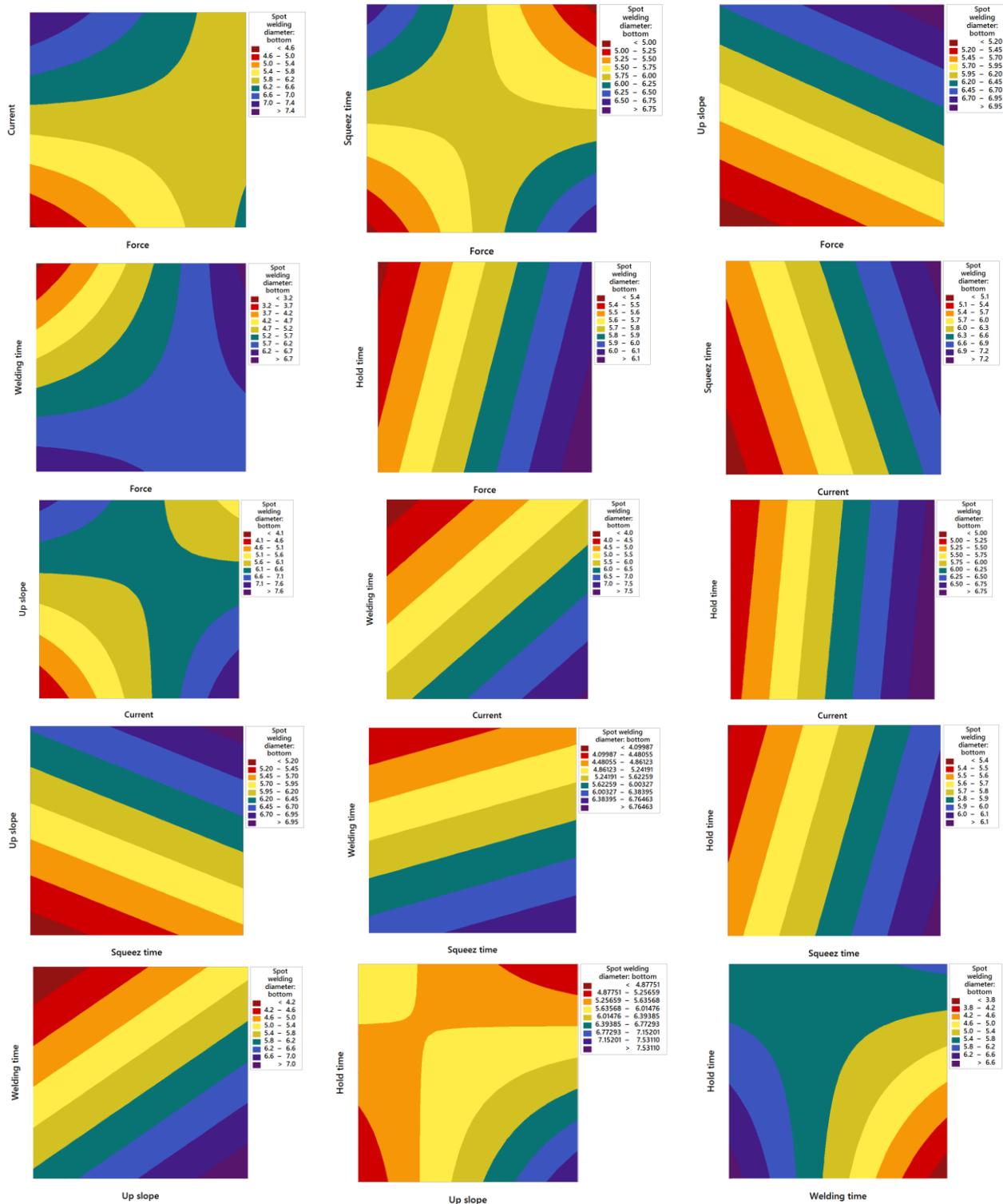


Figure 11. The RSM results for nugget diameter between the middle and bottom sheets in a three-sheet spot-welded joint

2- The variation trends of the nugget diameter on both sides of the specimen in terms of the binary interaction of the force and squeeze time parameters are different.

Thus, the force and squeeze time parameters should be set to the maximum and minimum levels, respectively to achieve the highest nugget diameter between the top

and middle sheets. Also, the minimum size of the nugget diameter will be obtained by setting the lowest and highest levels for the electrode force and squeeze time, respectively. However, in order to obtain the maximum value of the nugget diameter between the middle and bottom sheets, it is suggested that both parameters be adjusted at the opposite levels (one parameter at minimum and the other parameter at maximum value). Hence, if both parameters are at the highest level, the lowest nugget diameter will occur between the middle and bottom sheets. In addition, there is a stationary region with no change in the nugget diameter.

3- To have the largest nugget diameter on both sides of the spot-welded joint, it is necessary to consider the maximum level settings for both process parameters including electrode force and upslope time.

4- The behavior of nugget diameter changes on both sides of the three-sheet spot-welded joint in terms of the binary interaction of the electrode force and welding time is different. For example, in order to achieve the maximum nugget diameter between the middle and bottom sheets, it is necessary to adjust the parameters in one of the purple areas (the highest level in both parameters or conversely).

5- Raising the force level and the hold time leads to an increase and decrease in the nugget diameter on both sides of the spot-welded joint, respectively. When the process parameters are set to the minimum hold time and the maximum electrode force, then the largest diameter of the welding core is formed and vice versa.

6- The results show that the nugget diameter increases by raising the electric current. But, there is a difference in the trend of diameter variations over the binary interaction of the process parameters such as electric current and squeeze time. In other words, settings that have a positive effect on the size of the nugget diameter between the top and middle sheets have negative effects on the size of the nugget diameter between the middle and bottom sheets. Therefore, it is necessary to extract optimal values for them.

7- The findings of this study reveal that increasing the welding time while keeping the hold time at the maximum level results in an increase of nugget diameter.

8- As the squeeze time increases, the nugget diameter of the spot-welded joint increases. Also, increasing the time of upslope leads to an increase the nugget diameter on both sides of the three-sheet spot-welded joint.

4. CONCLUSION

The present research has attempted to examine the influence of various welding process parameters on the spot weld quality. To this end, different techniques including finite element simulation, Taguchi approach, multiple regression, and response surface method were

used. In all analyzes, the process parameters of electric current, electrode force, squeeze time, upslope time, welding time, and hold time were considered as input variables. Also, the nugget diameter and the depth of electrode penetration were considered as quality criteria of the spot weld.

The results of the Taguchi sensitivity analysis showed that electric current and welding time had the most effect on the spot weld quality, respectively. Moreover, the electrode force plays the least role in the health of spot weld. Therefore, it is recommended that in order to achieve a healthy spot weld in the automotive industry, it is advisable to adjust the two controllable parameters of electric current and welding time. It is also expected to change the level of electrode force when there are some welding defects such as holes, deformations, etc. Next, the linear relationships were presented to predict the nugget diameter on both sides of the spot-welded specimens in terms of welding process parameters using multiple regression technique. The results obtained from the relationships have a 13% difference compared to the results of finite element analysis. Therefore, using these relationships is very useful for the automotive industry from an economic point of view (reduction of computational costs, experimental costs, and spending time). Finally, the results of the data analysis by RSM reveal that in order to reach the largest nugget diameter, it is necessary to adjust the parameters of the electric current and welding time to the maximum level.

It is also preferable that the electrode force parameter is kept to a minimum value. Moreover, the behavior of the nugget diameter on the two sides of the specimen is different with respect to the two-way interaction of the other parameters. Hence, it is suggested that these parameters should not be changed as much as possible because by improving the quality of the spot weld on one side of the three-sheet specimen, it will reduce its quality on the other side.

5. ACKNOWLEDGEMENTS

The authors wish to thank M. Behroozi, V. Grigorian and R. Ghorbani for their valuable assistance in this research.

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Analysis of Resistance Spot Welding Process Parameters Effect on the Weld Quality of Three-steel Sheets Used in Automotive Industry: Experimental and Finite Element Simulation

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P A P E R I N F O

چکیده

Paper history:

Received 17 October 2019

Received in revised form 03 November 2019

Accepted 08 November 2019

Keywords:

Resistance Spot Weld
Spot Welding Process Parameters
Nugget Diameter
Taguchi Approach
Multiple Regression
Response Surface Method

در این مقاله به بررسی اثر پارامترهای فرایند نقطه‌جوش بر اندازه‌ی قطر هسته جوش و عمق نفوذ الکتروود در اتصال سه‌ورقی پرداخته شده است. به منظور دست‌یابی به این هدف، یک اتصال سه‌ورقی نقطه‌جوش از جنس فولاد کم کربن (با ضخامت‌های یک‌سان ۰.۸ میلی‌متر) در نرم‌افزار المان محدود به‌صورت آنالیز کوپل الکتریکی-حرارتی-مکانیکی شبیه‌سازی سه‌بعدی شده است. پس از اعتبارسنجی مدل المان محدود ارایه شده توسط مقایسه با نتایج آزمایشگاهی برای اندازه‌ی قطر هسته‌ی جوش، به شبیه‌سازی المان محدود فرایند نقطه جوش بر اساس حالت‌های مختلف پیشنهادی توسط روش طراحی آزمایش (برای مثال تاگوچی) پرداخته شده است. شش متغیر شامل نیروی الکتروود، جریان الکتریکی و زمان‌های چهارگانه در سه سطح مختلف به عنوان ورودی الگوریتم تاگوچی در نظر گرفته شده است. نتایج تحلیل حساسیت تاگوچی نشان داد که پارامترهای جریان الکتریکی (۲۲٪) و زمان جوش‌کاری (۱۷٪) موثرترین فاکتور بر قطر هسته جوش هستند. در ادامه، به منظور ارایه‌ی یک رابطه‌ی جدید برای محاسبه‌ی قطر هسته‌ی جوش بر حسب پارامترهای فرایند از تکنیک رگرسیون چندمتغیری استفاده شد. دستاوردهای این پژوهش نشان می‌دهد که اختلاف بین نتایج شبیه‌سازی المان محدود و تکنیک رگرسیون چندمتغیری برای تخمین قطر هسته‌ی جوش کمتر از ۱۳ درصد است. در نهایت، به منظور تعیین نحوه‌ی اثرگذارای تعامل دو به دو پارامترهای فرایند بر کیفیت نقطه‌جوش از تحلیل رویه‌ی پاسخ استفاده شده است.

doi: 10.5829/ije.2020.33.01a.17