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Research Article

Comparison of taguchi method and response surface methodology in determining optimal parameters for welding two metal plates

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ABSTRACT

Welding technology plays an important role in manufacturing and gas metal arc welding is one of the most popular welding methods. There are many input parameters that affect the quality of the welding seam such as welding current, welding voltage, welding speed, etc. One of the problems in controlling welding robots is determining the optimal parameters that maximize the quality of welding. There are several designs of experiment techniques that can be used to get the desired results with a small number of experiments. In this paper, Taguchi method and response surface methodology are chosen to estimate the value of residual stresses of the seam path of welding two metal plates. In the case of response surface methodology, both Box-Behnken design and central composite design are used in determining the optimal parameters. The estimation of residual stresses is done by ABAQUS software. Comparison among the designs is done and many conclusions about the optimal parameters and mathematical model are presented. In this research, the optimal value of the tensile residual stress can be obtained by maximizing the value of welding voltage, maximizing the value of welding current, and minimizing the value of welding speed. From the simulation results, it can be concluded that the Taguchi design can give the optimal value with the smallest error and the smallest number of simulations. The Box-Behnken design gives the smaller error and smaller number of simulations compared with the central composite design. The analysis of variance is a computational technique to quantitatively estimate the contribution that each parameter makes on the overall observed response. From the simulation results, the contribution of speed welding is largest. The effect of the welding voltage is smallest among the three factors.

Key words: Taguchi method, response surface methodology, optimal parameters, industrial robot, gas metal arc welding

INTRODUCTION

Welding technology plays an important role in manufacturing and gas metal arc welding (GMAW) is one of the most popular welding methods. GMAW is used in automation manufacturing systems, such as in automotive industry, to increase productivity and the quality of the product. In these systems, the welding work is done by the industrial manipulators because of their high repeatability and high performance. The engineer needs to give the input parameters to the controller of robots so that the robots can do welding automatically.

There are many input parameters that affect the quality of the welding seam such as welding current, welding voltage, welding speed, etc. One of the problems in controlling welding robots is determining the optimal parameters that maximize the quality of welding. This work can be done by simulation or experiments. To reduce the number of experiments, the design of experiments (DOE) technique is used. The engineer should determine the objectives of the experiments and the factors that affect this objective. There are several DOE techniques that can be used to get the desired results with a small number of experiments. Taguchi method and response surface methodology are two most used methods.

Lenin et al. used Taguchi method (L9) to optimize the welding process parameters in welding of dissimilar metals to obtain greater weld strength [1]. Deshmukh et al. presented the application of Taguchi technique to determine the optimal process parameters for submerged arc welding (SAW) process [2]. Experimentation was done according to Taguchi's design of experiments (L8) used to predict the SAW process parameters for any given welding conditions. Mishra et al. presented a method of using Taguchi technique to determine the effect of welding parameters on penetration depth of AISI 1020 steel during welding [3]. The

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used parameters are welding current, welding voltage, and welding speed.

Sada used response surface methodology to optimize the weld strength properties of Tungsten inert gas mild steel welds[4]. The tensile strength and hardness were modeled with quadratic regression models as functions of the process parameters of current, voltage, gas flow rate and filler rod dia. Celik et al. used response surface methodology for modeling the mathematical relation between the tensile strength and friction welding parameters[5]. RSM is an effective method for developing models and prediction with minimum number of experiments. Hooda et al. made research on the effect of process parameters such as welding voltage, current, wire speed to tensile strength of inert gas metal arc welded AISI 1040 medium carbon steel joints[6]. The optimal parameters are predicted using the response surface model of a four-factor, three-level, face centered composite design matrix.

However, there is little research that uses both the Taguchi method and response surface methodology to look for the optimal parameters. The comparison between Taguchi method and response surface methodology is necessary to conclude which method should be used.

Sivaraos et al. applied both Taguchi method and RSM method to modelling the laser parameters when machining industrial PVC foams[7]. The value of the kerf width was influenced by the laser parameters such as cutting speed, laser power, frequency etc. The paper compared the Taguchi method and RSM method and concluded that RSM technique seems to be more promising in predicting the response via mathematical modelling over the Taguchi technique. Akhmad et al. discussed optimization from welding parameters in friction welding[8]. Both the Taguchi method and RSM method were used to predict the optimal parameters such as rotation speed, diameter specimen, and joining time. Daniyan et al. presented optimization of welding parameters using Taguchi and response surface methodology for rail car bracket assembly[9]. The optimal input parameters were determined by Taguchi orthogonal array of L9. The cross effect of various process parameters on the weld distortion was studied by RSM method.

The research about determining optimal parameters of welding process (GMAW) often uses Taguchi method or response surface methodology. There is little research about using both Taguchi and RSM methods. In this research, both Taguchi method and response surface methodology are used to determine the optimal parameters for welding two metal plates. In addition, in the RSM method, the comparison between the Box–Behnken design and central composite design is also considered. Thus, it can conclude which method is suitable for the GMAW process.

To reduce the cost for doing experiments, many researchers do simulations to get the desired results. There are some responses that can be estimated by the simulation such as heat history diagram or residual stresses of the welding part.

Bonnaud et al. presented the method to simulate the weld residual stresses in 2D and 3D of start/stop and weld repair effects[10]. Chen et al. studied the thermal history and thermomechanical process in the butt-welding of aluminum alloy 6061-T6 using a 3D model and finite element analysis[11]. Nezamdost et al. proposed the method to apply the Goldak model for predicting thermal distribution in submerged arc welding (SAW) of APIX65 pipeline steel and this solution was verified by numerical and experimental results[12]. Lu et al. established integral mathematic model of fluid flow and heat transfer of GTAW arc and weld pool[13]. Deng et al. presented a computational procedure for analyzing temperature fields and residual stress states in multi-pass welds in SUS304 stainless steel pipe[14].

In this paper, a mathematical model is presented for making the simulation of welding two metal plates. Next, the Taguchi method of L9 is chosen to estimate the desired value of the residual stresses. After that, the response surface methodology including two designs of Box–Behnken design and central composite design are done. Finally, the comparison among three designs has been made to conclude about which design could give the best accuracy model and is suitable for the GMAW process.

MATERIALS AND METHODS

Research methods

In this research, the paper uses the Taguchi method and response surface methodology to estimate the residual stresses in welding two metal plates using simulation method in ABAQUS. Three factors are chosen as the input parameters are welding voltage, welding current, and welding speed. The output or the response of the model is the residual stress along the axis that is parallel with the welding path.

In this paper, three factors that affect the value of residual stresses are welding voltage, welding current, and welding speed. According to "Welding Handbook Volume 2 – Welding process by American Welding Society (AWS)"[15], the range of welding voltage can be chosen from 28 to 32 volts, the range of welding current can be chosen from 140 to 180 amperes, and the range of welding speed can be chosen from 0.005 to 0.006666 meters per second (or 5 to 6.666 millimeters per second).

Because the model has three factors, the L9 orthogonal matrix of 9 experiments is chosen for Taguchi method[2]. In case of response surface methodology, two designs are chosen are Box–Behnken design of 13 experiments and central composite design of 15 experiments[16]. Table 1 shows the value of 3-level factors of Taguchi L9 orthogonal matrix. The values of the factors of Box–Behnken design and central composite design are shown in Table 2 and Table 3.

There is a difference between the voltage value and the voltage level. For example, in Table 1 (Taguchi L9 Table), the voltage has 3 voltage levels including levels 1, 2, and 3. Voltage level 1 has a voltage value of 28 (V), voltage level 2 has a voltage value of 30 (V), and voltage level 3 has a voltage value of 32 (V). A similar explanation can be applied for Table 2 and Table 3.

In each design, the minimum value of the residual stress and the mathematical model are estimated. After that, a few more simulations can be done to verify the estimated results. From these results, the conclusions about which design gives the best results can be drawn.

Simulation model

The object of this research is to estimate the residual stresses of welding two metal plates made of SUS304 by GMAW technology. The dimensions of the metal plate are 100 x 50 x 5 mm. The thermal physical properties and mechanical properties of SUS304 can be found in the reference[14].

Residual stress is the stress component that exists after all loads have been removed[17]. There are two types of residual stress including tensile residual stress and compressive residual stress. The first type causes harm to components and needs to be reduced in the welding process. The goal of this research is to look for the optimal welding parameters to minimize the value of the tensile residual stress to reduce the effect of this stress to the quality of the welding path.

In this research, the thermo-mechanical behavior of the weldment during welding is simulated using uncoupled formulation. Firstly, the heat conduction problem is solved to obtain the temperature history. After that, the stress problem is considered to get the results of stress analysis[14]. The heat from the moving welding arc is applied as a volumetric heat source with a double ellipsoidal distribution proposed by Goldak et al.[18] and is expressed by equations (1) and (2).

For the front heat source:

$$Q(x,y,z,t) = \frac{6\sqrt{3}f_f Q_w}{abc_f\pi\sqrt{\pi}} e^{-3x^2/a^2} e^{-3y^2/b^2} e^{-3z^2/c_f^2} \tag{1}$$

For the rear heat source:

$$Q(x,y,z,t) = \frac{6\sqrt{3}f_r Q_w}{abc_r\pi\sqrt{\pi}} e^{-3x^2/a^2} e^{-3y^2/b^2} e^{-3z^2/c_r^2} \tag{2}$$

Where x, y, and z are the local coordinates of the double ellipsoid model. f_f and f_r are parameters which give the fraction of the heat deposited in the front and the rear parts. a, b, c_f, c_r are the dimensions of the two ellipses, the front ellipse and the rear ellipse. Q_W is the power of the welding heat source, can be calculated by equation (3), where U, I, η are welding voltage, welding current, and arc efficiency of GMAW process. All the value of these parameters can be seen in Table 4.

$$Q_W = UI\eta \tag{3}$$

Table 4: The parameters of the double ellipsoidal heat source model.

Parameters	Value
a	0.003 m
b	0.003 m
c_f	0.003 m
c_r	0.009 m
f_f	0.6
f_r	1.4
η	0.7

RESULTS AND DISCUSSION

Results of thermal and mechanical analysis

The welding simulation includes thermal analysis and mechanical analysis processes. Firstly, the thermal analysis is modeled to receive the temperature history. The heat conduction process at the time of 11.46 seconds can be seen in Figure 1. The moving heat which is modeled by equations (1), (2), and (3) is moved from start point to the end point. The welding step happens in 15 to 20 seconds depending on the welding speed. The cooling step happens after the welding step in 3000 seconds.

Figure 2 shows the thermal cycles during the welding at three different locations comparing with the welding seam path. The coordinates of these points along Z-axis is 0.05 m and along Y-axis is 0.005 m. The

Table 1: Welding parameters and 3-level factors of Taguchi L9 table.

Factors	Levels		
	1	2	3
Voltage (V)	28	30	32
Current (A)	140	160	180
Speed (mm/s)	5	5.833	6.666

Table 2: Welding parameters and level values of 3 factors Box-Behnken design.

Factors	Levels		
	-1	0	1
Voltage (V)	28	30	32
Current (A)	140	160	180
Speed (mm/s)	5	5.833	6.666

Table 3: Welding parameters and level values of 3 factors of central composite design.

Factors	Levels				
	-1.68	-1	0	1	1.68
Voltage (V)	28	28.81	30	31.19	32
Current (A)	140	148.1	160	171.9	180
Speed (mm/s)	5	5.337	5.833	6.329	6.666

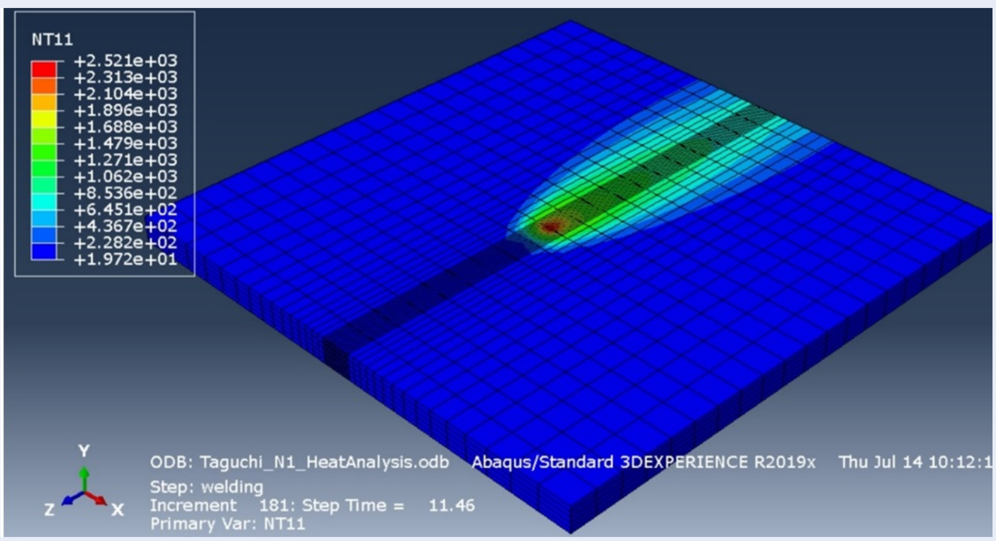

Figure 1: Welding simulation at the time of 11.46 seconds

positions along X-axis of these nodes are respectively 0.0042 m for node 1300, 0.0071 m for node 1338, and 0.0109 m for node 1376. The maximum temperature of the node 1300 (label Series1) is about 1320 ^{0}C, of the node 1338 (label Series2) is about 780 ^{0}C, and of the node 1376 (label Series3) is about 500 ^{0}C. These above values are reasonable because the temperature of the further point comparing the welding path is smaller than the nearer point.

Next the mechanical analysis is conducted using the temperature histories computed by the thermal analysis as the input data. The residual stresses can be divided into the axial stress and the perpendicular-axis stress along the welding path. The object of this research is to look for the optimal welding parameters so that the axial stress at the considered point is minimum. Figure 3 shows the axial stress distribution of the welding process. It can conclude that the maximum axial stress happens at the points in the middle and near the welding path. Figure 4 shows the values of axial stresses of the points that are located near the welding path. From this result, the maximum value of axial stress is at the middle point (node 1300) of the path. Thus, the node 1300 is considered a point for comparison between Taguchi method and response surface methodology.

Results of Taguchi L9 design

The axial stress values of the considered point (node 1300) according to Taguchi L9 design are shown in Table 5. In these simulations, the unit of the stresses S33 is 10^8 Pa. According to Taguchi's theory, the signal-to-noise ratio represents the quality characteristics for the observed data. In this research, the optimal values of the factors need to minimize the axial tress at node 1300 to increase the quality of the welding process.

Figure 5 shows the main effects plot of design parameters over the axial stress S33. Because the optimal value happens when the signal-to-noise gets the maximum value, greater voltage and current give the better value of axial stress. On the other hand, the smaller value of speed will reduce the value of axial stress. The response function calculated from Taguchi design can be seen in equation (4), where *S33*, *U*, *I*, *V* are respectively axial stress, welding voltage, current, and speed.

$$\begin{aligned} S33 = 3.19497 - 0.009283U \\ -0.001812I + 48.183V \end{aligned} \tag{4}$$

Results of Box–Behnken design

The axial stress values of the considered point (node 1300) according to Box-Behnken design are shown in Table 6. In this design, the number of simulations is 13. From the simulated results, the second-order response of the stresses *S33* can be seen in equation (5). In this function, there are some effects that are significant, others are not significant. Figure 6 shows the Pareto chart of the standardized effects to determine the magnitude and the importance of the effects. In this Pareto chart, the bars that represent factors Speed, Current, and Voltage cross the reference line that is at 2.57. These factors are statistically significant at the 0.05 level with the current model terms. Because the second factors are not significant so that they can be deleted from equation (5) and the new first model can be seen in equation (6).

$$\begin{aligned} & S33 = 3.442 - 0.0198U - 0.00233I + 40.1V \\ & -0.000014U^2 - 0.000007I^2 - 6087V^2 \\ & +0.000036UI + 0.9UV + 0.303IV \end{aligned} \tag{5}$$

$$\begin{aligned} S33 = 3.2343 - 0.00964U \\ -0.001845I + 44.74V \end{aligned} \tag{6}$$

Results of central composite design

The axial stress values of the considered point (node 1300) according to central composite design are shown in Table 7. In this design, the number of simulations is 15. The linear model from the simulated results can be seen in equation (7). The optimal plot of central composite design, can be seen in Figure 7, shows the effect of each factor including Voltage, Current, and Speed on the StressS33. The current factor settings are represented by the vertical red lines on the graph. The red numbers displayed at the top of a column show the current factor level settings. The responses for the current factor level are represented by the horizontal blue lines and numbers. From this figure, the optimal combination of the parameters for the minimum value of the axial stress (2.8169 10^8Pa) can be achieved by using a voltage of 32 volts, current of 180 amperes and speed of 0.005 meters per second.

$$\begin{aligned} S33 = 3.135 - 0.00718U \\ -0.001874I + 49.76V \end{aligned} \tag{7}$$

Discussion

Look for the minimum value of the residual stresses

The goal of optimal problem-solving is looking for the factor values that minimize the value of the axial stress *S33*. According to Taguchi design, Figure 5

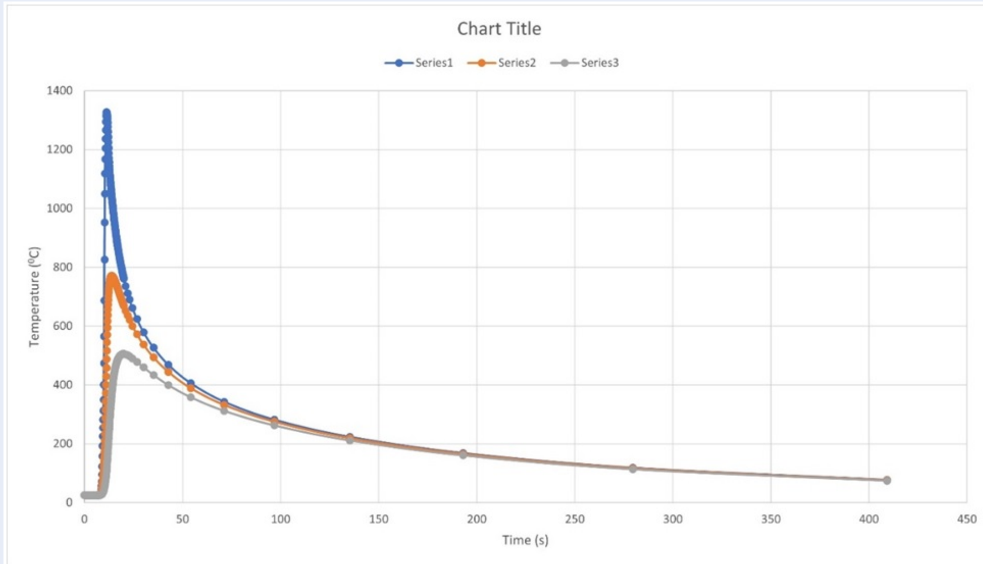

Figure 2: Thermal cycles of welding process at 3 points

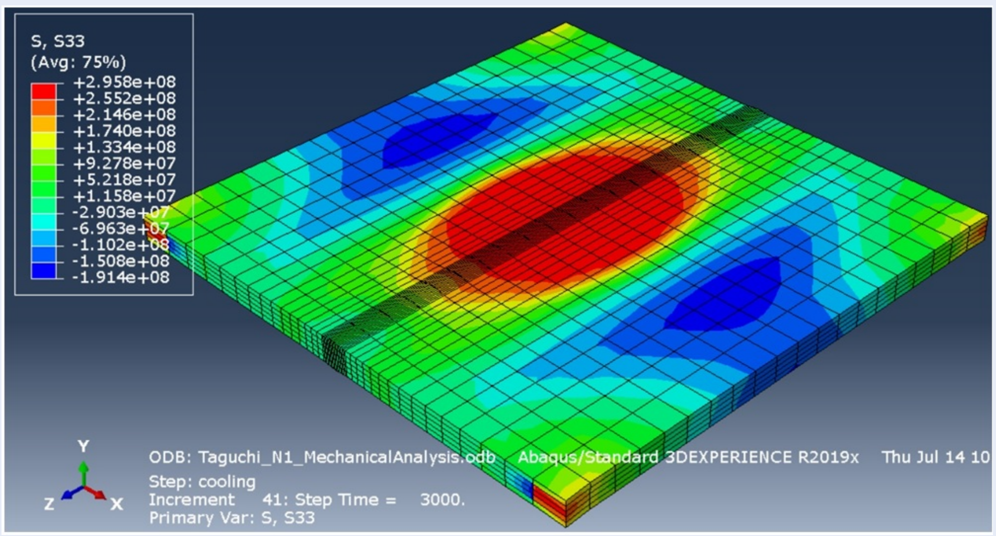

Figure 3: Axial stresses along the Z-axis in simulation

shows that the minimum values of *S33* can be reached by maximizing the signal-to-noise value using a voltage of 32 volts, current of 180 amperes and speed of 0.005 meters per second. In case of response surface methodology, both Box-Behnken design and central composite design give the optimal values with similar input parameters with Taguchi design. It means that the minimum value of axial stress can be achieved by using a voltage of 32 volts, current of 180 amperes and speed of 0.005 meters per second. A simulation with the above parameters has been done to verify and compare the results of these designs. The results can be seen in Table 8. It can conclude that the Taguchi design can give the optimal value with the smallest error and the smallest number of simulations. The Box-Behnken design gives the smaller error and smaller number of simulations compared with the central composite design.

Depth of penetration is one parameter that shows the quality of welding process[3]. A good welding process has maximum depth of penetration because it reduces the effect of the tensile residual stress in the weld-

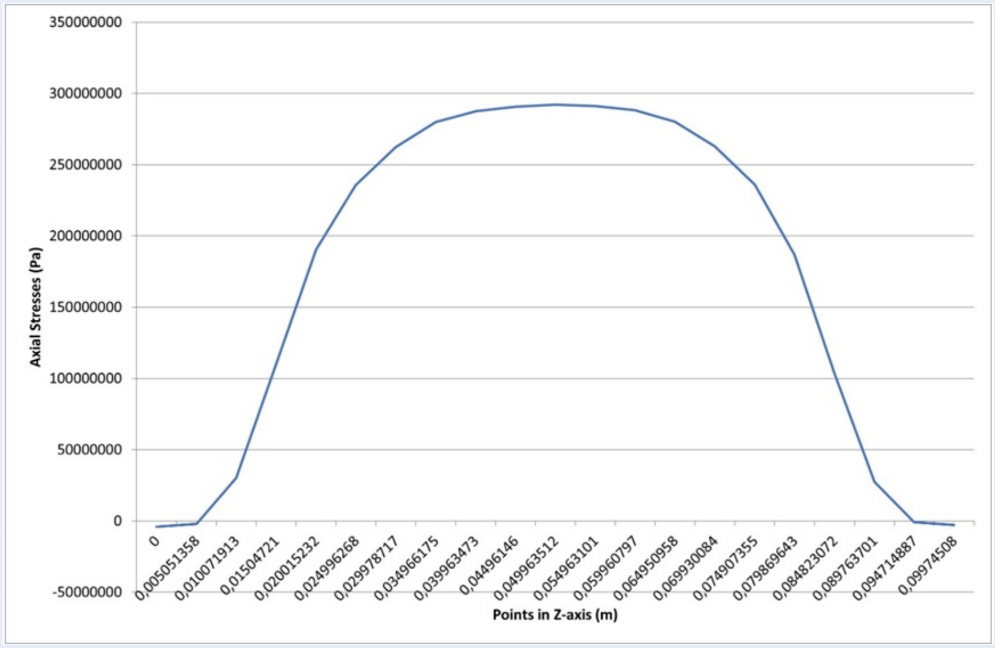

Figure 4: Axial stresses along the Z-axis

Table 5: Taguchi L9 matrix and results of response.

	Factors https://doi.org/10.32508/stdjet.v5i4.1041			Response
	Vol	Cur	Speed	Stresses S33 (10^8 Pa)
1	1	1	1	2.92187
2	1	2	2	2.92692
3	1	3	3	2.92893
4	2	1	2	2.94305
5	2	2	3	2.94898
6	2	3	1	2.83282
7	3	1	3	2.96605
8	3	2	1	2.84845
9	3	3	2	2.85182

ing joint. Increasing the welding current and welding voltage will increase the depth of penetration. Otherwise reducing the speed welding will increase this parameter.

In this research, the optimal value of the tensile residual stress can be obtained by maximizing the value of welding voltage, maximizing the value of welding current, and minimizing the value of welding speed. It can be concluded that the thickness of the metal will affect the range of the value of welding current, welding voltage, and welding speed. However, the optimal results still can be determined by maximizing the value of welding voltage, maximizing the value of welding current, and minimizing the value of welding speed.

Look for the most affected factor

The analysis of variance is a computational technique to quantitatively estimate the contribution that each parameter makes on the overall observed response. Table 9 shows the contribution of each factor of each

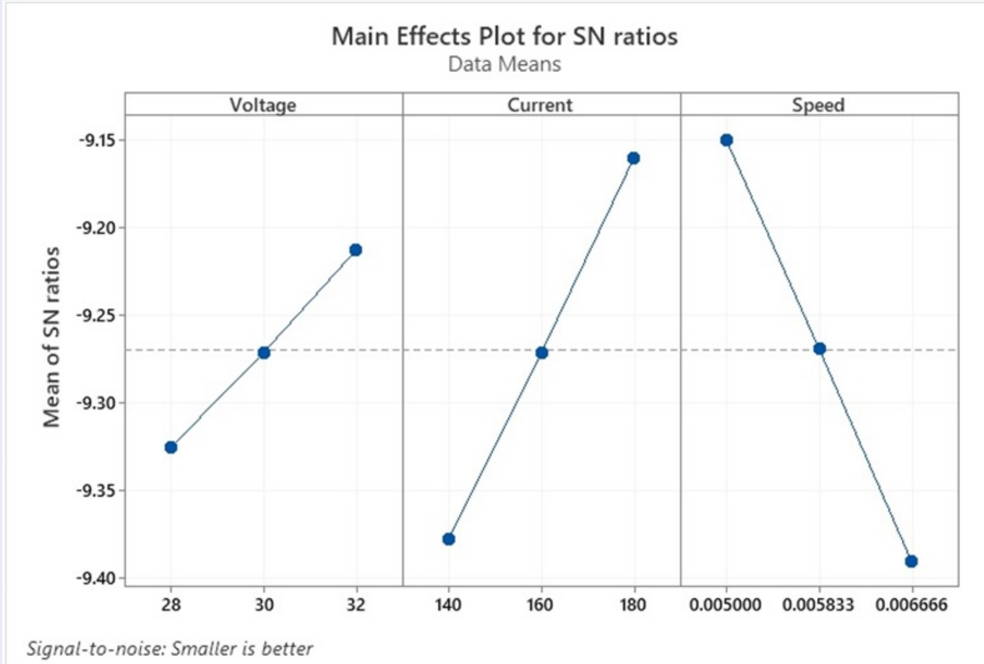

Figure 5: Main effects plot of design parameters over axial stress

Table 6: Box-Behnken design matrix and results of response.

	Factors			Response
	Vol	Cur	Speed	Stresses S33 (10^8 Pa)
1	-1	-1	0	2.97111
2	1	-1	0	2.92692
3	-1	1	0	2.89028
4	1	1	0	2.85182
5	-1	0	-1	2.88725
6	1	0	-1	2.84845
7	-1	0	1	2.96605
8	1	0	1	2.93325
9	0	-1	-1	2.91255
10	0	1	-1	2.83282
11	0	-1	1	2.96883
12	0	1	1	2.90926
13	0	0	0	2.91303

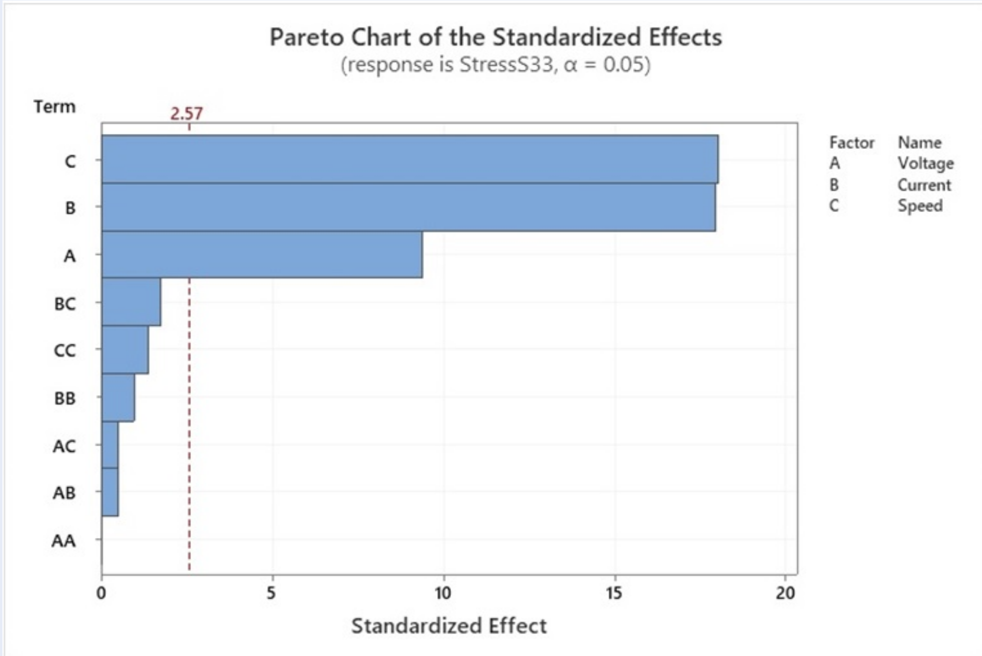

Figure 6: Pareto Chart of the Standardized Effects

Table 7: Central Composite design matrix and results of response.

	Factors (α = 1.68)			Response
	Vol	Cur	Speed	Stresses S33 (10^8 Pa)
1	-1	-1	-1	2.90952
2	1	-1	-1	2.90246
3	-1	1	-1	2.86841
4	1	1	-1	2.85144
5	-1	-1	1	2.96937
6	1	-1	1	2.93941
7	-1	1	1	2.91837
8	1	1	1	2.90531
9	-α	0	0	2.92692
10	α	0	0	2.89745
11	0	-α	0	2.94305
12	0	α	0	2.86749
13	0	0	-α	2.87168
14	0	0	α	2.95253
15	0	0	0	2.91303

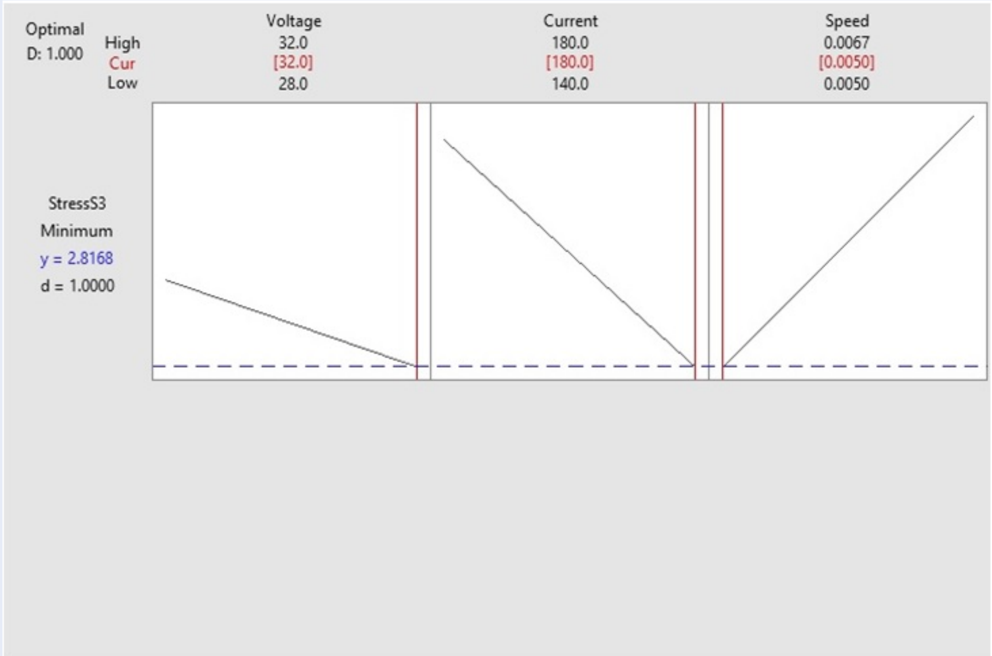

Figure 7: The optimal plot of central composite design

Table 8: The optimal value of the axial stress according to DOE methods.

Methods	Number of Simulation	Optimal value (10^8 Pa)	Error (%)
Simulation Results		2.80688	
Taguchi L9 Design	9	2.81272	0.2080
Box-Behnken Design	13	2.81595	0.3231
Central Composite Design	15	2.81679	0.3530

Table 9: Analysis of contribution of each factor to the response.

Factors		Voltage	Current	Speed
Taguchi Design	F-Val.	1251.89	4767.76	5850.33
	Contri. (%)	10.5467	40.1665	49.2868
Box-Behnken Design	F-Val.	86.11	315.45	317.79
	Contri. (%)	11.9705	43.8521	44.1774
Central Composite Design	F-Val.	53.00	360.95	441.63
	Contri. (%)	6.1946	42.1878	51.6176

design to the total response using F-value. The contribution of speed welding is largest. The effect of the welding voltage is smallest among the three factors.

Check the accuracy of proposed models

To verify the accuracy of the established model, five randomly picked validation simulations were carried out within the range of simulation parameters. Tables 10, 11, and 12 respectively present the experiments order, the actual values, the predicted values, and their deviations (percentage errors) for Taguchi regression model, Box-Behnken model, and central composite model. The Taguchi method gives the error of 0.1807%, the Box-Behnken design shows the error of 0.2287%, and the error of the central composite design is 0.2000%. The average errors of these above designs are so small that the linear model and the optimal values can be accepted.

CONCLUSION

In this paper, the research of determining the optimal parameters for welding two metal plates has been mentioned. The goal of the research is choosing the optimal parameters so that the value of the residual stresses is minimum. Two design of experiment methods used in this paper are Taguchi method and response surface methodology. In the case of response surface methodology, two chosen designs are Box-Behnken design and central composite design. It can conclude that the model according to Taguchi design gives the smallest value and the smallest number of experiments comparing two other designs. This model also gives the smallest value of error of estimated residual stresses. However, Box-Behnken design and central composite designs also could be used in several complex models that have a degree of freedom larger than one.

In the future, several experiments will be considered to verify the results of simulation. By comparing between experiments results and simulation results, the more exact conclusion can be made.

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LIST OF ACRONYMS

GMAW: Gas Metal Arc Welding
DOE: Design of Experiments
RSM: Response Surface Methodology
CCD: Central Composite Design

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

AUTHOR CONTRIBUTION

Tri Cong Phung has written and edited the manuscript. Huynh Nhat Do has made the simulations under the instruction of Tri Cong Phung.

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Table 10: Simulation validation for Taguchi design.

	Factor levels			Values	Response
	Vol (V)	Cur (A)	Speed (mm/s)		S33 (10^8 Pa)
1	29	150	5.416	Act. Pre. Error	2.9109 2.9149 0.1382 (%)
2	29	170	6.249	Act. Pre. Error	2.92867 2.9188 0.3364 (%)
3	31	150	6.249	Act. Pre. Error	2.93993 2.9365 0.1169 (%)
4	31	170	5.416	Act. Pre. Error	2.85729 2.8601 0.0989 (%)
5	29.5	175	6	Act. Pre. Error	2.88697 2.8931 0.2130 (%)
				Ave. Error	0.1807 (%)

Table 11: Simulation validation for Box-Behnken design.

	Factor levels			Values	Response
	Vol (V)	Cur (A)	Speed (mm/s)		S33 (10^8 Pa)
1	29	150	5.416	Act. Pre. Error	2.9109 2.9188 0.2728 (%)
2	29	170	6.249	Act. Pre. Error	2.92867 2.9190 0.3308 (%)
3	31	150	6.249	Act. Pre. Error	2.93993 2.9366 0.1132 (%)
4	31	170	5.416	Act. Pre. Error	2.85729 2.8627 0.1879 (%)
5	29.5	175	6	Act. Pre. Error	2.88697 2.8939 0.2388 (%)
				Ave. Error	0.2287 (%)

Table 12: Simulation validation for central composite design.

	Factor levels			Values	Response
	Vol (V)	Cur (A)	Speed (mm/s)		S33 (10^8 Pa)
1	29	150	5.416	Act.	2.9109
				Pre.	2.9152
				Error	0.1470 (%)
2	29	170	6.249	Act.	2.92867
				Pre.	2.9192
				Error	0.3251 (%)
3	31	150	6.249	Act.	2.93993
				Pre.	2.9423
				Error	0.0796 (%)
4	31	170	5.416	Act.	2.85729
				Pre.	2.8633
				Error	0.2117 (%)
5	29.5	175	6	Act.	2.88697
				Pre.	2.8938
				Error	0.2366 (%)
				Ave. Error	0.2000 (%)

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Bài nghiên cứu

So sánh giữa phương pháp Taguchi và phương pháp Response Surface trong việc xác định các thông số tối ưu của quá trình hàn 2 tấm kim loại

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TÓM TẮT

Công nghệ hàn đóng vai trò quan trọng trong sản xuất và hàn hồ quang bằng điện cực nóng chảy trong môi trường khí bảo vệ (GMAW) là 1 trong các phương pháp được sử dụng nhiều nhất. Có nhiều thông số đầu vào ảnh hưởng đến chất lượng của mối hàn như điện áp hàn, dòng điện hàn, tốc độ hàn, ... Một vấn đề quan trọng khi điều khiển robot hàn là phải xác định các thông số hàn tối ưu để nâng cao chất lượng mối hàn. Có nhiều phương pháp thiết kế thực nghiệm có thể được sử dụng với số thí nghiệm nhỏ. Trong bài báo này phương pháp Taguchi và phương pháp response surface được sử dụng để đánh giá ứng suất dư của vật liệu khi hàn 2 tấm kim loại lại với nhau. Đối với phương pháp response surface, cả phương pháp thiết kế Box-Behnken và thiết kế trung tâm được sử dụng trong việc xác định các thông số tối ưu. Việc đánh giá ứng suất dư được thực hiện bằng phần mềm ABAQUS. So sánh giữa các phương pháp thiết kế thực nghiệm được thực hiện và nhiều kết luận về thông số tối ưu và mô hình toán của quá trình hàn được trình bày.Trong nghiên cứu này, giá trị tối ưu của ứng suất dư kéo có thể đạt được bằng cách tăng giá trị điện áp hàn cực đại, giá trị dòng điện hàn cực đại và giá trị tốc độ hàn cực tiểu. Từ kết quả mô phỏng, có thể kết luận rằng thiết kế Taguchi có thể cho giá trị tối ưu với sai số nhỏ nhất và số lần mô phỏng nhỏ nhất. Thiết kế Box-Behnken cho sai số nhỏ hơn và số lượng mô phỏng nhỏ hơn so với thiết kế tổng hợp trung tâm. Phân tích phương sai là một kỹ thuật tính toán để ước tính một cách định lượng mức độ đóng góp mà mỗi tham số đầu vào tạo ra đối với giá trị ngõ ra được quan sát. Từ kết quả mô phỏng, đóng góp của tốc độ hàn là lớn nhất. Ảnh hưởng của điện áp hàn là nhỏ nhất trong ba yếu tố.

Từ khoá: Phương pháp Taguchi, phương pháp response surface, thông số tối ưu, robot công nghiệp, hàn hồ quang trong môi trường khí bảo vệ

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