Green manufacturing initiative through the optimization of parameters in resistance spot welding using response surface methodology

Pretty Princess Pontororing[1], Stanley Gilbert[1], Iwan Tutuka Pambudi[2], Ajat Suryanto[2], Aditya Andika[1*]

[1] Industrial Engineering Department, Faculty of Engineering, Bina Nusantara University, Jakarta, Indonesia 11480
[2] PT. Astra Daihatsu Motor, Jakarta, Indonesia 14330

*Corresponding Author: aditya.a@binus.ac.id

Abstract. Welding quality of a product is very important. Resistance Spot Welding (RSW) is a process widely used in the industrial, mostly in the automotive industry. RSW is used to joint two or more materials in order to form the structure of the car. Resistance spot welding requires parameters that play as an important role in the welding process. There are three important parameters in the welding process, namely welding current (kA), welding time (cycle), and electrode force (kN). All three parameters should be optimized in order to produce high quality spot weld joints and less welding defects. In relation to Green Manufacturing, less defects means less waste and less consumption of materials. In the present study, we utilized RSM (Response Surface Method) to optimize the parameters by using statistical and mathematical techniques to analyze the problem. Optimal result parameters on welding current 8.7 kA, welding time 19,25 cycle, and electrode force 1,6 kN with diameter nugget 6,969 mm.

1. Introduction

Nowadays, Resistance spot welding (RSW) is one of the joining processes that widely used in the industry, such as cars, nuclear power, civil infrastructure, transportation, etc.[1]. RSW is mostly implemented in the automotive industry due to its excellence techno-economic benefits such as low operating costs, high production levels due to the strength, speed, flexibility of RSW, and the adaptability for automation [2] [3]. In the automotive industry, RSW is used to combine two or more materials of the car's structure commonly known as Body in White (BIW) and a car in general has 4000-6000 welding points [2]. One way to produce a high-quality spot weld joints is by observing various factors that involved in the process such as voltage, welding current, welding time, electrode force, surface condition, electrode type, etc. [4] [5]

A common problem encountered in the manufacturing world is the determination of input parameters in order to obtain good weld joints [6], which is crucial in order to obtain an effective and efficient process. There are 3 parameters that should be adjusted that affect the quality of a welding, which are current, time, and electrode force. In practice, 20% - 30% spot welding contains uncertainty in the quality of weld joints, therefore an optimization process is necessary [6]. In the present study, we utilized Response Surface Methodology which is a statistical and mathematical method to optimize the spot welding process [7].

2. Literature Review

2.1. Green Manufacturing
Green manufacturing is a manufacturing way of thinking that focuses on becoming eco-efficient and uses green methods in order to develop products and systems that consume fewer materials, uses eco friendly materials, reducing waste, and recycling [8]. Green manufacturing considers ecological factors in manufacturing, saving energy, reducing the usage of natural resources, and expect minimal pollution and defects [9][10][11]. Green Manufacturing focuses on improving industrial processes, e.g., welding, because all industrial processes consume energy and materials and creates waste and pollution [12].

2.2. Response Surface Methodology
Response Surface Method (RSM) is a collection of statistical and mathematical techniques useful for developing, improving, and optimizing a process [13]. Response surface methodology has two designs, namely Central Composite Design (CCD) and Box-Behnken Design [14]. The experimental is using Box-Behknen Design, because this experimental uses only three levels and three independent variables which only have 15 runs orders [14].

2.3. Resistance Spot Welding

One of the most common electric welding methods in joining metal in the automotive industry is Resistance Spot Welding (RSW) [15][16]. RSW has been used as a joining technique for decades in the automotive industry [17]. The automotive industry prefers to use RSW because it has techno economic benefits, such as low operation cost, fast process, and the possibility for automation [19]. RSW is also excellent for reproducibility [19].

3. Methodology

3.1. Materials
In this research, we used 2 SCGA270D materials with different thickness; 1.2 mm and 2.0 mm, with different sizes that follow JIS G 3136 standard. Both materials were attached (as in figure 1) in order to support the welding process. The chemical composition material of SCGA270D can be seen in table 1.

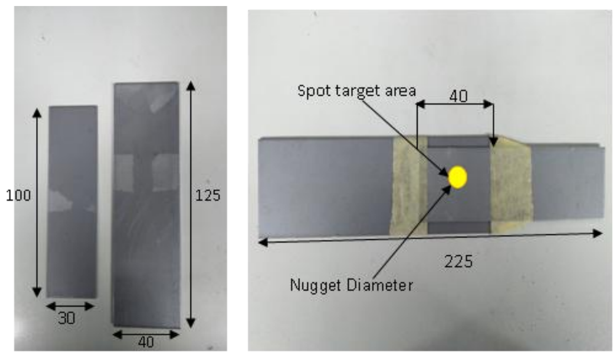

Figure 1. SCGA270D Material

Table 1. Chemical Composition and Mechanical Properties SCGA270D Material

Material	Element				Yield Strength (MPA)	Tensile Strength (MPA)
	C	Mn	P	S		
SCGA270D	0.01%	0.14%	0.018%	0.005%	158	304

3.2. Materials

In this experiment the tool that was used is KDC30-1065N. The table shown below informs the values selected for each parameter. Experimental results for the spot welding process using Box-Behnken Design can be seen in table 3.

Table 2. Parameter Design and Experimental Level

Parameter	Level-1	Level-2	Level-3
Welding Current (kA)	6.7	7.7	8.7
Welding Time (cycle)	18	19	20
Electrode Force (kN)	1.6	1.9	2.2

Table 3. Box-Behnken Design and Experimental Results

Runs Order	Welding Current (kA)	Welding Time (cycle)	Electrode Force (kN)	Nugget Diameter (mm)
1	0	0	0	6,18
2	-1	0	1	5,96
3	1	0	-1	6,68
4	-1	1	0	4,76
5	0	1	1	5,93
6	0	-1	1	5,18
7	0	1	-1	5,92
8	-1	0	-1	5,85
9	1	1	0	6,76
10	0	-1	-1	5,97
11	1	0	1	6,51
12	-1	-1	0	5,16
13	1	-1	0	5,83
14	0	0	0	6,11
15	0	0	0	6,28

3.3. Software
This research uses Design-Expert® Software Version 11 for Response Surface Methodology. Design-Expert® Software is commonly used in Response Surface Methodology especially when using Box-Behnken Design. Several examples of other researches that use Design-Expert® Software for Box-Behnken Design are [20], [21], [22], and [23].

4. Results and Discussions

4.1. Mathematical Model Analysis of Nugget Diameter
Mathematical model has two steps, namely first-order model and second-order model (Vining & Kowalski, 2010). First-order model is the first step forprocessing data by using response surface methodology. The following is the result of mathematical model obtained using Design Expert Software Version 11:

$$\text{Nugget Diameter} = -0{,}2157 + (0{,}5063 \text{ x current}) + (0{,}1537 \text{ x welding time}) - (-0{,}3500 \text{ x electrode force}). \quad (1)$$

Second-order model is the second step for processing data by using response surface methodology. This second step is used, if a result in the first step is found that model does not allow to be used. The following is the results of the mathematical model obtained using Design Expert Software Version 11:

$$\text{Nugget Diameter} = -120{,}64055 - (4{,}88667 \text{ x current}) + (16{,}51433 \text{ x weldingtime}) - (15{,}07278 \text{ x electrodeforce}) + (0{,}332500 \text{ x current x weldingtime}) - (0{,}233333 \text{ x current x electrode force}) + (0{,}666667 \text{ x welding time x electrode force}) - (0{,}031250 \text{ x Current}^2) - (0{,}531250 \text{ x welding time}^2) + (1{,}01389 \text{ x electrode force}^2) \quad (2)$$

4.2. Analysis of Variance (ANOVA)
In the Response Surface Methodology, ANOVA is used to see the results of first-order models and second-order models can be used or not to predict response results. The first-order model (seen in table 4) cannot be used, because the lack of fit in the model is statistically significant which means the model is not suitable.

Table 4. ANOVA First-order Model

Source	Sum of Squares	DF	Mean Square	F-value	p-value
Model	2,33	3	0,7759	4,23	0,032
A-Current	2,05	1	2,05	11,17	0,007
B-Welding Time	0,1891	1	0,1891	1,03	0,332
C-Electrode Force	0,0882	1	0,0882	0,4804	0,503
Residual	2,02	11	0,1836		
Lack of Fit	2,01	9	0,2228	30,52	0,032
Pure Error	0,0146	2	0,0073		
Cor Total	4,35	14			
Std. Dev		0,4285	R^2		0,5354
Mean		5,94	Adj. R^2		0,4087
C.V.%		7,22	Pred R^2		0,0517
			Adeq Precision		5,9654

The ANOVA table for the second-order model (seen in table 5) can be used, because the model is statistically significant (p-value ≤ 0.05) which means the independent variables is affect the response (diameter nugget). The lack of fit has p-value = 0,0743 greater than the degree of significance α = 0.05 which indicate the model is insignificant (the model is suitable). The result of R2= 0.9331 indicating that 93.31% the second-order model can be used to predict the response and parameters on spot welding process.

Table 5. ANOVA Second-order Model

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	4,06	9	0,4507	7,74	0,0182
A-Current	2,05	1	2,05	35,23	0,0019
B-Welding Time	0,1891	1	0,1891	3,25	0,1313
C-Electrode Force	0,0882	1	0,0882	1,52	0,2731
AxB	0,4422	1	0,4422	7,60	0,04
AxC	0,0196	1	0,0196	0,3367	0,5869
BxC	0,1600	1	0,16	2,75	0,1582
A^2	0,0036	1	0,0036	0,0619	0,8133
B^2	1,04	1	1,04	17,9	0,0082
C^2	0,0307	1	0,0307	0,5282	0,4999
Residual	0,2910	5	0,0582		
Lack of Fit	0,2764	3	0,0921	12,62	0,0743
Pure Error	0,0146	2	0,0073		
Cor Total	4,35	14			
Std. Dev		0,2413	R^2		**0,9331**
Mean		5,94	Adj. R^2		0,8126
C.V.%		4,06	Pred R^2		-0,0249
			Adeq Precision		10,0959

4.3. Graph Analysis

The graph shows the effect of the welding current and welding time parameters on the nugget diameter. If welding current and welding time is high, the result of nugget diameter is high. If welding current is low and welding time is high, the nugget diameter result is low. If current welding is high and welding time is low, the result of nugget diameter is high.

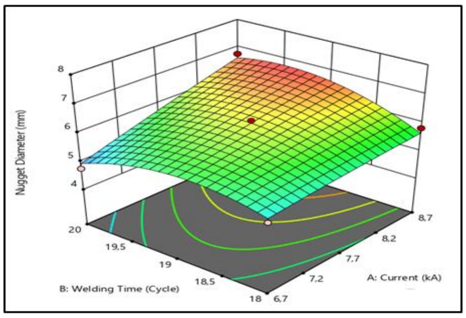

Figure 2. Surface Plot Welding Current – Welding Time

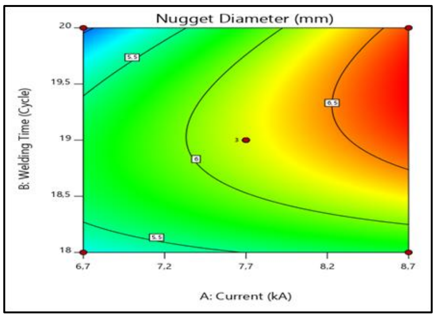

Figure 3. Contour Plot Welding Current – Welding Time

The graph shows the effect of the welding current and electrode force parameters on the nugget diameter. If welding current and electrode force is high, the result of nugget diameter is high. If welding current is low and electrode force is high, the nugget diameter is low. If current welding is high and electrode force is low, the result of nugget diameter is high.

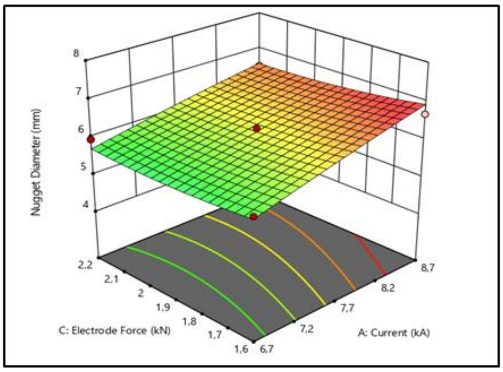

Figure 4. Surface Plot Welding Current – Electrode Force

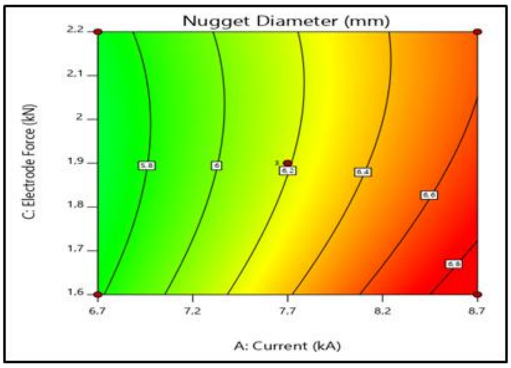

Figure 5. Contour Plot Welding Current – Electrode Force

The graph shows the effects of welding time and electrode force parameters on nugget diameter. If welding time and electrode force is high, the nugget diameter is high. If welding time and electrode force is low, the nugget diameter is low.

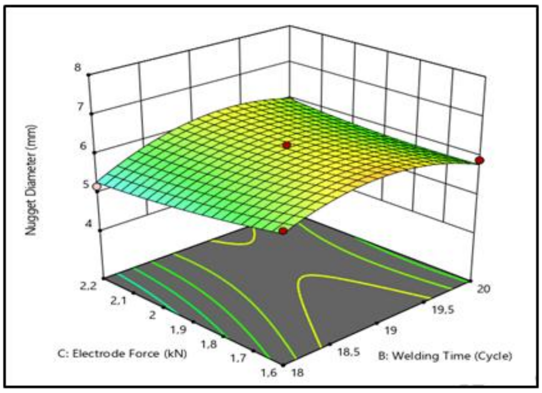

Figure 6. Surface Plot Welding Time – Electrode Force

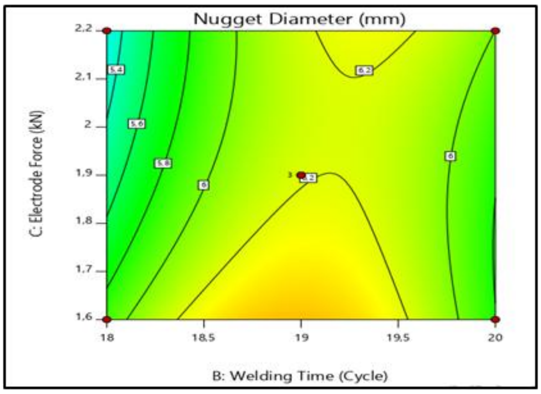

Figure 7. Contour Plot Welding Time – Electrode Force

4.4. Optimal Results Parameter

Table 6 shows the optimal result for resistance spot welding parameters with the desirability 0.835 which means 83.5% the desired optimal results in welding current 8.7 kA, welding cycle time 19.25, and electrode force of 1.6 kN with diameter nugget 6,969 mm.

Table 6. Parameter Optimization Results

Welding Current (kA)	Welding Time (Cycle)	Electrode Force (kN)	Nugget Diameter (mm)	Desirability
8,7	19,25	1,6	6,969	0,835

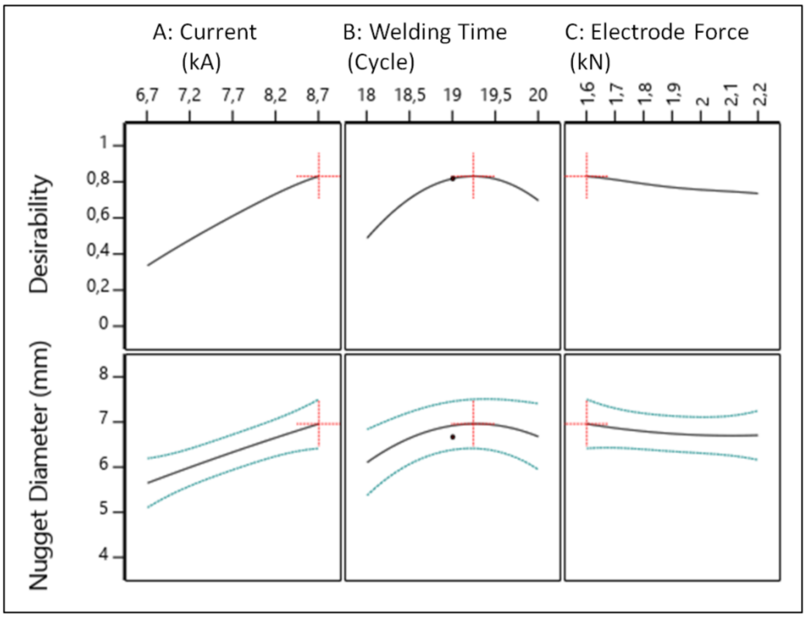

Figure 8. Parameter Optimization Results

5. Conclusion and Suggestions

The optimization of parameters in Resistance Spot Welding is crucial for creating high quality spot weld joints. The Response Surface Methodology is used to optimize the parameters. Based on Analysis of Variance (ANOVA), the mathematical model used is second-order, because the result statistically significant for the model, insignificant for lack of fit, and R2= 93,31% that means the mathematical model can be used. Based on 3D graphic and contour plot, parameters that have an effect on nugget diameter is welding current.The result in ANOVA for welding current is significant (p-value $\leq$ 0,05) which means welding current has an effect on diameter nugget. The mathematical models obtained on second-order models can be seen in formula (2). The optimum result for parameters is welding current 8,7 kA, welding time 19,25 cycle, and electrode force 1,6 kN with diameter nugget 6,969 mm. With this optimized parameters, it is expected that the welding process will be able to produce high quality spot weld joints and to reduce defects. The reduction of defects translates to less waste in material usage and adheres to Green Manufacturing principles.

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