OPTIMIZATION OF STAINLESS STEEL 304 AND 316 WELDED JOINTS ON CORROSION RATE BY THE TAGUCHI METHOD

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(Received: 10 December 2024; Accepted: 16 January 2024; Published on-line: 1 March 2025)

***ABSTRACT*:** The Water Treatment Plant (WTP) is a water purification system designed to meet the water demands for power generation and operational requirements in the petrochemical industry. The current pipeline network in the Demin Plant unit employs carbon materials with rubber cladding, which presents drawbacks, such as extended recovery times during system failures. To address the issue, the research explored welding SS 304 and SS 316 materials as an alternative to the existing carbon pipes with rubber cladding. The study utilized the Taguchi experimental design method, employing an orthogonal array (L9) table to optimize quality improvement while minimizing costs. The experiment included 9 test specimens with three repetitions, examining four welding parameters, each with three levels. Variance (ANOVA) was analyzed using the Minitab software and manual calculations in Microsoft Excel. The results indicated that the factors influencing the corrosion rate of the specimens include the welding method, electrode type, welding speed, and welding current. ANOVA results showed that the welding method (F-value = 5.9176) and welding current (F-value = 8.3492) significantly affected the corrosion rate, whereas the electrode type (F-value = -3.5949) and welding speed (F-value = -2.8321) did not. A confirmation experiment yielded an optimal corrosion rate of 3.0231 mm/y, lower than experiment number 7.

KEY WORDS: Stainless Steel 304; Stainless Steel 316; Taguchi Methods; Corrosion Rate.

1. INTRODUCTION

A water Treatment Plant is a place for the water treatment process to get the water produced. It qualifies according to the criteria used to provide water needs for power generation and processing. A water treatment plant (WTP) is an installation system that treats raw water (inlet) into clean water so humans can accept it for specific uses. The process at the Water Treatment Plant controlling the pH level is a relatively important aspect of the coagulation process [1].

Kosim, M. E., dkk (2021) in this research suggests that demineralization is one of the water treatment process technologies to remove minerals from water, whereby demineralization uses cation and anion exchange resins in two tubes or one tube simultaneously [2].

Welding procedures have been applied to almost every industry since it was first invented in 1800. Welding is a manufacturing process in which two or more metal parts are joined through the engineering of heat, pressure, and both to form a joint [3]. Welding processes have been applied to many industries and constructions, such as railroads, bridges, shipping, steel structures, and automotive and maritime industries. Based on the joining process, welding can be grouped into shielded metal arc welding (SMAW), submerged arc welding (SAW), gas metal arc welding (GMAW), gas tungsten arc welding (GTAW), and others. Welding based on welded materials can be divided into similar and dissimilar welding [4]. (Hafeez et al. 2002) Their research revealed that three welding parameters are involved in obtaining optimum conditions, including welding current [5].

Stainless steels are a class of Fe-based alloys noted for their high corrosion and oxidation resistance, typically containing 12 to 27% Cr and 1 to 2% Mn by weight, with Ni added in some grades. Its corrosion-resistant properties are obtained from the oxide layer (mainly Chrome) on the surface and protect the steel against corrosive environments with a Chrome content above 11% [6]. The welding method determines the basic process and mechanism of joining metals. Each method has advantages and disadvantages that affect joint quality, efficiency, and the types of materials that can be welded. Electrodes are selected based on chemical compatibility with the base material to ensure good fusion, reduce defects, and improve corrosion resistance. Welding speed parameters affect heat distribution and weld bead size. Too high a speed can cause shallow penetration, while low speeds can cause overheating and distortion. In contrast, the welding current determines the intensity of the heat generated, which affects the penetration depth and fusion quality.

According to Arifin (2024) [7], the geometry of the weld pool plays an important role in determining the thermal conditions in and around the weld pool. It affects the flow of fluid formed—the welding volume—as well as heat input and welding speed.

Staicontrol the volume of the weld pool nless steel can be classified according to its classification as below:

- Ferritic Stainless Steels:

Standard ferritic grades are alloyed with Cr (11.2-19%) Type 430 but with no or little nickel addition. Ferritic stainless steels have metallurgical characteristics similar to Fe-Cr alloys containing sufficient amounts of Cr (more than 12%) to remain outside the γ-loop. These Ferritic Stainless steel are mainly composed of BCC phases.

- Martensitic and precipitation-hardening stainless steel.

Martensitic grades are the smallest group of stainless steel. These stainless steels can be said to behave like Fe-Cr alloys containing less than 12% Cr (within the γ loop). These alloys harden as δ-ferrite and transform to austenite during cooling. When the cooling rate is fast enough, as in the case of welding, the formed austenite transforms into martensite.

- Austenitic Stainless Steel.

Cahya dan Abdulah (2019) suggests that austenitic stainless steel is a widely used stainless steel group. It contains an 18-8 component (CrNi) with a heat resistance of more than 760ºC. However, its oxidizing properties are limited by its high-temperature corrosion resistance and weldability, which are superior to other stainless steels [8]. Austenitic stainless steels contain at least 15% Cr and enough Ni to maintain a stable austenitic structure over a temperature range from 1100°C to room temperature without martensite formation. Also known as 18-8 stainless steel due to its composition of 18% Cr and 8% Ni [9].

- Duplex Stainless Steel.

Duplex grades have a ferritic-austenitic microstructure with a phase balance of approximately 50% ferrite and 50% austenite. Duplex grades combine many beneficial properties of ferritic and austenitic stainless steels. The chemical composition of commercial grade DSS duplex stainless steels contains 22–26% chromium, 4–7% nickel, 4.5% molybdenum, and some copper, tungsten, and nitrogen. DSS can be applied in the onshore and offshore sectors of the oil industry as a piping system (process piping, seawater piping, tube and pipe fittings, instrumentation, and hydraulic tubing), heat exchanger, and reaction vessel due to its corrosion-resistant properties and high strength [10].

Austenitic stainless steel is popular for its corrosion resistance. However, it is susceptible to stress corrosion cracking (SCC) type of corrosion. Lu et al. (2012) proved that the surface coating on AISI 304 (austenitic) stainless steel exhibits a massive LP effect, which induces deep residual stress and triggers stress corrosion cracking (SCC) [11], a process determined to obtain the maximum value of a specific function that works optimally. This process is called optimization [12].

Therefore, the problem in this research is related to corrosion rate analysis on the optimization of 304 and 316 stainless steel welding joints in the demin plant piping system in the petrochemical industry using the Taguchi method. In this case, the L9 orthogonal array table is used to design efficient experiments and analyze data when conducting experiments. It determines the minimum number of experiments that can provide as much information as possible on all level factors that influence parameters in a welding process.

The most important part of the orthogonal array lies in selecting the combination of control factors and level factors as input variables in experiments. The author limits himself to conducting experiments with 3-factor levels in the four control factors as the main parameters for welding SS 304 and 316. Therefore, this research has 9 test specimens with three repetitions. It aims to determine the best quality by finding the optimum parameters. The best value for analyzing research data using Analysis of Variance (ANOVA) with manual calculations from Excel and Minitab applications will be obtained at this point.

2. RESEARCH METHODS

This research belongs to the type of research conducted by conducting experiments. The research follows complete steps, starting before the experiment is carried out and ending with analyzing the results of the experiments so that the data obtained in this study can support objective analysis. In this case, the independent variable is used as an experimental variable and is the result of the experiment.

In order to obtain robust designs in the welding process, the Taguchi method is used as it has a more structured and efficient approach to obtain robust designs compared to the complete classical factorial design method [13]. The Taguchi method is a robust methodology that has been shown to improve the performance of manufacturing processes [14]. The Taguchi method is an option for determining process parameters and interactions between process parameters and multi-output responses. The Taguchi method is very efficient. A structured and reliable method for design, performance, quality, and cost optimization [15][16].

2.1. Data Collection

Data source is a process of collecting data needed in research. This study used both primary and secondary data. As supporting data, several primary data, including parameters in a welding process, experimental corrosion tests, and hardness and microstructure tests, are provided. Secondary data in this study are data and theories related to the results of previous Taguchi method research.

2.2. Test Specimens

The materials used in this study were Stainless Steel 304 and Stainless Steel 316 in the form of pipes cut with dimensions of 30 mm x 30 mm x 6 mm, as many as nine specimens according to the Orthogonal Array L9 experimental table using the Taguchi optimization method for welding.

Fig. 1. Making a V-shape on the Specimen.

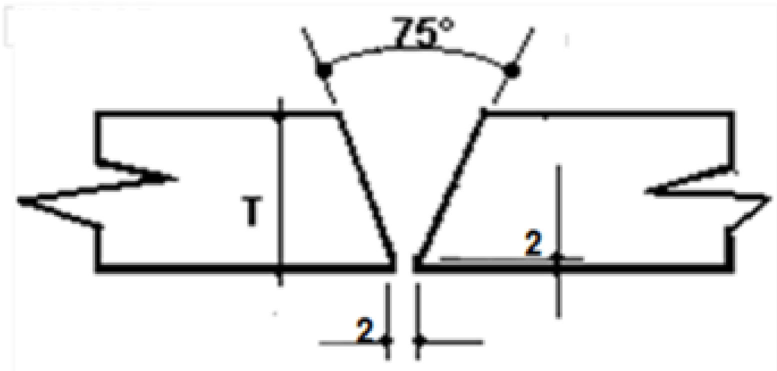

Fig. 2. Chamfer of 37.5° in making a V-shape.

In the welding process, the pipe is chamfered on the side at an angle of 37.5° to form a V-shoulder.

Fig. 3. Shape of Test Specimen after the welding process.

In general, the test specimens are welded using the Orthogonal Array L_9 matrix (3^4) table as a reference, in which there are four main factors and 3-factor levels. In this case, four factors are determined, which are the main welding parameters that are considered to have an important influence in the process of making test specimens: welding methods, electrodes, welding speed, and welding current. Then, the results were randomized using the Orthogonal Array table, and three repetitions were carried out in each experimental run process.

2.3. Experimental Design

The Taguchi method is based on an orthogonal array experiment, a matrix of rows and columns. Each column represents a specific factor or condition that can change from one experiment to another because each level of each factor is balanced and can be separated from the influence of other factors in the experiment. The determination of degrees of freedom is based on the main factor to be observed and the interaction observed, the number of levels of the factor to be observed, and the number of trials desired.

The research journal conveyed that quality engineering aims to design quality into each product and process accordingly. This quality improvement effort is known as the offline quality control method. This study designs the Orthogonal Array matrix in the Taguchi method based on the degrees of freedom, factors, and factor levels [17].

Table 1. Orthogonal Array L_9 (3^4)

No	Factor				Repetition		
	A	B	C	D	R1	R2	R3
1	1	1	1	1	X	X	X
2	1	2	2	2	X	X	X
3	1	3	3	3	X	X	X
4	2	1	2	3	X	X	X
5	2	2	3	1	X	X	X
6	2	3	1	2	X	X	X
7	3	1	3	2	X	X	X
8	3	2	1	3	X	X	X
9	3	3	2	1	X	X	X

Source: A primer on the Taguchi method. Society of Manufacturing Engineers [18].

This study uses an Orthogonal Array design L_9 matrix (3^4), as shown in Table 1 above. It selects factors expected to influence the response value and determines the level of the influential factor, as described in Table 2.

Table 2. Factor and Factor Level Assignment.

Factor	Level Factor		
	1	2	3
(A) Welding Method	SMAW	GTAW	KOMB
(B) Electrodes	308	316	316L
(C) Welding Speed	4	8	12
(D) Welding Current	70	90	110

3. RESULTS AND DISCUSSION

3.1. Metode Taguchi

The Taguchi method was widely introduced by a Japanese scientist, Dr. Genichi Taguchi. The Taguchi method aims to optimize the manufacturing process or system. It is carried out more efficiently and systematically to optimize the design for performance, quality, and cost. This method is widely applied in various engineering industries and others as one of the most important tools for designing high-quality systems or processes at lower costs [19].

The Taguchi method uses a statistical measure of performance called the signal-to-noise (S/N) ratio that considers both mean and variability. The method explores the concept of a quadratic quality loss function, where the S/N ratio is the ratio of the mean (signal) to the standard deviation (noise). The ratio depends on the quality characteristics of the product or process to be optimized. Some of the S/N ratio standards used are nominal-is-best (NB), lower-the-better (LB), and higher-the-better (HB).

Taguchi divides quality characteristics into three categories as follows:

1. Lowwer – is - Better

The smaller the nominal amount generated, the higher the product yield.

The S/N values for lower-is-Better are:

$$\frac{S}{N} = -10\, log \left(\frac{1}{n}\right) \sum_{i=1}^{n} \frac{1}{y^2} \quad (1)$$

2. Nomial – is – Better

The closer the nominal is to be produced, the more the product yield will increase.

The S/N values for Nominal-is-Better are:

$$\frac{S}{N} = 10\ \ log \frac{\bar{y}}{S^2} \quad (2)$$

3. Nominal – is – Better

The higher the nominal to be produced, the yield of a product will increase.

The S/N values for Higher-is-Better are:

$$\frac{S}{N} = -10\, log \left(\frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_{i=1^2}}\right) \quad (3)$$

3.2. Corrosion Tests

The quality characteristics in this study are lower and better with its response, namely the quality of welding resistance of SS 304 and SS 316 materials to the corrosion rate. Corrosion testing uses the weight loss method, and the corrosion rate in one year (mm / y) is calculated. The principle of this method is to calculate the amount of material that loses weight after being tested for immersion according to the ASTM G 31-72 standard. According to Fontana (1978) in his book "Corrosion Engineering," the corrosion rate can be defined in various ways, such as the percentage of mass loss, milligrams per square centimeter per day, and grams per square inch per hour. In addition, mils per year (mpy) is also used [20].

Corrosion testing was conducted in the Analyst Laboratory of the Chemistry Department at the Faculty of Mathematics and Natural Sciences, Chemistry, Unsri. Hardness and microstructure testing were conducted on validation specimens from the Taguchi method in the laboratory of the Mechanical Engineering Department, Unsri, for additional testing as supporting data.

Corrosion rate testing was carried out using a sulfuric acid solution; the test was carried out for 144 hours. The test stages are as follows:

1. Initial stages

Cleaning the test specimen that has been welded. The square test specimen is 60mm x 30mm x 6mm. The test specimen is dried using an oven heated to a temperature of 105 ° C; this is done to remove the water content still contained in the test specimen. Then, the initial weight (Wo) is weighed on the specimen. Weighing using a calibrated digital laboratory scale.

2. Determining Soak Test Volume

The minimum solution volume per specimen area is 0.20 mL/mm^2 (129 mL/in^2) and 0.40 mL/mm^2 (258 mL/in^2) of the specimen surface area. (ASTM G31-72. 2004:5) [21].

3. Checking the pH of sulfuric acid solution

Checking pH using pH indicator strips Mcolorp Hast TM with pH indicator.

4. Determining Specimen Soaking Time

According to the testing standard (ASTM G31-72. 2004:6), this method for estimating the test duration is only helpful in deciding, after the test has been performed, whether it is necessary to repeat the test over a more extended period. The most common test period is 48 to 168 hours (2 to 7 days). This study's soaking time was 144 hours (6 days) [22].

5. Start the Soaking process.

The soaking process is 144 hours (6 days). Initially, prepare a test container in the form of a petri dish with a volume of 60 mL with a concentration of sulfuric acid H_2SO_4 5% and H_2O 95%.

6. Final Stage

After removing the specimen from the test container, cleaning is carried out using clean water, rinsed with distilled water, and rubbed using a sponge to remove the rust attached to the test specimen. Furthermore, the test specimens are dried again using an oven so that the remaining water content is completely lost. The final weighing (W_1) was carried out.

Analysis of corrosion rate calculation. The corrosion rate equation uses the following formula:

$$Corrosion\ rate = \frac{K\ x\ W}{A\ x\ T\ x\ D} \quad (4)$$

Description:

Cr (Corrosion rate) = Corrosion rate in units of mpy (mils per year) (mm/y)

K = Constant

T = Exposure time in hours to the nearest 0.01 hours (hour)

A = Surface Area (cm^2)

W = Weight Loss (gram)

*D = Specimen Density (grams/cm³) (*Source: *Appendix X1 of Practice G1-Densities for a variety of metals and alloys)* [22].

Corrosion Rate Calculation Constant based on its unit ASTM G 31 – 72. (2004).

Table 3. Corrosion Immersion Test Result Specimen of SS 304 and SS 316 materials.

Specimen	**Corrosion Test Results Metode Weight Gain Loss**			
	R1 (gr)	**R2 (gr)**	**R3 (gr)**	**Mean**
1	0,5676	0,4412	0,4845	0,4978
2	0,1490	0,4013	0,7342	0,4282
3	0,4908	0,3635	0,2037	0,3527
4	0,1642	0,2361	0,2293	0,2099
5	0,4479	0,0456	0,5237	0,3391
6	0,4426	0,1973	0,0288	0,2229
7	0,0343	0,3615	0,0471	0,1476
8	0,4089	0,2568	0,0809	0,2489
9	0,4813	0,3778	0,4936	0,4509

Table 4. The Results of Corrosion Rate Calculation *(mm/y*).

Specimen	**Corrosion Rate Calculation Results**			
	R1 (*mm/y*)	**R2 (*mm/y*)**	**R3 (*mm/y*)**	**Average (*mm*/y)**
1	20,0924	16,4195	16,0675	17,5265
2	5,0729	17,3602	27,6481	16,6937
3	17,3828	10,9945	8,7806	12,3860
4	6,1507	8,5740	7,7723	7,4990
5	16,9809	1,6545	20,0893	12,9082
6	17,8827	8,0302	1,1321	9,0150
7	1,3615	13,4841	1,7836	5,5431
8	16,1349	9,2362	3,0547	9,4753
9	19,5653	15,4543	16,5663	17,1953

3.3. Data Processing

3.3.1. Mean Value Calculation and Signal-to-Noise Ratio

The following is the calculation of the mean and Signal-to-Noise Ratio (SNR) values from the Analysis of Variance (ANOVA) method:

1. Here is an example of calculating the mean value for the first specimen result:

$$\mu = \sum_{i=0}^{n} yi$$

$$\mu = \frac{1}{3}\,(20{,}0924 + 16{,}4195 + 16{,}0675)$$

$$\mu = 17{,}5265\,\frac{mm}{y}$$

2. An example of calculating the SNR value for the first experimental result is as follows:

$$\frac{S}{N} = -10\,log\left(\frac{1}{n}\right)\sum_{i=1}^{n}\frac{1}{y^2}$$

$$\frac{S}{N} = -10\left|\frac{1}{3}\left(\frac{1}{20{,}0924^2} + \frac{1}{16{,}4195^2} + \frac{1}{16{,}0675^2}\right)\right.$$

$$\frac{S}{N} = -24{,}920468\text{ dB}$$

Table 5. Mean and Signal-to-Noise-Ratio (SNR) Calculation Results.

Specimen	Factor Control				Mean	SNR
	A	B	C	D		
1	SMAW	308	4	70	17,5265	-24,9205
2	SMAW	316	8	90	16,6937	-25,6091
3	SMAW	316 L	12	110	12,3860	-22,2197
4	GTAW	308	8	110	7,4990	-17,5778
5	GTAW	316	12	70	12,9082	-23,6466
6	GTAW	316 L	4	90	9,0150	-21,0897
7	Combination	308	12	90	5,5431	-17,9439
8	Combination	316	4	110	9,4753	-20,7308
9	Combination	316 L	8	70	17,1953	-24,7522

3.3.2. Anova Calculation of Mean Value

The following are the steps for calculating the ANOVA average value:

1. Calculating the mean for all experiments:

$$\bar{y} = \frac{\sum y}{n}$$

$$\bar{y} = \frac{20{,}0924 + 16{,}4195 + 16{,}0675 + \cdots\cdots\cdots + 16{,}5663}{27}$$

$$\bar{y} = \frac{324{,}7258}{27}$$

$$\bar{y} = 12{,}02688$$

2. For example, calculate the average value (mean) for each factor level at factor A level 1.

$$\bar{\bar{y}}_{jk} = \frac{\sum \bar{\bar{y}}_{ijk}}{n_{ijk}}$$

$$\bar{\bar{y}}_{A1} = \frac{17{,}5265 + 16{,}6937 + 12{,}3860}{3}$$

$$\bar{\bar{y}}_{A1} = 15{,}5353$$

3. Create a response table and response graph,

Table 6. Response table of means values

Source	Factor			
	A	B	C	D
Level 1	15,5354	10,1895	12,0056	15,8767
Level 2	9,8074	13,0257	13,7960	10,4172
Level 3	10,7379	12,8654	10,2791	9,7867
Delta	5,7280	2,8362	3,5169	6,0899
Ranking	2	4	3	1

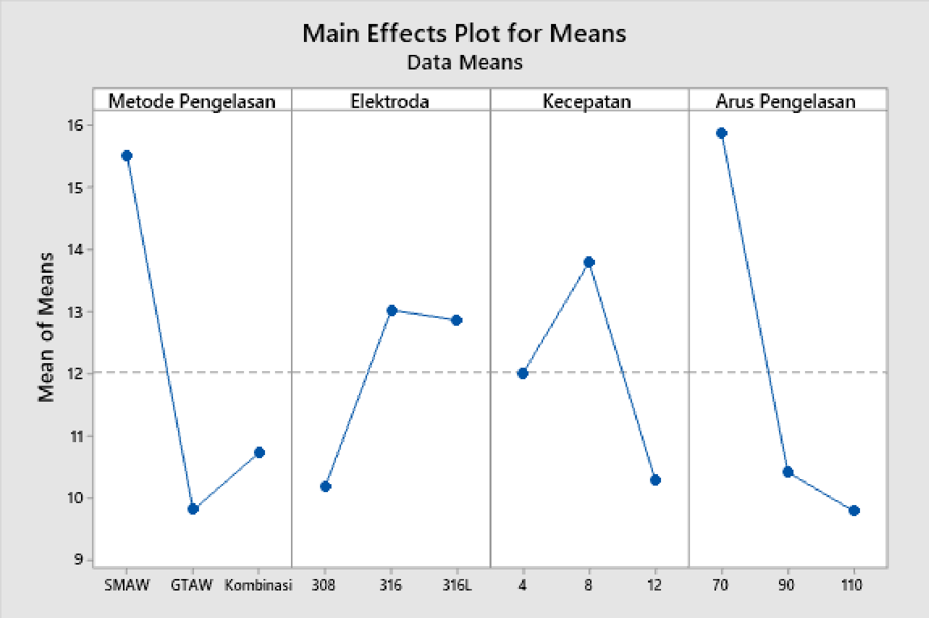

Fig. 4. A response graph shows a value mean of the factors and the most optimal factor level (Software Minitab).

4. Calculating the total sum of squares value,

$$SS_{total} = \sum y^2$$
$$SS_{total} = 20{,}0924^2 + 16{,}4195^2 + 16{,}0675^2 + \cdots + 16{,}5663^2$$
$$SS_{total} = 5213{,}0180$$

5. Calculating the value of the sum of squares due to mean,

$$Mean\ (S_m) = n\bar{y}^{\,2}$$
$$Mean\ (S_m) = 27 \times 12{,}0268^2$$
$$Mean\ (S_m) = 3905{,}4390$$

6. Calculating the value of the sum of squares due to factor, for example, for factor-A

$$SS_A = (n_{A1} \text{ x } \overline{A1^2}) + (n_{A2} \text{ x } \overline{A2^2}) + (n_{A3} \text{ x } \overline{A3^2}) - S_m$$
$$SS_A = (9 \text{ x } 15{,}5353^2 + (9 \text{ x } 9{,}8074^2) + (9 \text{ x } 10{,}7378^2) - 3905{,}4390$$
$$SS_A = 170{,}0746$$

7. Calculating the value of the sum of squares due to error,

$$SS_{error} = SS_{total} - SS_m - \sum Sj$$
$$SS_{error} = SS_{total} - SS_m - (SS_A + SS_B + SS_C + SS_D)$$
$$SS_{error} = 5213{,}0180 - 3905{,}4390 - (170{,}0746 + 45{,}6910 + 55{,}6654 + 201{,}8695)$$
$$SS_{error} = 834{,}2782$$

8. Calculating the value of degrees of freedom, for example, for factor A

$$DF_A = Jumlah\ level - 1$$
$$DF_A = \text{X} - 1$$

$DF_A = 3 - 1 = 2$

9. Find the value of the mean sum of squares, for example, for factor A,

$$MS_A = \frac{SS_A}{DF_A}$$
$$MS_A = \frac{170{,}0746}{2}$$
$$MS_A = 85{,}0373$$

10. Calculating the value of the F-ratio, for example, for factor A,

$$F_A = \frac{MS_A}{MS_{error}}$$
$$F_A = \frac{85{,}0373}{46{,}3487}$$
$$F_A = 1{,}8347$$

11. Calculating the value of the pure sum of squares, for example, for factor A,

$$SS'_A = SS_A - DF_A \times MS_{error}$$
$$SS'_A = 170{,}0746 - 2 \times 46{,}3487$$
$$SS'_A = 77{,}3770$$

12. Calculating the value of percent contribution, for example, for factor A,

$$\rho_A = \frac{SS_A}{SS_{total}} \text{ x } 100\ \%$$
$$\rho_A = \frac{77{,}3770}{5213{,}0180} \text{ x } 100\ \%$$
$$\rho_A = 5{,}9175\ \%$$

The results of all ANOVA calculations for the mean values are presented in Table 8.

Table 7. ANOVA mean before pooling.

Source	SS	DF	MS	F *Ratio*	SS’	% *Ratio*	F *Table*	P
A	170,07	2	85,04	1,83	77,38	5,92	3,55	Significant
B	45,69	2	22,85	0,49	-47,01	-3,59	3,55	*Insignificant*
C	55,67	2	27,83	0,60	-37,03	-2,83	3,55	*Insignificant*
D	201,87	2	100,93	2,18	109,17	8,35	3,55	Significant
Error	834,28	18	46,35	1,00	1205,07	92,16		
SSt	1307,58	26	50,29		1307,58	100		
Mean	3905,44	1						
SStot	5213,02	27						

From the ANOVA table above, it can be seen that factors A and D significantly influence the corrosion rate value, where the F-ratio is greater than the F-table (F0.05;2;18) = 3.55.

13. Pooling up,

At the Pooling-up stage, it is recommended to use half of the number of degrees of freedom in the orthogonal array used. It aims to avoid excessive estimation values and errors in the experiment. Pooling up is applied to less significant factors, namely factor B and factor C; the calculation of pooling up is as follows:

$$SS\ (period\ e) = SS_{error} + SS_B + SS_C$$
$$SS\ (period\ e) = 834{,}2782 + 45{,}6911 + 55{,}6654$$
$$SS\ (period\ e) = 935{,}6347$$

$$DF\ (period\ e) = DF_{error} + DFC + DFD$$
$$DF\ (period\ e) = 8 + 2 + 2$$
$$DF\ (period\ e) = 22$$

$$\text{MS (period e)} = \frac{SS\ (periode\ e)}{DF\ (periode\ e)}$$
$$MS\ (period\ e) = \frac{935{,}6347}{22}$$
$$MS\ (period\ e) = 42{,}5288$$

The ANOVA calculation shows the average value after pooling, as shown in Table 9.

Table 8. ANOVA After Pooling.

Source	Pooling	SS	DF	MS	F Ratio	SS'	% Ratio	F Table
A		170,07	2	85,04	2,00	85,02	7%	3,55
B	Y	-	-	-	-	-	-	-
C	Y	-	-	-	-	-	-	-
D		201,87	2	100,93	2,37	116,81	9%	3,55
Pooled		935,63	22	42,53	1,00	1105,75	85%	
SSt		1307,58	26	228,50		1307,58	100%	
Mean		3905,44	1					
SStot		5213,02	27	85,04			7%	3,55

Based on the ANOVA table after pooling, it is known that the welding method factor (A) and the welding current factor (D) affect the resistance to corrosion rate values. In other words, these two factors significantly contribute to increasing the average value of the experiment. Factors B and C also contribute, but the value is very small.

3.3.3. Anova Calculation SNR Value

1. Calculating the mean of the SNR (Signal-to-Noise-Ratio) of all experiments,

$$\bar{\eta} = \frac{\Sigma \eta}{n}$$
$$\bar{\eta} = \frac{(-24{,}9205)+(-25{,}6091)+(-22{,}2197)\ldots\ldots\ldots+(-24{,}7522)}{9}$$
$$\bar{\eta} = -22{,}0545$$

2. Calculate the mean SNR for each factor level; for example, for factor A with the first level,

$$\bar{\bar{\eta}}_{jk} = \frac{\Sigma \eta_{ijk}}{n}$$
$$\bar{\bar{\eta}}_{jk} = \frac{(-24{,}9205)+(-25{,}6091)+(-22{,}2197)}{3}$$
$$\bar{\bar{\eta}}_{jk} = -24{,}2497$$

3. After getting the signal-to-noise ratio (SNR) value from the factor and its factor level, the next step is determining the response table and response graph to the SNR. The following

table shows the response results of the SNR value to the results of each factor and its factor level, which shows the optimal value,

Table 9. Response of experimental signal-to-noise-ratio (SNR) values.

Source	Factor			
	A	B	C	D
Level 1	-24,2498	-20,1474	-22,2470	-24,4398
Level 2	-20,7714	-23,3288	-22,6464	-21,5476
Level 3	-21,1423	-22,6872	-21,2700	-20,1761
Delta	3,4784	3,1814	1,3764	4,2637
Ranking	2	3	4	1

The following is a picture of the response graph for the signal-to-noise ratio (SNR) value.

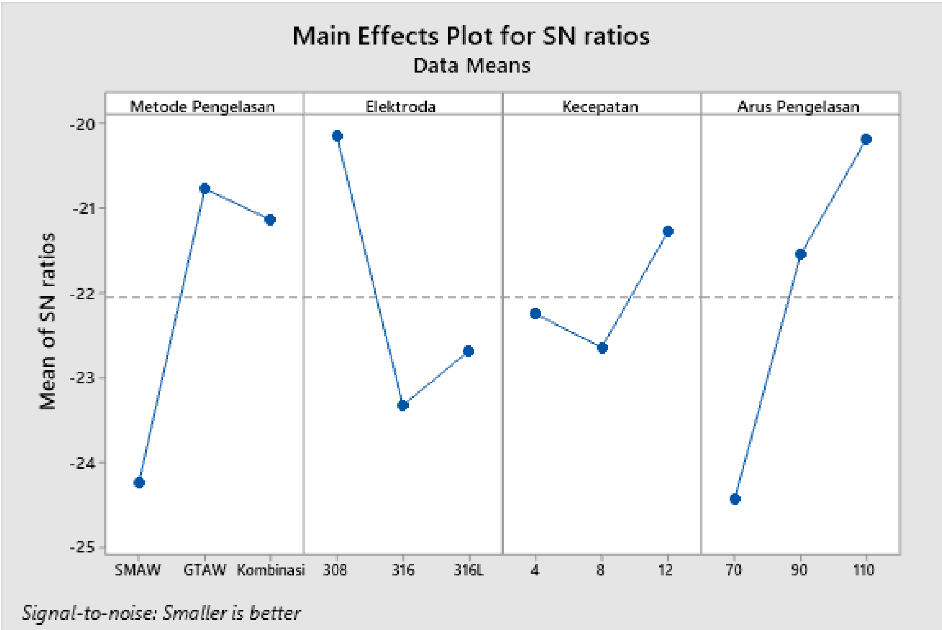

Fig. 5. Response graph showing SNR value (Software Minitab).

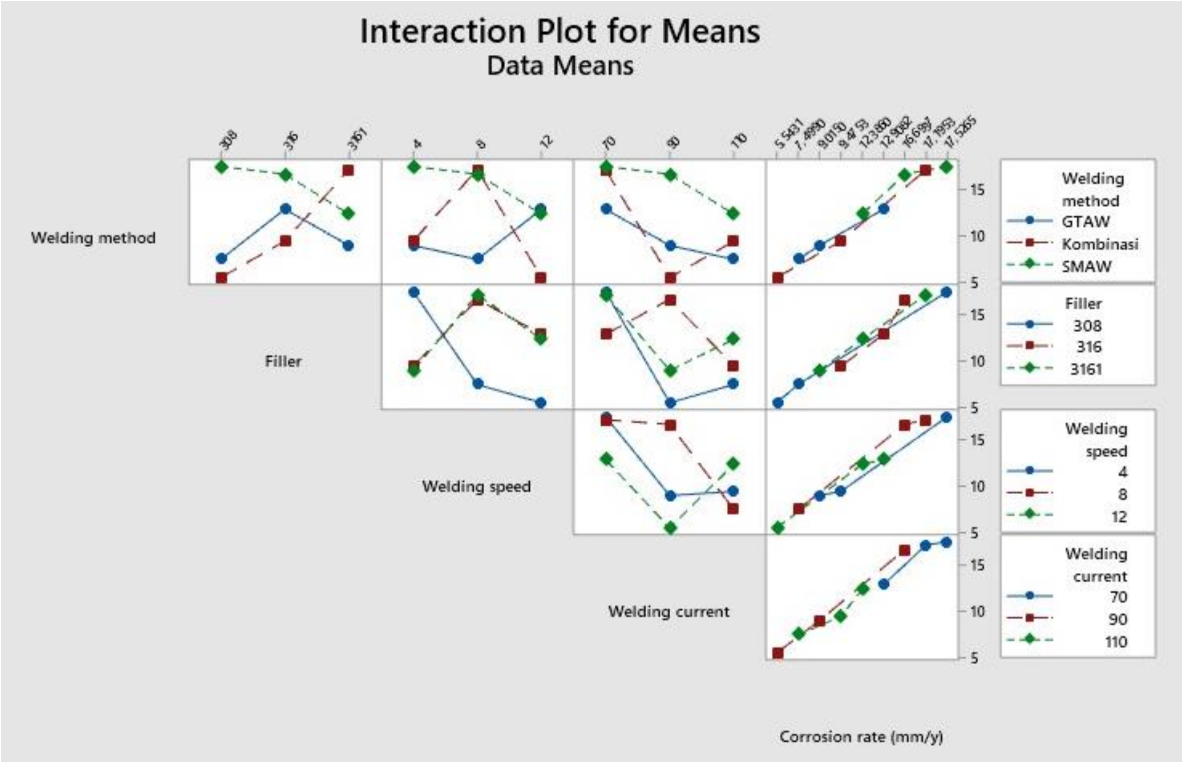

Fig. 6. The following graph shows this interaction plot for means (Software Minitab).

4. Calculate the total sum of the squares value

$SS_{total} = \sum y^2$

$SS_{total} = (-24{,}9205)^2 + (-25{,}6091)^2 + (-22{,}2197)^2 + \cdots + (-24{,}7522)^2$

$SS_{total} = 4447{,}9058$

5. Calculates the value of the sum of squares due to mean,

$Mean\ (S_m) = n\bar{y}^2$

$Mean\ (S_m) = 27 \times (-22{,}0545)^2$

$Mean\ (S_m) = 4377{,}5958$

6. Calculate the value of the sum of squares due to factor, e.g., for factor A,

$SS_A = (n_{A1} \text{ x } \overline{A1^2}) + (n_{A2} \text{ x } \overline{A2^2}) + (n_{A3} \text{ x } \overline{A3^2}) - S_m$

$SS_A = (3 \text{ x } (-24{,}2498)^2) + (3 \text{ x } (-20{,}7714)^2) + (3 \text{ x } (-21{,}1423)^2) - 4377{,}5958$

$SS_A = 21{,}8933$

7. Calculate the value of the degrees of freedom, e.g., for factor A,

$DF_A = \text{number of levels} - 1$

$DF_A = \text{X} - 1$

$DF_A = 3 - 1 = 2$

8. Find the value of the mean sum of squares, e.g., for factor A,

$MS_A = \frac{SS_A}{DF_A}$

$MS_A = \frac{21{,}8933}{2}$

MS_A = 10,9466

9. Calculate the value of the F-ratio, e.g., for factor A,

$$F_A = \frac{MS_A}{MS_{error}}$$

$$F_A = \frac{10,9466}{4,9980}$$

F_A = 2,1902

10. Calculate the value of the pure sum of squares, e.g., for factor A,

$$SS'_A = SS_A - DF_A + MS_{error}$$

$$SS'_A = 21,8933 - 2 \times 4,9980$$

SS'_A = 11,8973

11. Calculate the percent contribution value, e.g., for factor A,

$$\rho_A = \frac{SS_A}{SS_{total}} \text{ x } 100\%$$

$$\rho_A = \frac{21,8933}{4447,9058} \text{ x } 100\%$$

ρ_A = 17 %

The results of all ANOVA calculations for SNR values are presented in

Table 10. ANOVA of SNR values after pooling-up.

Source	Pooling	SS	DF	MS	F Ratio	SS'	% Ratio	F Table
A		21,89	2	10,95	2,19	11,90	17%	6,94
B	Y	16,98	-	-	-	-	-	-
C	Y	3,01	-	-	-	-	-	-
D		28,42	2	14,21	2,84	18,43	26%	6,94
Pooled		19,99	4	5,00	1,00	39,98	57%	-
SSt		70,31	8	-	-	70,31	100%	-
Mean		4377,60	1	-	-	-	-	-
SStot		4447,91	9	-	-	-	-	-

3.3.4. Determining the Optimal Level Setting

After the calculation process above, we get the ANOVA results for the mean and SNR values. Then, the results of the characteristics with the most optimal factors and levels are obtained for this research activity. The following is a comparison table of the influence of significant factors in determining the optimal level.

Table 11. Comparison Table of The Influence of Significant Factors.

Factor	Contribution	Level
(A) **Welding Method**	*Significant*	A1
(B) **Filler**	*Insignificant*	B2
(C) **Welding Speed**	*Insignificant*	C2
(D) **Welding Current**	*Significant*	D1

3.3.5. Optimal Condition Confidence Interval

Furthermore, after we determine the optimal factor level, calculations are necessary to determine the confidence interval value for the mean under optimal conditions. This is to compare with confirmation experiments. If a value produced is close to even the same value, then the Taguchi design can be said to be qualified. The following calculates the average confidence interval value (mean).

1. Estimated confidence interval of optimal condition mean value,

The optimal condition estimate of the mean value for all data is $\bar{y}$ = 12.02688

$$\mu_{prediction} = \bar{y} + (\overline{A1} - \bar{y}) + (\overline{D1} - \bar{y})$$

$$\mu_{prediction} = \overline{A^2} + \overline{D^3} - \bar{y}$$

$$\mu_{prediction} = 7{,}5672$$

Confidence interval calculation,

$$Cl_{mean} = \pm\sqrt{F_{a\,;v1\,;v2} \times MS_e \times \left|\frac{1}{neff}\right|}$$

Where neff as follows:

$$neff = \frac{Total\ number\ of\ experiment}{s\ of\ degrees\ of\ freedom\ used\ in\ the\ estimate\ of\ \text{the}\ mean}$$

$$neff = 5{,}4$$

The confidence interval can be found using the following formula,

$$Cl_{mean} = \pm\sqrt{F_{a\,;v1\,;v2} \times MS_e \times \left|\frac{1}{neff}\right|}$$

$$Cl_{mean} = \pm\, 5{,}8194$$

The results of the confidence interval value that has been calculated from the optimum mean value of the maximum and minimum intervals are as follows:

$$\mu_{prediction} - Cl_{mean} \le \mu_{prediction} \le \mu_{prediction} + Cl_{mean}$$

$$7.5672 - 5.8194 \le \mu_{prediction} \le 7.5672 + 5.8194$$

$$1{,}7478 \le \mu_{prediction} \le 13{,}3866$$

3.3.6. Experiments Validation

Validation testing is the final step in a series of Taguchi design processes, where tests are run using settings at the optimal level of factors and test levels carried out by previous researchers. The purpose of this validation test experiment is to confirm the conclusions that will be obtained from the first experiment. Furthermore, three repetitions were performed to obtain optimal parameter processes. The following is the value of the corrosion rate test results on Stainless steel 304 and Stainless steel 316 welding joints confirmation experiments obtained.

Table 12. Corrosion rate test results of welding joints of validation test specimens.

Control Factor				Corrosion rate result (mm/y)			Mean	SNR
Welding Method	**Filler**	**Weld speed**	**Current**	**1**	**2**	**3**		

SMAW	E316	8	70	4,1934	2,6808	2,1950	3,0231	-9,9401

After obtaining the results of the verification experiment or validation test, the next step is to calculate the signal-to-noise ratio (SNR) value from the results of the validation test experiment. The following is to find the mean and get the confidence interval value compared to the best-case value. The following are the calculation results of the validation test specimen:

1. Calculation of the mean value of the validation test specimen,

$$\mu = \sum_{i=0}^{n} yi$$

$$\mu = \frac{1}{3}\,(4{,}1934 + 2{,}6808 + 2{,}1950)$$

$$\mu = \ 3{,}0231\ mm/y$$

2. Calculation of Signal-to-Noise-Ratio (SNR) values from 3 replications,

$$\frac{S}{N} = \ -10\ \log\left(\frac{1}{n}\right)\sum_{i=1}^{n}\frac{1}{{y_i}^2}$$

$$\frac{S}{N} = -9{,}9401\text{dB}$$

3. Calculating the confidence interval of the validation test experiment,

$$Cl_{mean} = \pm\sqrt{F_{a\,;v1\,;v2}\times MS_e\ \times\left|\frac{1}{neff}\times\frac{1}{n}\right|}$$

$$Cl_{mean} = \pm\ 9{,}7377$$

So, the results of the confidence interval can be seen as follows:

$$\mu_{konfirmation} - Cl_{mean} \leq \mu_{konfirmation}\ \leq\ \mu_{konfirmation} + Cl_{mean}$$

$$9.9401 - 9.7377 \leq \mu_{konfirmation} \leq -9.9401 + 9.7377$$

$$-19.6779 \leq \mu_{konfirmation} \leq -0.2023$$

Fig. 7. Comparison of mean value confidence intervals.

After calculating the confidence interval of the confirmation experiment, the next step is to compare it with the confidence interval of the optimal condition presented in Figure 7.

Figure 7 and Table 12 show the average value (mean) of the optimal and confirmation results: optimal, confirmation, difference, and percentage difference. The optimal values range from 1.7478 to 13.3867, while the confirmation values range from -19.6779 to -0.2024. The difference between these two parameters is -1.9502, with a percentage difference of -15%. These numbers may indicate a significant difference between the expected optimal value and the confirmation results. This analysis can be used to evaluate the efficiency or success of a process in meeting the expected optimal value in Taguchi process experiments of SS304 and SS316 welded joints on corrosion rate.

4. CONCLUSION

Based on the research findings, several conclusions can be drawn regarding the factors influencing the corrosion rate (mm/y) of welded joints made of SS304 and SS316 materials. The corrosion rate's primary factors are the welding method, welding electrode, welding speed, and welding current. Among these, the welding method (A) and welding current (D) contribute significantly to the quality characteristics. The optimal levels determined are the SMAW (Shielded Metal Arc Welding) method (A1) and a welding current of 70 amperes (D1), as indicated by both the average value and the signal-to-noise ratio (SNR). Conversely, the welding electrode (B2, Filler E316) and welding speed (C2, 8 cm/min) have less significant contributions to the corrosion rate than the other factors.

The ANOVA results confirm that the welding method and welding current significantly impact the corrosion rate. At the same time, the welding electrode and welding speed also influence the outcome but to a lesser extent. The SMAW method demonstrates a significant advantage in producing strong and durable joints. As noted by Cary and Helzer (2005) in Modern Welding Technology, the flux protection in SMAW effectively prevents atmospheric contamination during welding, ensuring joints are free of porosity or inclusions, while the resulting slag protects the molten metal until it cools, enhancing joint quality and homogeneity.

Current settings also play a crucial role in welding performance. A low current setting may result in insufficient penetration, leading to weak joints, whereas excessively high currents can cause overheating, deformation, or cracking. Electrodes with a diameter of 2.5 mm, combined with a current of approximately 70 amperes, produce a stable arc, easily removable slag, and high-quality welds. As documented in The Welding Handbook by the American Welding Society, this current level strikes a balance between adequate penetration and minimal deformation, resulting in precise and robust weld joints. These findings highlight the importance of optimizing welding parameters for superior joint quality and corrosion resistance.

ACKNOWLEDGEMENT

The authors are grateful to Sriwijaya University, PT. Perusahaan Listrik Negara and PT. Pupuk Sriwidjaya for supporting and providing the facilities for this research.

REFERENCES

[1] Suwandi, I. A. P., Sumaryo, S., & Yuwono, S. (2021). Pengendalian Kadar Ph Air Berbasis Kontrol Pid Pada Prototipe Water Treatment Plant. eProceedings of Engineering, 8(2).

[2] Kosim, M. E., Prambudi, D., & Siskayanti, R. (2021). Analisis Efisiensi Penukar Ion Sistem Demineralisasi Pada Pengolahan Air di Proses Produksi Electroplating. Prosiding Semnastek.
[3] Pratiwi, D. K., Arifin, A., Gunawan, Mardhi, A., & Afriansyah. (2023). Investigation of welding parameters of dissimilar weld of SS316 and ASTM A36 joint using a grey-based taguchi optimization approach. Journal of Manufacturing and Materials Processing, 7(1), 39.
[4] Phillips, D.H. Welding Engineering: An Introduction; Wiley: Hoboken, NJ, USA, 2016.
[5] Hafeez, K., Rowlands, H., Kanji, G. & Iqbal, S. 2002. Design optimization using ANOVA. Journal of Applied Statistics 29 (6): 895-906.
[6] Yakub, Y. (2013). Variasi Arus Listrik terhadap Sifat Mekanik Mikro Sambungan Las Baja Tahan Karat AISI 304. Widya Eksakta, 1(1), 249172.
[7] Arifin, A. (2024) Pengantar Teknologi Pengelasan. 1st edition. Palembang. Universitas Sriwijaya
[8] Cahya, M. R., & Abdulah, A. Analisis Terjadinya Korosi Batas Butir Akibat Proses Pengelasan Gtaw Pada Material Austenitic Stainless Steel AISI A304.
[9] Kou, S. (2003). Welding metallurgy. A John Wiley & Sons Inc.
[10] Surya, I. (2019). Pengaruh Panas Las Gtaw (Gas Tungsten Arc Welding) Pada Material Stainless Steelgrade 316L Terhadap Uji Tarik Dan Komposisi Kimia Material. Jurnal Teknik Mesin, 6(2), 4.
[11] Lu, J. Z. et al. (2012) "Effects Of Laser Peening On Stress Corrosion Cracking (SCC) Of ANSI 304 Austenitic Stainless Steel," Corrosion Science. Elsevier, 60, hal. 145–152.
[12] Skripsi akbar
[13] Arifin, Amir, et al. "Optimization of Angular Distortion on Weld Joints Using Taguchi Approach." Jurnal Kejuruteraan 31.1 (2019): 19-23.
[14] Arifin, A. (2022). Taguchi Approach of Dissimilar Welds. Journal of Mechanical Engineering, 1913, 189-203.
[15] N. Ghosh, P. K. Pal, and G. Nandi, "GMAW dissimilar welding of AISI 409 ferritic stainless steel to AISI 316L austenitic stainless steel by using AISI 308 filler wire Engineering Science and Technology, an International Journal, vol. 20, no. 4, pp. 1334-1341, 2017.
[16] R. Unal and E. B. Dean, "Taguchi approach to design optimization for quality and cost: an overview.," presented at the 13th Annual Conference of the International Society of Parametric Analysts, ISPA, New Orleans, LA., 1991.
[17] Wuryandari, T., Widiharih, T., & Anggraini, S. D. (2009). Metode Taguchi untuk optimalisasi produk pada rancangan faktorial. Media Statistika, 2(2), 81-92.
[18] Roy, R.K. (2010). A Primer on the Taguchi Method. Society of Manufacturing Engineers.
[19] Ghosh, N., Pal, P. K., & Nandi, G. (2016). Parametric optimization of MIG welding on 316L austenitic stainless steel by Taguchi method. Archives of Materials Science and Engineering, 79(1), 27-36.
[20] Sinaga, A. J., & Manurung, C. (2020). Analisa Laju Korosi dan Kekerasan Pada Stainless Steel 316 L Dalam Larutan 10% NaCl Dengan Variasi Waktu Perendaman. *Sprocket Journal of Mechanical Engineering*, *1*(2).
[21] Standard Practice for Laboratory Immersion Corrosion Testing of Metals. Designation: G31-72. (Reapproved 2004).
[22] Standard Practice for Preparing Cleaning and Evaluation Corrosion Test Specimen (Appendix XI). Designation: G1-90(Reapproved 1999).