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Optimization Parameters in Cold Metal Transfer (CMT) Welding of SUS 316 to SPHC

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Keywords： Cold Metal Transfer (CMT) welding, cycle arcing phase, wire feed phase, pause time interval phase, Taguchi, dissimilar material.

ABSTRACT

Cold Metal Transfer (CMT) welding produces very precise welds with the assistance of a welding robot. This technology can be used to weld joints between materials that have different mechanical properties. This research aims to improve production quality in welding by identifying optimal parameters from the machine, simultaneously reducing production costs through welding two different materials. The welding results are expected to achieve optimal strength and functionality. Emphasizing that welding of dissimilar materials is not only feasible but also an effective solution for various industrial needs, such as the production of medical equipment, food services, energy industries, and others. This study was conducted to determine the optimal parameters of CMT welding machine for joining SUS 316 and SPHC materials. The two materials will be welded by adjusting several specified parameters. During welding, temperature fluctuations have a significant impact on material properties, the precision of the welding shape, and residual stress. The cycle arcing phase, wire feed phase, and pause time interval phase can be adjusted to generate enough energy to reach a specific temperature and achieve satisfactory welding results. The cycle arcing phase has a range of 20-60 times, the wire feed phase is 10-14 m/min, and the pause time interval phase has a range of 0.01s-0.1s. Each specimen is analyzed for tensile strength in order to determine the highest value among the existing parameters. The optimal combination of parameters is achieved 40 times in the cycle arcing phase, 14 m/min in the wire feed phase, and 0.01s in the pause time interval phase which can be seen from the highest of tensile strength result, specifically 362.7 N/mm². The Taguchi method is used to obtain the optimal parameters. The S/N Ratio calculation shows that higher values for the cycle arcing phase, wire feed phase, and pause time interval phase can result in higher tensile strength values. These parameters can be used to produce precise welds on SUS 316 and SPHC materials, resulting in the highest tensile strength.

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INTRODUCTION

In industry, joining dissimilar materials is crucial, particularly in the welding process, to minimize production and operational expenses, decrease material weight, and achieve optimal mechanical and thermal properties [1]. Nowadays, the Cold Metal Transfer (CMT) method is commonly used for welding joints of dissimilar materials. This technology has revolutionized the welding of dissimilar metals by producing better weld bead quality with controlled metal deposition [2]. CMT utilizes a novel droplet separation method in combination with reverse wire electrode motion. The wire is continuously fed to the workpiece using the typical short arc technique. If a short circuit occurs, the current is increased to disrupt the short circuit and reestablish the arc. Droplet detachment and reignition in the CMT process, on the other hand, are regulated by the reverse movement of the wire electrode. CMT welding method is widely used for dissimilar welding joints, such as joining aluminum alloy to zinc-coated steel [3], aluminum alloy to magnesium [4], aluminum to low carbon steel [5], titanium to copper alloy [6], and titanium to stainless steel [7]. This research focuses on welding dissimilar materials, specifically stainless steel 316 (SUS 316) and steel plate hot rolled coiled (SPHC).
SUS 316 is an austenitic stainless steel that is widely used in various industries such as pharmaceuticals, chemicals, hospitals, surgery equipment, food services, semiconductor manufacturing, energy industries, and outdoor structures and enclosures. It is commonly used for containers to hold liquids and solids [8]. This is

emphasized by the character of SUS 316, which possesses high mechanical strength, excellent chemical composition, good weldability, and superior corrosion resistance, despite its high cost. On the other hand, hot-rolled mild steel plate, sheet, and strip, or what we call SPHC, are relatively inexpensive compared to other types of steel. SPHC still possesses excellent formability, weldability, and durability for numerous applications, while also offering sufficient structural integrity [9].

This paper will investigate obtaining parameter settings from the CMT machine for welding joints, with a particular focus on the cycle arcing phase, wire feed phase, and pause time interval phase. The final result obtained a tensile strength of Stainless Steel 316 and SPHC that meets industrial requirements.

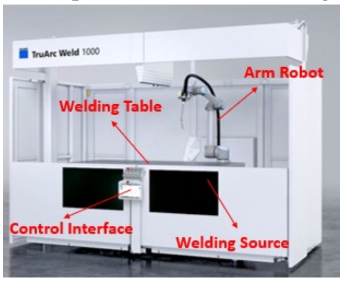
METHODOLOGY

Experiment design, as part of scientific investigation, is a widely used research approach [10]. The influence of multiple independent variables on the dependent variable can be evaluated through experimental design. Four stages must be carried out in this method, including data collection and processing, material preparation, experiment implementation, and results analysis. The data collection and processing stage begins with determining the factors and levels and calculating the minimum number of experiments to be performed using the Taguchi optimization method. The preparation stage is for preparing the specimens used in the tensile test. At the implementation stage, the tensile test is conducted, and the results will be analyzed using the S/N Ratio. The S/N ratio is used to evaluate the impact of various factors on the performance of a system. The methodology begins with the identification of key factors and their respective levels, followed by the design of orthogonal arrays to conduct experiments efficiently. Through carefully planned experiments, the S/N ratio is calculated as a performance metric, considering both the mean and variance of the responses. This research elaborates on the steps involved in calculating the S/N ratio and its interpretation, emphasizing the importance of choosing an appropriate characteristic for optimization. The result of the S/N ratio is to obtain the optimal process performance.

COLLECTING AND PROCESSING DATA

The range of parameters for the cycle arcing phase, wire feed phase, and pause time interval phase were determined for collecting and processing data using The TruArc 1000 machine for materials SUS 316 and SPHC. This machine, depicted in Figure 1, is capable of performing CMT welding within an acceptable range of parameters. The cycle arcing phase ranges from 20 to 60 times, the wire feed phase ranges from 10 to 14 m/min, and the pause time interval phase ranges from 0.01 to 0.10 s.

Figure. 1. Trumpf TruArc 1000 welding machine



There are three parameters used in the research, and three levels have been determined: minimum, medium, and maximum. The level values for each factor can be seen in Table 1.

Table 1. CMT Weld Parameters for Taguchi Method

Factor	1	2	3
Cycle arcing phase (Ca)	20 x	40 x	60 x
Wire feed phase (Wf)	10 m/min	12 m/min	14 m/min
Pause time interval phase (Pi)	0.01 s	0.05 s	0.10 s

In experimental design, orthogonal arrays (OAs) are used to analyze the experimental data in order to maximize information while minimizing the number of experiments required to design an efficient experiment [11]. The choice of orthogonal array type used for experiments depends on the number of degrees of freedom (DoF). In addition, the determination of degrees of freedom is influenced by the number of levels (l_k) used in the experiment. The concept of DoF calculation is illustrated in Equation 1.

$$DoF = \sum_{k=1}^{n}(l_k - 1) \quad (1)$$

where l_k is number of levels.

Orthogonal array tables are determined as L9(3)3, as shown in Table 2. This means that 9 combinations of welding parameters will be used for the experiments [12]. The combinations are determined based on the level value of each parameter. The welding of SUS 316 and SPHC will be repeated 5 times for each parameter variation to minimize deviations in the results.

Table 2. Orthogonal array for welding CMT parameters

Number of parameters	Ca (x)	Wf (m/min)	Pi (s)
1	20	10	0.01
2	20	12	0.05
3	20	14	0.1
4	40	10	0.05
5	40	12	0.1
6	40	14	0.01
7	60	10	0.1
8	60	12	0.01
9	60	14	0.05

MATERIAL PREPARATION

In this research, the primary materials considered are SUS 316 austenitic stainless steel and SPHC. Dissimilar plates are fabricated using the test specimens. When designing the test specimens, refer to the European Standards ISO 4136:2022 [13] and ISO 6892-1:2019 [14] are employed to determine dimensions, proper test object preparation, and tensile test conditions. The specimen shapes and dimensions can be seen in Figure 2.

In creating the specimen, SUS 316 and SPHC materials were welded using a Trumpf TruArc 1000 machine with predetermined parameters. After the welding process, the dimensions of the material are 250 mm x 180 mm x 4 mm from each welding process, following the parameters set for all nine welding processes. Then, each welding plate was cut using a laser cutting machine into five specimens that have dimensions 180 mm x 37 mm x 4 mm based on the welded specimen in Figure 2. The results of the welding and cutting process on specimens can be seen in Figure 3.

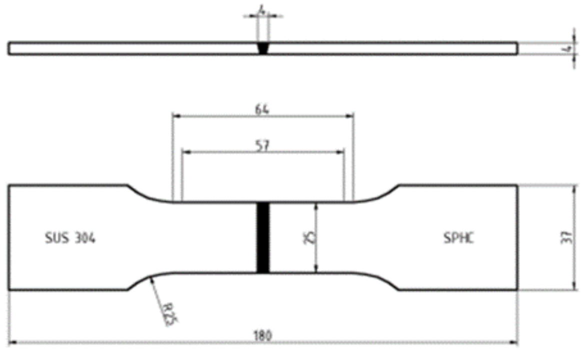


Figure 2. Shape and dimensions of the welded specimen (unit: mm)

EXPERIMENT IMPLEMENTATION

The tensile test is a method used to measure the strength of a material by creating a specialized specimen for testing. In this process, nine parameters will be analyzed. Each parameter will be tested five times to ensure the accuracy of the results. The main objective of each tensile test is to obtain the average value of the tensile stress and elasticity of the material being tested. The data obtained from this test includes information about the maximum stress that the material can withstand, as well as its ability to return to its original shape after being loaded, as shown in Table 3. By analyzing the information generated from this test, it is possible to evaluate the performance of the material under specific conditions and gain a clear understanding of its reliability and characteristics.

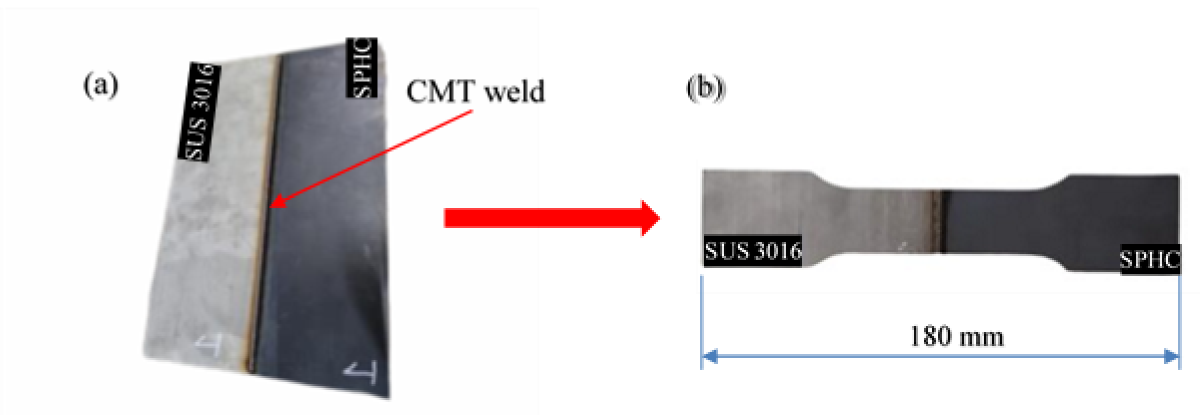


Figure 3. Specimens after being welded by CMT (a) and after being cut with laser cutting (b)

Table 3. The result of Tensile Stress and Elasticity

Number of parameters	Ca (x)	Wf (m/min)	Pi (s)	Tensile Stress (N/mm²)	Elasticity (N/mm²)
1	20	10	0.01	195.4	5726.2
2	20	12	0.05	231.8	6325.4
3	20	14	0.1	246.9	6139.3
4	40	10	0.05	222.6	5527.1
5	40	12	0.1	241.5	6182.7
6	40	14	0.01	362.7	7529.4
7	60	10	0.1	202.3	5547.2
8	60	12	0.01	300.8	6825.5
9	60	14	0.05	298.2	6802.3

Based on the data presented in Table 3, it can be concluded that parameter 6 exhibits the highest tensile stress, reaching 362.7 N/mm². On the other hand, parameter 1 yields the lowest tensile stress at 195.4 N/mm².
Further analysis of the relationship between tensile stress and elasticity in the welding joint is depicted in Figure 4. The graph illustrates that the highest elasticity value is also associated with parameter 6, reaching 7529.4 N/mm². These findings provide crucial insights into the correlation between the selected parameters and the mechanical performance of the welding joint. Parameter 6 stands out as a choice that delivers robust and elastic results.

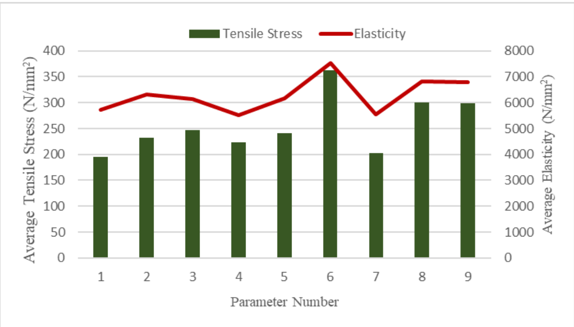


Figure 4. Tensile Stress and Elasticity Graphic

RESULT ANALYSIS

In this research, Taguchi orthogonal arrays were utilized to create matrix designs that efficiently covered the entire spectrum of parameters while conducting a limited number of experiments [15]. Following the principles of the Taguchi orthogonal array design, a methodology widely acclaimed for optimizing engineering problems [16]. The analysis of the data obtained from these tensile stress experiments will utilize the Taguchi method, specifically focusing on the Signal-to-noise Ratio (S/N Ratio) with a larger-the-better characteristic. This analytical approach aims to precisely ascertain the individual impact of each parameter, providing comprehensive insights into their contributions to the experimental outcomes [17].

The formula for S/N Ratio analysis, which indicates that a larger value is preferable, is shown below:

$$S/N\ Ratio = -10log_{10}\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{Y_i^2}\right] \qquad (2)$$

where n is the number of replications and Y_i is the measured observation

Table 4 presents the calculations for the S/N Ratio, revealing that parameter 6 has the highest value among all parameters

Table 4. S/N Ratio of Each Parameter

Number of parameters	Ca (x)	Wf (m/min)	Pi (s)	S/N Ratio (N/mm²)
1	20	10	0.01	45.81
2	20	12	0.05	47.30
3	20	14	0.1	47.85
4	40	10	0.05	46.95
5	40	12	0.1	47.65
6	40	14	0.01	51.19
7	60	10	0.1	46.11
8	60	12	0.01	49.56
9	60	14	0.05	49.49

The data retrieved from Table 4, which includes S/N ratios for individual parameters, serves as a foundational step in the subsequent phase of the analysis. In Table 5, the focus shifts towards examining the S/N ratios associated with each factor and its corresponding levels. This approach aims to thoroughly examine the assessment of factors and their corresponding levels, clarifying their influence on the desired performance characteristics within the study's context.

Table 5. Response of average S/N Ratio for Each Factor and Level

Level	Cycle arcing phase (Ca)	Wire feed phase (Wf)	Pause time interval phase (Pi)
1	46.99	46.29	48.85
2	48.59	48.17	47.91
3	48.39	49.51	47.20
Delta	**1.61**	**3.21**	**1.65**

Based on Table 5, it can be seen that the wire feed phase (Wf) has the highest average S/N Ratio. This indicates that the parameters of the wire feed phase have the greatest influence on the tensile strength of SUS 316 and SPHC welded joints. The S/N Ratio value is more clearly depicted in the graph shown in Figure 5.
The best parameter combination is selected by

identifying the level with the highest average S/N Ratio for each parameter. Based on the calculation of the average S/N Ratio and the analysis of the graph in Figure 5, it can be observed that the highest S/N ratio for the Cycle arcing phase is at level two, for the wire feed phase is at level three, and for the Pause time interval phase is at level one. Therefore, the optimal parameters based on the S/N ratio analysis are presented in Table 6.

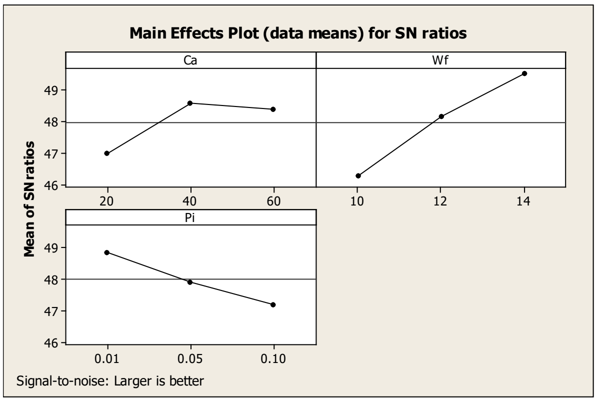


Figure 5. Mean Signal-to-Noise Ratios

Tabel 6. Best Parameter Combination on average S/N Ratio Analysis

Factor	Maximum mean S/N Ratio	Parameter Value
Cycle arcing phase (Ca)	48.59	40 x
Wire feed phase (Wf)	49.51	14 mm/min
Pause time interval phase (Pi)	48.85	0.01 s

Analysis of Variance (ANOVA)

ANOVA was conducted to determine the most influential parameter for the tensile strength of the welding joint by calculating the percentage contribution of each parameter [18]. ANOVA initially organizes the data into distinct groups based on the categorical variable under investigation, with each group representing various levels or treatments of the independent variable [19]. This segmentation is exemplified in a hypothetical study comparing the effectiveness of three distinct teaching methods, where each method forms an individual group. Subsequently, ANOVA was used to partition the total variability in the data into two components: variability between groups and variability within groups. The primary aim is to evaluate whether the observed variation among group means surpasses what would be anticipated by chance alone. ANOVA calculates the F-statistic, a ratio of the variability between groups to the variability within groups. Under the null hypothesis of no significant differences between group means, this statistic adheres to an F-distribution. Significance is then determined by comparing the calculated F-statistic to a critical value from the F-distribution at a predetermined significance level. If the computed F-statistic exceeds the critical value, it signals the rejection of the null hypothesis, indicating that at least one group mean significantly differs from the others

The analysis begins with finding the sum of squares (SS), mean squares or variance (V), and F-test using the equations.

$$SS_{total} = \left(Y_1^2 + Y_2^2 + \ldots + Y_n^2\right) - \frac{(Y_1+Y_2+\ldots+Y_n)^2}{n} \quad (3)$$

The basic formula for ANOVA is SSTotal, where n represents the number of parameter variations, and Y represents the experimental result. The sum of squares is calculated for each factor and level, referred to as SSfactor, where k represents the number of levels in the factor.

$$SS_{factor} = \left(\frac{(\Sigma Y_1)^2}{k} + \ldots + \frac{(\Sigma Y_n)^2}{k}\right) - \frac{(Y_1+Y_2+\ldots+Y_n)^2}{n} \quad (4)$$

Variance (V) or Mean Squares (MS) are derived by dividing the sum of squares (SS) by the corresponding degrees of freedom (DoF). This calculation method allows for a quantitative assessment of the dispersion or variability within the dataset, providing valuable insights into the distribution and spread of the experimental results across different parameters.

$$MS = \frac{SS}{dof} \quad (5)$$

The F-test is a statistical tool used to evaluate the significance of individual factors that impact the tensile strength of a welding joint. This test involves calculating the F-value by dividing the mean square of the factor (MS_{factor}) by the mean square error (MS_{error}). To determine the extent of influence that each factor has on the tensile strength, one can calculate the percentage contribution (P) of each factor. The contribution percentage (P) is calculated using the following formula:

$$P = \frac{SS_{factor}}{SS_{error}} \ x \ 100\% \quad (6)$$

Evaluating these percentages helps in understanding the relative impact and significance of the different parameters on the overall tensile strength of the welding joint.

From the formula above, the ANOVA results are summarized in the ANOVA of tensile strength table shown in Table 7.

Table 7. ANOVA of Tensile Strength

Factor	Dof	SS	V	F-test	P
Cycle Arcing Phase (Ca)	2	4460.82	2230.41	6.98	18.80%
Wire Feed Phase (Wf)	2	13798.49	6899.24	21.60	58.17%
Pause Time Interval Phase (Pi)	2	4824.73	2412.36	7.55	20.34%
Error	2	638.69	319.34		2.69%
Total	8	23722.72	11861.36		100%

Based on Table 7, the ANOVA for tensile strength displays crucial statistical insights into the influence of different factors on welding joint strength. Among these factors, the Wire Feed Phase exhibits the highest F-test value of 21.60, indicating its significant impact on the tensile strength of the weld joint. This phase contributes significantly, accounting for 58.17% of the overall joint strength, as indicated by the percentage contribution (P) in the ANOVA table. Additionally, the pause time interval phase also demonstrates a notable impact, contributing 20.34% to the joint's tensile strength. Conversely, the Cycle Arcing Phase has the least effect on tensile strength, contributing 18.80% to the overall strength of the welding joint. These findings highlight the different levels of influence that these parameters have on the tensile strength of the welding joint, with the Wire Feed Phase being identified as the most influential factor in this analysis.

Macroscopic Photographs on Welding Joint

Macroscopic photographs are captured to meticulously examine the outcomes of welding joints within the specimen. The aim is to discern the extent of penetration achieved during the welding process, especially when dissimilar materials are involved [20]. Macroscopic photographs are captured specifically at welding joints that exhibit the lowest and highest tensile strengths to identify the most significant differences in the welding process [21].

Figures 7 and 8 depict a detailed analysis that specifically focuses on parameters one and six, aiming to emphasize the notable variations that arise from the welding procedures.

Differences in coloration can be observed in the weld layer of the welded joints between parameter one and parameter six, which highlights the distinction between the melting materials SUS 316 and SPHC. The varying depths of material melting between SUS 316 and SPHC are depicted by the dotted lines in Figures 7 and 8.

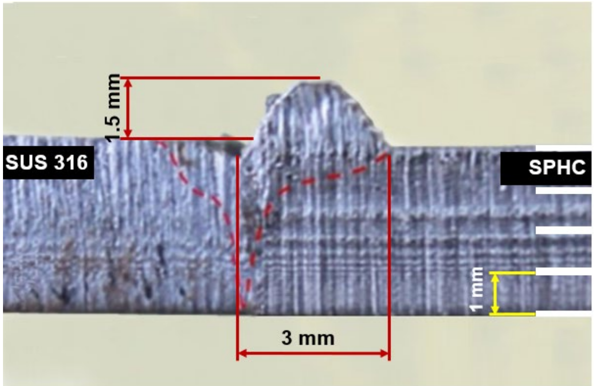


Figure 7. Macroscopic photographs of the welding joint for parameter 1

Figures 7 and 8 serve to illustrate the degree and distribution of porosity within the welds, with discernible impacts on the strength and performance of the joints evident from the tensile testing results. Notably, specimen six exhibits superior performance compared to specimen one. The identification of cracks, including their location, size, and orientation, is distinctly visible in the comparative analysis of the welding outcomes, influencing the severity of defects. In Figure 7, incomplete fusion or penetration is apparent, contrasting with Figure 8, where a more complete fusion is observed. This discrepancy has significant implications for the overall strength of the joint, highlighting the importance of meticulous examination in assessing weld quality.

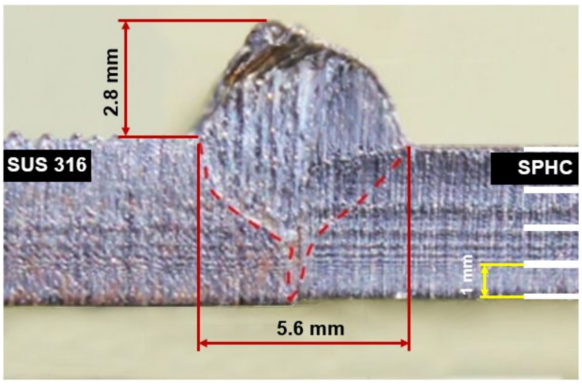


Figure 8. Macroscopic photograph of welding joint for parameter 6

Within parameter one, the weld seam measures 3 mm, resulting in a height of 1.5 mm. In contrast, the weld seam extends to 5.6 mm, with a height of 2.8 mm in parameter six. This comparison, derived from Figures 7 and 8, clearly illustrates that the weld seam within parameter six is larger than parameter one in both size and height. Upon analyzing the size of the weld seam, it becomes evident that a larger seam correlates with a higher tensile strength in the resulting weld joint.

CONCLUSION

The experiment was conducted to determine the effect of the cycle arcing phase, wire feed phase, and pause time interval phase on the tensile strength of SUS 316 and SPHC using CMT welding joint. The objective was to identify the optimal parameters that would result in the maximum tensile strength. Based on the experimental results, the optimal parameters for the CMT welding process with SUS 316 and SPHC were determined. Parameter 6 showed the best results, with a variation of the cycle arcing phase at 40x, wire feed phase at 14 m/min, and pause time interval phase at 0.01 s. These parameters resulted in a tensile stress of 362.7 N/mm². This is further supported by the fact that parameter 6 has the highest elasticity of 7529.4 N/mm². The parameter that has the greatest influence, based on the S/N ratio analysis and ANOVA, is the wire feed phase. The percentage contributions of the cycle arcing phase, wire feed phase, and pause time interval phase on cold metal transfer welding joints between SUS 316 and SPHC materials are as follows: the cycle arcing phase is 18.80%, the wire feed phase is 58.17%, and the pause time interval phase is 20.34%.

This research is limited to demonstrating an experimental approach to obtaining the optimal parameters for joint welding using the cold metal transfer method on dissimilar materials. However, future research could further explore this approach in fabricating other types of materials. Optimization of the obtained parameters can be utilized to enhance the production of manufactured goods in terms of quality and tensile strength.

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