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OPTIMAL TENSILE-SHEAR STRENGTH OF GALVANIZED/MILD STEEL (SPCC-SD) DISSIMILAR RESISTANCE SPOT WELDING USING TAGUCHI DOE

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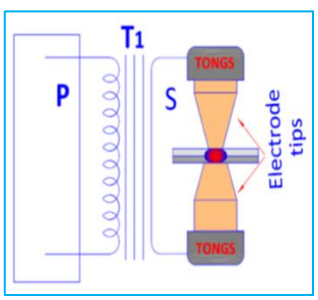
Graphical abstract



Schematic of resistant spot welding

Abstract

This paper demonstrates the optimization of resistance spot welding on different connections of galvanized steel sheets and low carbon steels. The zinc coating on galvanized steel sheets will have an effect to reduce the welding ability in the resistance welding process. The practical Taguchi experimental technics were used by implemented adequately to optimize input factors, namely squeezing time, welding current, welding time and holding time. Statistical software implemented an analysis of variance (ANOVA) and multilinear regression to investigate and evaluate the significant input factors and compare them with the experimental output factors of resistance spot welding. The 'signal to noise ratio' (S/N ratio) results shows that the welding time and the welding current are the most significant factors on the output. The delta values of welding time and welding current are 3.15 and 2.25, respectively. The ANOVA results showed that welding current and welding time are the most contributing factors by 23.5% and 51.4%, respectively. Taguchi recommends an optimal squeezing time of 20 cycles, a welding current of 27 kA, a welding time of 36 cycles, and a hold/cooling time of 15 cycles. The highest output reaches a tensile shear strength of 5762.04 N on the third iteration. The present research has successfully identified significant variable inputs for resistance spot welding, namely welding current and welding time. In the future, the relevant research may use our corresponding results to improve the RSW practical procedure for other significant impacts.

Keywords: Hot-dipped galvanized, Resistance spot welding, Signal to noise ratio, Taguchi method, T-S strength

1.0 INTRODUCTION

Resistance spot welding (RSW) is a joining steel method commonly used in automotive industries. It was also rapidly applied in other sectors such as office equipment, household application industries, bridges, and building construction [1]. Advanced coating technology on metal surfaces such as painting and galvanized applications will influence welding technic in metal. Nowadays, the utilization of galvanized material in the automotive industry increases because it has excellent rust resistance. However, the zinc coating will degrade the resistance spot weldability in galvanized steel [2]. It's a new challenge to solve these issues, especially in the RSW method to join the dissimilar material of galvanized steel uncoated steel sheet. It can be understood because there is a difference in the melting point between the zinc layer on the galvanized steel surface and the uncoated steel sheet material. In this case, reviewing the RSW parameters is essential so that the connection strength on the nuggets meets the requested specifications.

The automotive industry needs to increase efficiency and effectiveness during manufacturing processes, and RSW is one of the most reliable methods of joining steel [3]. That causes the RSW method to be the most widely used in the steel joining technique. The RSW joining process has many advantages: more substantial joining results, easy to apply, no need for filler/electrode, a full skill worker, and an inexpensive and efficient process [4]. In the RSW processes, the current of electricity run throughout the workpiece and generates heat resistance. The pressure is at the same time applied and holds the two or more parts at once to be a single-part connection. The purpose of the pressuring process in the RSW method is to prevent the deformation (curvature) on the connection surface and forged weld metal after heating. The pressuring process applies during squeeze time, and the current flows to the tip of the electrode. The contact area of the joining steel sheet material becomes hot. It occurs fusion on both the surface of the metal attached. The fusion process occurs when both metal surfaces stick together to melt the surface contact of the steel sheet caused by the emergence of electrical resistance [5], [6].

Several studies have been conducted to optimize RSW process parameters. Thakur *et al*. [7] used galvanized steel sheet material and the Taguchi method by implementing six-parameters and mixed-level experimental including 2-level for preheating current and 3-level for squeeze time, current density, welding time, holding time, and electrode pressure (MPa.). The ANOVA showed that the highly effective factors were 'welding time' and 'welding current.' At the same time, 'squeeze time' and 'hold time' were less effective. The improvement in the S/N ratio for tensile shear (T-S) strength and nugget diameter for optimal RSW factors are 19.50 and 8.6, respectively. T-S strength and the nugget diameter are increased by 21.0 and 12.80, respectively [7].

The RSW applied for low carbon steel and CR3 different material thickness was investigated by Shafee *et al*. The Taguchi method used 3-parameter inputs and 3-levels experimental, including the force electrode in kN, welding current in kA, and welding time in the second. The ANOVA results from welding-current and welding time were significant parameter inputs for tensile shear (T-S) strength. Whereas, on direct tensile (D-T) strength, the welding time and welding-current were substantial. The electrode force was ineffective in both variable responses. The improvement in the signal to noise ratio (S/N ratio) from the starting welding parameters to optimal welding parameters is 1.71 dB for D-T strength) 2.4 dB for T-S strength [8].

Optimization of RSW process parameters for joining SUS 316L steels and 2205 duplex stainless steel in dissimilar materials connecting was applied by Vignesh *et al*. using 3-variable and 3-level of the Taguchi technic. The 3-variable selected for optimization in RSW process parameters, namely, the electrode tip diameter, the welding current, and the heating time. Significant RSW process parameters were analyzed using ANOVA. The ANOVA result shown the welding-current was an essential factor in the T-S strength test, followed by the heating diameter and the electrode tip. The optimal process parameters in RSW technic achieved by applying the electrode tip diameter in 6.0 mm, the welding current in 9 kA, and the heating time in 9 cycles [9]. The RSW investigation was continued and performed by different mild steel materials and two hot galvanized steel sheets with different zinc layer thicknesses [2]. The RSW investigation was conducted using two schemes, including one-step and two-step processes, which did not involve heating and involved heating levels, respectively, followed by primary classification levels. In terms of the material's weldability, the welding current's application is directly proportional to the increased thickness of the zinc layer. The two-step scheme resulted in the interface failure mode, achieving a higher peeling force at lower welding currents, a larger nugget diameter, and a higher cross-tensile load for a given welding current. Regardless of the thickness of the zinc layer, the two-step scheme achieves better classification quality than the one-step scheme [2].

Further study has been performing in application with typical and clinching RSW parameters for the galvanized steel to 5083 Al alloy [10]. Optimization used the Taguchi method with three parameters and a three-stage experiment, including a 3-stages welding current in kA, welding time in a cycle, and electrode force in kg. It increased the maximum failure load increased to 4.5 kN. The range of factors for obtaining high strength is quite wide at RSW. The interaction of classification time and welding current has a significant effect on strength. Advance studies were conducted RSW for different materials AISI-1008 steel and aluminium-1100 alloy by enhancing graphene nanoplatelet (GNP) interlayers. Detailed analysis of the experiment worked at 6.5 kA, 7.0 kA, and 7.5 kA for the welding current, followed by 0.5 s, 0.6 s & 0.7 s for the welding time. A significant increase of ~124% investigated the effect of GNP on joint weld strength in one of the welded samples was reported by [10].

Unlike previous research, this paper conducted optimization tensile shear strength in the RSW parameter process with dissimilar materials of the SPCC-SD (JIS 3141) and SGCC (JIS 33032) steel sheet materials. This study aimed to achieve the highest T-S strength and evaluate the essential factors/ parameters process of RSW technic for joining SPCC-SD and SGCC steel sheets in different materials. This paper used the Taguchi experimental method by having four elements and three levels. The four factors namely squeezing time, welding current, welding time, and holding time.

2.0 METHODOLOGY

2.1 Material and Test Specimens

This study used SPCC-SD and SGCC 0.8 mm steel sheet material thickness. The SPCC-SD (JIS 3141) material is a type of low carbon steel, and it is similar to ASTM A366-91 standards [10]. Low-carbon steels are generally well-considered to be spot weldable [1], [11]. The SPCC-SD steel sheet plate is widely used in the manufacturing industry [15]. SGCC is commonly produced from SPCC-SD steel sheets and coated by hot-dip zinc-coated processes [18]. The SGCC material is galvanized steel, and it consists of two elements, namely zinc and iron. Both materials have distinct characteristics. The zinc layer thickness has inversely proportional to material weldability. The zinc causes SGCC to have a low melting point, low resistance, and high conductivity compared to the base low carbon steel [7]. Table 1 and Table 2 presented the mechanical properties and chemical composition of the SPCC-SD and SGCC material.

The first step preparation stage for T-S shear strength is the cutting process of the steel sheet by the shearing machine. The secondary step was to join the sample with the RSW method and work for the overlapping method. The T-S coupon has been preparing according to AWS D8.9.M:2012 standard [12]. The coupon has the specifics dimensions according to Figure 1.

The experiment used the Taguchi L9 (3^4) array experimental method with orthogonal L9, nine iterations provided with carried out two test samples of each iteration. It is essential to obtain good objective results. The total sample provided 18 units—data analysis defined as transforming, cleaning, and modelling data to discover useful information for technical decision-making. Data analysis aims to extract useful information from data and make a decision based on the data analysis. The coupons used in the RSW process are labelled with a unique identifier consisting of the sample number (*Sn*) and the run number/ iteration (*r*), denoted as *Sn-r*.

Figure 2 displays all representative samples obtained from the RSW process for S1 and S2, identified by their respective labels.

2.2 Experimental Set-up

The heat resistance depends on the resistance of the workpiece materials, the applied electric current, and the time of welding current is applied [5]. The metal melts in the nugget region formed by the heat generated by the electric current in the contact resistance region. In joining for two or more metals in steel, both sides of the surface are pressured to provide surface contact. The pressure applied throughout the RSW cycle process simultaneously used both electrode tips-pressure applied before, during, and after the welding current was worked. The RSW cycle is generally divided into four processes: squeeze time, welding time, holding time, and off-time [6]. The time between applying pressure and welding, namely the squeeze time cycle. The pressure was holding the time after welding finish, called by hold time cycle. The time of metal release from the electrode is called by off-time cycle. The heat/weld time is called the welding time cycle.

Table 1 Mechanical properties and chemical composition of SPCC-SD [13]

Specification	Mechanical properties			Chemical composition (%)			
	Y.P. (N/mm^2)	**T.S. (N/mm^2)**	**E.L. (%)**	**C**	**Mn**	**P**	**S**
JIS G-3141[14]	≤ 240	≥ 270	≥ 37	≤ 0.15	≤ 0.60	≤ 0.04	≤ 0.05
SP51023*	195	315	44	0.0364	0.192	0.010	0.0050

* Mill Test Certificate

Table 2 Mechanical properties and chemical composition of SGCC Plates [15]

Specification	Mechanical properties				Chemical composition (%)			
	Y.P. (N/mm^2)	T.S. (N/mm^2)	C. Weight (gr/m^2)	C.Thickness (μm) **	C	Mn	P	S
JIS G-3302	≤ 205	≥ 270	≥ 80.0	≥ 11.2	≤ 0.15	≤ 0.60	≤ 0.04	≤ 0.05
CSV4505B*	231	333	91.0	12.75	0.0364	0.194	0.0017	0.0043

*Mill Test Certificate; **Thickness = coating weight/ density, where zinc density is 7,14 gr/ cm^3

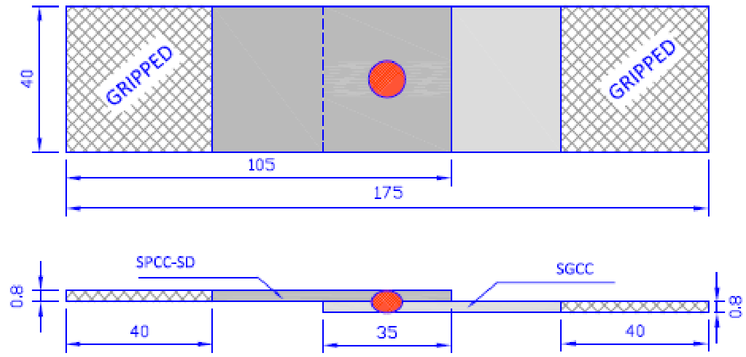


Figure 1 Sample for the tensile-shear test (All dimensions are in mm)

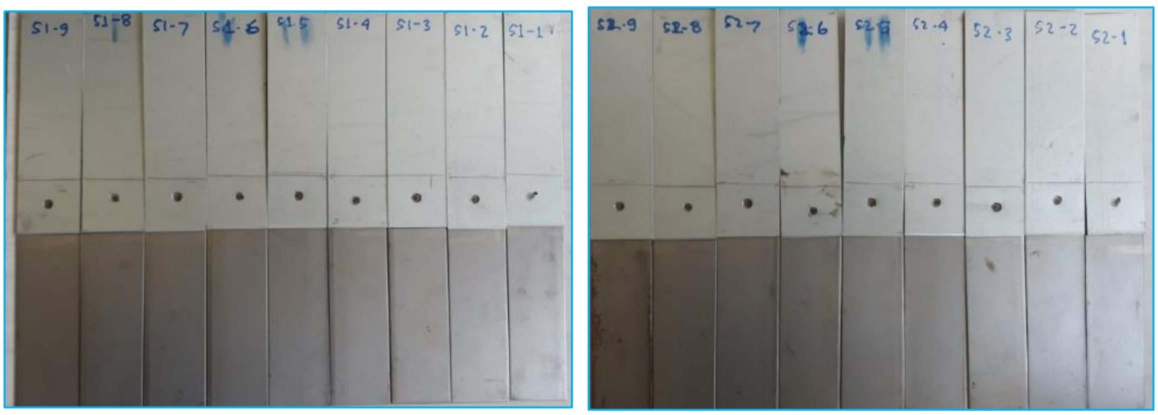


Figure 2 18 units of the T-S strength test samples

The top and bottom electrode diameters have a diameter of 5 mm and 8 mm, respectively. The force acting on the electrode can be calculated using Equation (1). This experiment used the pneumatic pressure of 3.5 MPa. According to Equation (1), the pressuring force is about 68.7 N. The RSW machine, 35 kVA, was used to prepare the sample presented in Figure 3. Figure 3 shows the RSW machine with 35 kVA in the capacity used in this experiment. The electrode was pressuring controlled by a pneumatic system at 3.5 MPa in the pressure. The bottom and upper electrodes have diameters of 8 mm and 5 mm, respectively. The pressuring force is applied as long as the RSW cycle processes. The pressuring force on the electrode welding tip was calculated with Equation (1) [16], [17].

$$F = P.A \tag{1}$$

F, P, and A are the normal force in Newton (N), the pressure of electrode tip in MPa or N/mm^2, and the surface area on contact from both electrode diameters in mm^2. The calculation of the surface area is used with the smaller electrode diameter. The schematic of the RSW schedule is presented in Figure 4.

RSW optimization parameters using four parameters, namely squeeze time (cycles), welding current (kA), welding time (cycles), and hold time (cycles). Figure 4 showing the stages of the welding cycle used in the study [2]. The Taguchi design used four parameters and three levels of the experiment listed in Table 3.

The electrode diameter should be specified to the thinner sheets material when welding two or more sheets of different steel sheet thickness [18]. This study used SGCC and SPCC materials at 0.8 mm in thickness sheet material. The minimum diameter of the electrode welding tip is calculated with Equation (2) [19]. It is essential to have to achieve the pull-out failure mode that the RSW process expected. The minimum diameter of the nugget must achieve 4.27 mm.

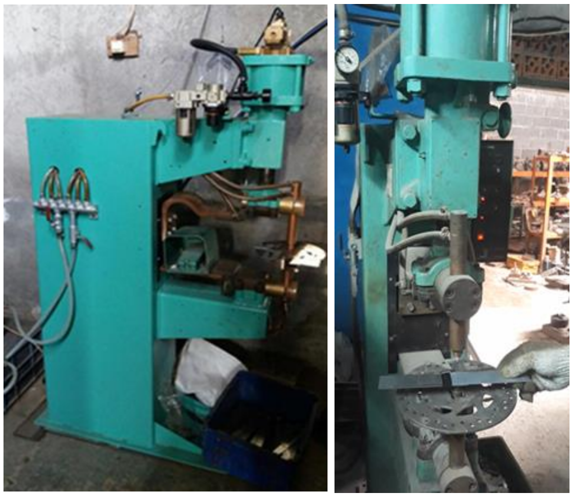


Figure 3 RSW machine 35 kVA capacity

$$D_{min} = 4.5\sqrt{t} \tag{2}$$

Where *D* is the smaller (top) electrode tip diameter, and *t* is the thickness of the thinner steel sheet material to be joined. Furthermore, to meet these requirements, the RSW will be processed using a 5.0 mm electrode diameter. It is about 0.63 mm higher than required in Equation (2).

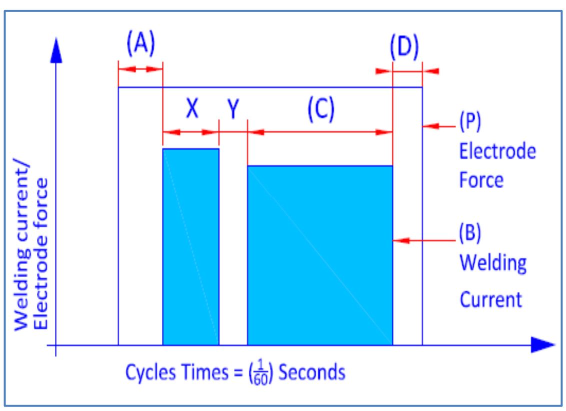


Figure 4 Schematics of RSW

Interface failure is another failure mode on an overlapping of the RSW joining method. This type of failure is undesirable in the metal joining process using the RSW method. The interfacial failure model occurs because the mechanical bonding on the nugget zone is weaker than the metal that joined [7] [20]. The nugget diameter can cause it to be smaller than the minimum diameter specified in Equation (2). Another cause of the interfacial model is welding fusion between materials during the RSW process (poor welding)[21]. Lack of fusion (not optimum) because of the inaccurate setting of the variables used.

2.3 The Tensile Shear (T-S) Strength Test

The tensile shear (T-S) coupon was tested at the Buana Perjuangan Karawang Mechanical Engineering studio. The T– S strength test determined the highest T-S strength from the mixture of the optimized factors. The experimental tests were conducted using the SHIMADZU UTM Universal Testing Machine with a 10 kN capacity, model UTM AGS-X 10kN STD E200V. The machine has an indicated test force within ±0.5% (at 1/500 to 1/1 load cell rating) and conforms to various standards, including EN 10002-2 Grade 0.5, ISO 7500-1 Class 0.5, BS 1610 Class 0.5, ASTM E4, and JIS B7721 Class 0.5. The testing process refers to the JIS Z 2241 standard, *Pull Test Method for Metal Materials*. The test was performed by pulling retraction with a test sample speed of 25 mm. min.$^{-1}$, and the room temperature was controlled at 25°C. The test is stopped after passing the peak of the T-S strength graph so that the test sample that failed in the pull-out model does not tear the material. The test process and scheme are shown in Figure 5.

Figure 5 T-S strength schematic and testing

2.4 Signal to Noise Ratio (S/N Ratio)

In the Taguchi experiment technique, the term S/N Ratio analysis is essential. The term 'signal' reflects the desired value for the variable response variable (output characteristic), and the term 'noise' reflects the undesired value for the output. These points indicate the best parameters for the best or optimized tensile strength values [7]. The S/N Ratio calculation depends on the quality characteristics (for the variable response) being aimed. Taguchi provided the quality of data characteristics into three parts. The formulae for each are shown in Equations (3), (4), and (5) [22], [23].

Table 3 Process parameters with their values at three levels, four parameters, and constant parameters for dissimilar material lap joint sheets

Code	Parameters	Remarks	Level of experiments		
			1	2	3
(A)	Squeeze time (cycles)	Taguchi parameters	18	20	22
(B)	Welding current (kA)	Taguchi parameters	22	25	27
(C)	Welding time (cycles)	Taguchi parameters	24	30	36
(D)	Holding and cooling time (cycles)	Taguchi parameters	12	15	18
(X)	Preheat time (cycles)	Constant parameter	4	-	-
(Y)	Holding time without applying current (cycles)	Constant parameter	1	-	-
(P)	Electrode force (N)	Constant parameter	68.7	-	-

Larger is better:

$$S/N\ ratio = -10 \log \frac{1}{n_0} \sum_{i=1}^{n_0} \frac{1}{y_i^2} \quad (3)$$

Nominal is the best:

$$S/N\ ratio = -10 \log \frac{\bar{y}^2}{s^2} \quad (4)$$

Smaller is better:

$$S/N\ ratio = -10 \log \sum_{i=1}^{n_0} \frac{y_i^2}{n_0} \quad (5)$$

Where *n* is the number of samples, y is the response factor, $\bar{y}$ is the average response factor, and *s* is the response factor variant.

This experimental study used *'larger is better'* characteristics data. It is a measurable *S/N* ratio characteristic with a non-negative value with the infinite ideal value. These characteristics are commonly used to analyze other response data, such as building strength, welding strength, corrosion resistance, material tensile strength, and more.

2.5 Orthogonal Array (O.A.)

The Taguchi orthogonal array method was widely used to improve the manufacturing process. It has been successfully implemented in the manufacturing processes such as welding, plastic injection, metal forming, and others. The Taguchi method was successfully implemented widely in industries such as the textile industry [24], the painting industry [25], the machining process [20], the concrete precast industry [26], metal forming [27]and others.

An orthogonal array (O.A.) is a matrix in which the factors are balanced. The effects between factors can be separated experimentally. The OA commonly used a matrix to ensure a balanced comparison for any critical factor and a matrix unique consumed to determine the selected sample accurately of the specific group. The matrix used typically allows us to accurately assigned the specifications for the sample group efficiently produced. The OA matrix is typically used based on the critical number of essential factors and the practical levels develop for empirical research. Each critical factor uses three experimental levels in this experiment, and the O.A. is accurately detected in contrast L9 (3^4) array. This work used four three-level control factors, and the four control factors produced 8 degrees of freedom. Table 4 showed that the L9 OA with 8 degrees of freedom for selected in this work.

3.0 RESULT AND DISCUSSION

3.1 Failure Modes Analysis

Performance evaluations for all iterations of the RSW tested by the T-S test were investigated. Visual evaluation is carried out to determine the type of failure that occurs. It is focused on the failure mode, namely pull-out or interface failure mode. Even though the minimum diameter of the electrode has been applied and is following Equation (1), the interface model failure occurred during three iterations. The interface failure model has occurred for iterations 1, 6, and 8. It was caused by the lack of fusion in the nugget area as a material connection. The lack of fusion is caused by the lack of welding time during the RSW application process. All samples with interface failure mode occurred at 12 cycles of welding time. The entire sample nugget area with a welding time parameter of 24 cycles does not appear to have fusion. The interface failure in iteration 1 occurred in the setting of squeeze time, 18-cycles, welding current, 22 A, welding time, 24-cycles, and holding time, 12-cycles. The interface failure in iteration 6 occurred in the squeeze time setting, 20 cycles, welding current, 27 A, welding time, 24 cycles, and holding time, 15 cycles. The interface failure in iteration 8 occurred in the squeeze time setting, 22 cycles, welding current, 25 A, welding time, 24 cycles, and holding time, 18 cycles.

Figure 6 shows that the interface failure occurred for all samples with a welding time of 24 cycles. On the other hand, all samples using 30 cycles of welding and 36 cycles experienced failure of the pull-out model. Some samples that experienced interface failure mode are presented in Figure 6.

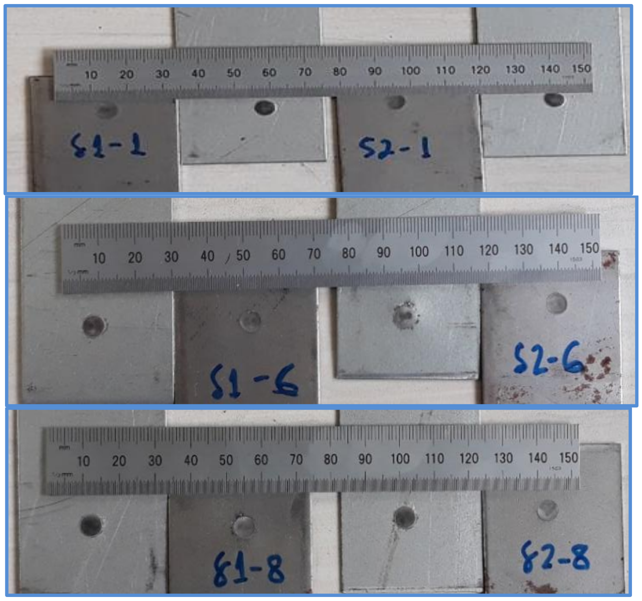


Figure 6 Interfacial failure mode observed in T-S strength test

The lowest T-S test result was obtained in iteration number 8. In contrast, the highest average T.S. strength test results in this study were achieved in iteration number 3. The highest average shear strength iteration consisted of S1 samples- 3 and S2 -3. Figure 7 shows the results of the T-S test for samples S1-3. The graph of T-S power in the range of 1200-1800 N extends to about 11 mm. It happened because the SGCC material has a smooth surface and affects the T-S testing process so that the extreme elasticity of the material is seen. The complete data of the Taguchi pull-sliding test results are presented in Table 4.

3.2. The Tensile Shear (T-S) Strength Analysis

The tensile shear (T-S) strength tests are provided in Newton units. It is desirable because the T-S strength test for the RSW method has difficulty measuring the nugget area of τηε sample accurately before or after the test. It is the reason why the study of T-S strength optimization for RSW using Newton units. The Newton unit for T-S strength RSW optimization was used by [11], [12], [22]. Table 4 shows that the highest T-S strength was achieved in sample no. 2 of the third iteration of 5770.0 N, and a pull-out failure mode was observed. The optimum parameters are squeezing time in 18 cycles, welding current in 27 kA, welding time in 36 cycles, and hold time in 18 cycles. The highest T-S strength test chart is shown in
Figure **7**.

Table 4 T-S test results performed on the samples

Run No.	RSW Parameters				T-S strength (Newton)		Average T-S strength (Newton)	S/N RATIO		Failure Mode
	A	B	C	D	S1	S2		Exp.	Predict.*	
1	18	22	24	12	4504.78	2542.27	3523.53**	69.91	71.06	IF
2	18	25	30	15	5622.08	5751.05	5686.57	75.10	73.87	PO
3	18	27	36	18	5762.04	5770.48	5766.26	75.22	76.25	PO
4	20	22	30	18	4469.03	5059.37	4764.20	73.51	72.39	PO
5	20	25	36	12	5225.15	5346.49	5285.82	74.46	75.35	PO
6	20	27	24	15	5386.81	5611.92	5499.37	74.80	73.01	IF
7	22	22	36	15	5228.93	5480.43	5354.68	74.57	73.87	PO
8	22	25	24	18	3410.32	3016.28	3213.30	70.09	71.96	IF
9	22	27	30	12	5630.10	5280.69	5455.40	74.72	74.49	PO

1 cycle = 1/60 sec.; IF= Interfacial failure mode; PO= Pull-out failure mode **= existing parameter; Exp.= Experimental; Predict = predicted by regression analysis. The RSW Parameters: A for squeeze time, B for welding current, C for welding time, and D for holding time

.

Pull-out failure modes were observed for all samples by 30 and 36 welding time cycles factors. Meanwhile, all samples using the RSW parameter with a classification of 24 welding times cycles had an interface failure mode. The nugget area appears inconsistent, incomplete fusion, and it has an interface failure mode. The interface failure mode is observed in iterations no. 1, 6 and 8. It seems to be inconsistent fusion results in the welding nuggets zone.

Based on Table 4, the mean T-S strength is approximately 4950 N, with minimum and maximum values of 3213 N and 5766 N, respectively. The standard deviation of the T-S strength is 944 N, which indicates a wide spread of values from the mean value. It suggests considerable variability in the T-S strength data, possibly due to differences in input parameters that significantly affect the T-S strength. The obtained standard deviation value is consistent with the results from the S/N ratio and ANOVA analyses conducted in sections 3.3 and 3.4, indicating the significant effect of input parameters on T-S strength. These results are relevant to previous research on galvanized steel applications with thin material thickness, which reported a standard deviation between 230 N to 830 N [28]. On the other hand, for RSW research using stainless steel material, the standard deviation of T-S strength is higher, around 6963 N [29].

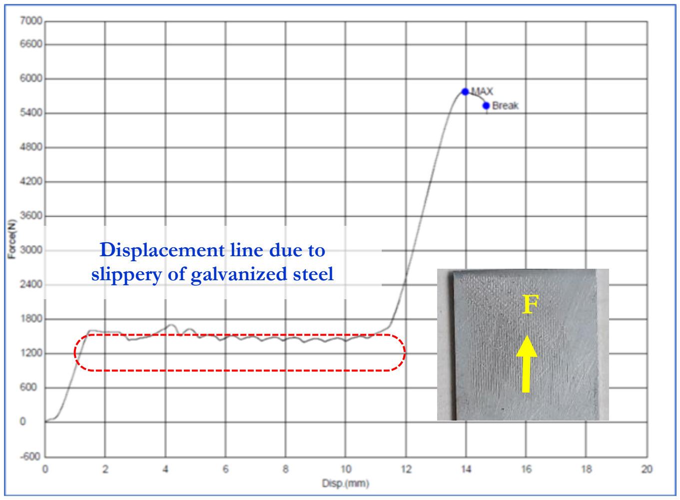


Figure 7 The tensile-shear test result for the S1-3 sample

3.3. Signal to Noise Ratio Analysis

The Taguchi experiment method used S/N Ratio to measure the sensitivity of the expected characteristics of variable inputs in a managed process [8]. Optimal conditions were achieved by defining the effect of each variable input for the response characteristics. The S/N ratio analysis aims to determine the right level of different inputs to achieve the best output. The value of the S/N ratio with the characteristics of 'larger is better was' calculated by applying Equation (3).

Table 5 shows that the highest and lowest S/N Ratio were observed in third and first iterations, respectively. It could see that the welding time input variable has the highest variable response followed by welding current, holding time, and squeeze time. They have delta values of 3.15, 2.25, 1.88, and 1.13 dB, respectively. The S/N Ratio with the 'larger is better' characteristic are listed in Table 5.

Table 5 Response table for S/N (Larger is better)

Level	A	B	C	D
1	73.41	72.66	71.60	73.03
2	74.26	73.22	74.44	74.82
3	73.13	74.91	74.75	72.94
Delta	1.13	2.25	3.15	1.88
Rank	4	2	1	3

The T-S strength test values were achieved from each experiment and analyzed by statistical software. The S/N ratio has developed a method to evaluate significant input factors. Table 5 showed that the higher the delta value for each parameter, the more essential that parameter is in the process. Therefore, essential parameters studied in this work include welding time, welding current, holding time, and squeeze time. They have a delta value of 3.15, 2.25, 1.88, and 1.13, respectively. It means the higher the S/N ratio will have, the better the response/outcome. The optimum T-S strength was achieved for squeeze time in 20 cycles, welding current in 27 kA, 36 cycles, and hold time in 15 cycles. The optimum response observed the results obtained by the following factors: squeeze time in level-2, the current density in level-3, welding time in level-3, and the holding time in level-2. The S/N Ratio analysis showed that welding time and electrical welding current are significant process factors. These process factors have directly proportional to the response. It means a higher level for both parameters will positively affect the T-S strength. Therefore, the parameters can be set at the optimal level and predicted by the Taguchi method. This result conforms with the authors previously studied [18] and other researchers such as[7], [9], [30], [31]. A summary of the S/N ratio analysis using statistical software is presented in Figure 8.

Regression analyses are developed for the S/N ratio using statistical software. The outputs variables are the S/N ratio and an average of T-S strength. In contrast, the predictors are A for squeeze time, B for welding current, C for welding time, and D for holding time. The experimental outcomes are used for modelling the response using Taguchi design [7], [25]. The linear regression equation of the fitted model for the S/N ratio and average of T-S strength are shown in Equation (6) and Equation (7). The results presented in Table 4.

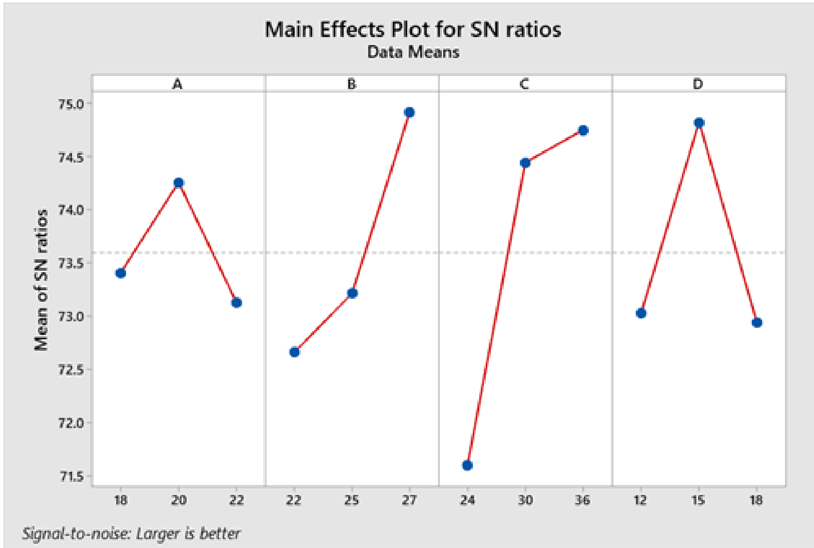


Figure 8 S /N ratio of T-S strength output of statistical software

$$Mean\ T - S_{pred.} = -1248 - 79A + 194B + 155.8C - 29\ D \tag{6}$$

$$SNR_{pred.} \quad = 56.8 - 0{,}071A + 0.42\ B + 0{,}263C - 0.016D \tag{7}$$

3.4. Analysis of Variant (ANOVA)

The primary objective of ANOVA is to evaluate the design parameters significantly affecting the variable response as the output variable [25]. ANOVA was conducted for all RSW statistically significant parameters at a 95% confidence level. The percent contribution shows the relative power to reduce the variant. The variance is obtained by dividing the sum of squares by the degree of freedom, which means that the percent contribution is directly proportional to the relative power of the parameter input. A parameter with a high percent contribution will significantly influence the achievement of the variable response. Table 6 provides that the percent contribution for welding time and electrical welding parameters is 51.4% and 23.5%, respectively. It means welding time and electrical welding current are the most influential factors in the response output. At the same time, holding time and squeeze time had less effect on the T-S strength. These results are consistent with previous studies conducted by [7], [8] and [27].

Table 6 ANOVA for T-S strength

Source	DF	SS	Variance	% Contribution
A	2	396,137	198,069	5.9
B	2	1,800,105	900,053	23.5*
C	2	3,456,993	1,728,497	51.4*
D	2	1,474,819	737,410	19.2
Total	8	7,128,055		100

Note: * Most significant parameters

3.5. Confirmation Test

The confirmation test is the last step in the first interaction of the experimental design process. The confirmation test validates the inference drawn during the analysis phase [25], [32]. It is carried out by conducting a test with a particular combination of the RSW parameters and levels beforehand evaluated. After determined the optimum conditions and predicted the output under these conditions, the experiment was conducted and achieved with the optimum levels of the RSW process factors. The experimental result determination using optimal RSW parameters and comparing the predicted average T-S strength with the existing average T-S strength using the optimal RSW process parameters are shown in Table 7. The average T-S strength in optimal RSW factors is higher in initial process factors. The average T-S strength in optimal RSW factors is higher in initial process factors. The optimal and initial factors code is A1; B1; C1; D1, and A3; B1; C3; D2, respectively. The confirmation test of the S/N ratio was validated by the linear regression method using Equation (6) and (7). The predicted and experimental S/N ratios improved by 7.3% and 7.6%, respectively. The improvement was observed and compared with the existing processes. Nevertheless, it has not been compared with other researchers because no RSW was applied with the same material. These results justify that the Taguchi method could provide information on the best RSW results regarding T-S strength results.

Table 8 Result of confirmation experiment

Description	Initial process factors		Optimal process factors		Improvement in S/N ratio (%)	
	Experimental	Predicted	Experimental	Predicted	Experimental	Predicted
Level	A_1; B_1; C_1; D_1		A_1; B_3; C_3; D_3			
T-S strength (Newton)*	3523.53	3993.20	5766.26	6178.80	7.6%	7.3%
S/N Ratio (dB)	69.91	71.06	75.22	76.25		

*) in average

4.0 CONCLUSIONS

The success of setting appropriate RSW parameters for joining different materials of low carbon steel (SPCC-SD, JIS G-3141) and galvanized (SGCC, JIS G-3302) sheet materials involving a pneumatic force system (PFS) can be summarised as follows: Based on the S/N ratio analysis, welding time and electrical welding current significantly influence T-S strength, followed by holding time and squeeze time. The highest average T-S strength was achieved in run number 3, with a value of 5766.26 N. In this study, the Taguchi method suggests using squeeze time at the 2nd level, welding current at the 3rd level, welding time at the 3rd level, and holding time at the 2nd level. The ANOVA results showed that welding time and electrical welding current were significant factors in the response, contributing about 75% of the total. The pull-out failure mode was achieved after a minimum of 30 cycles of welding time.

The experimental results confirmed the validity of the Taguchi method for enhancing the RSW optimizing and performance of their factors in RSW operations. Further research will evaluate and conduct the zinc layer thickness's effect on T-S strength.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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