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ANALYSIS OF PROCESS PARAMETERS FOR RESISTANCE SPOT WELDING ON GALVANIZED STEEL USING TAGUCHI METHOD

Resistance spot welding (RSW) involved two or more sheets of metal that are welded together with or without filler materials. This paper discussed the optimization of RSW process parameters that were varied on galvanized steel below 6 kA by using Taguchi method. Galvanized steel can be more difficult to spot weld than any other uncoated metal due to the tendency of zinc coating alloying with electrodes. The three process parameters are welding current, welding time and holding time. The type of OA used in this study was L9. Subsequently, tensile and Vickers microhardness tests were conducted on the sample. Results from these tests were used to calculate the S/N ratio, ANOVA and confirmation test. The optimal parameters value and percentage of contributing factors to the welding can be identified. It will help to produce high-quality weld joints.

Keywords: Spot Welding; Taguchi Methods; Galvanized Steel; S/N ratio; Tensile Strength

1. Introduction

Resistance spot welding (RSW) was presented to the world since a hundred years ago. It is known as sheet metal joining process that is simplest and most widely used method. In RSW, coalescence of metal is produced by the heat generated at the joint of contact resistance to the flow of electric current [1]. RSW was extensively used in aerospace and automation industry due to various reasons such as low cost, high speed, simple mechanism and adaptability for automation [2]. Some of the parameters involved in this process are current, time, electrode force, contact resistance, surface condition, thickness of the sheet materials and types of electrode used.

Researches shown that the joint quality of any welding process, not only RSW is directly affected by various input parameters [3]. Taguchi Method proposed by Dr. Genichi Taguchi is one of the important statistical tools of total quality management for designing high quality systems at reduced cost. Taguchi Method comprises three stages which are system design, parameter design and tolerance design to produce a high product quality.

Researchers have used Taguchi method for various process applications to determine optimum parameters. An experiment on 7075-T6 aluminium alloy sheets was conducted to determine optimal welding conditions by tensile-shear tests and analyse it by Taguchi Method. At the same time [4], carried out Taguchi method for the selection of process parameter of spot welded steel sheets and prove that Taguchi method are insensitive to the variation of environmental conditions and other noise factors. Whereas, a research on process optimisation of low carbon steel by Taguchi Methods was conducted and from the results of ANOVA, it has been found that the most affecting parameter for tensile shear strength is welding current carrying 78.815% and 59.63% for 0.8 mm and 1 mm thickness respectively [2]. Another research on Taguchi Method analysis on low carbon cold rolled mild steel sheets shows that welding current, hold time and pressure is 61%, 28.7% and 4% respectively towards tensile strength [5]. While other research aimed to focus on dissimilar galvanized steel material [6] and high-strength low-alloy steel [7] when RSW is applied. RSW on galvanized steel provides a unique challenge because the material has a zinc coating. Zinc melts at a lower temperature than the steel being spot welded.

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In order to produce a weld join with high strength, the process parameters must be well adjusted. Hence, Taguchi method has been used for this project.

There are eight steps that needs to be followed in Taguchi methodology [8]. First step is that identification of the main function, side effects, and failure mode. Secondly, identify the noise factors, testing conditions, and quality characteristics. Thirdly, identify the objective function to be optimized. Fourthly, identify the control factors and their levels. Next, select the orthogonal array matrix experiment. Then, conduct the matrix experiment. Later on, analyze the data, predict the optimum levels and performance. Finally, perform the verification experiment and plan the future action.

Thus, this paper is very crucial in determining and discussing the optimization of RSW process parameters that were varied on galvanized steel below 6 kA by using Taguchi method.

2. Materials and methods

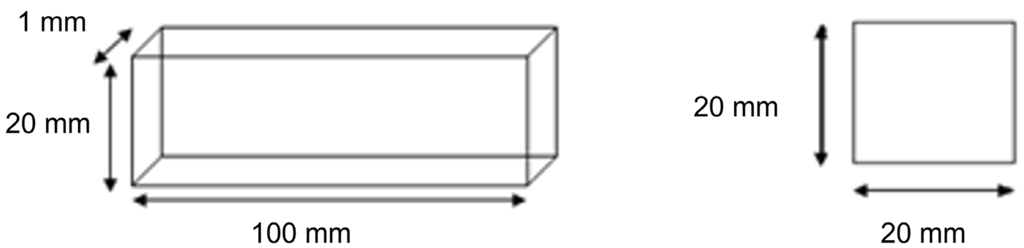
The raw material chosen for this project is galvanized steel. A batch of galvanized steel sheets was cut into a certain dimension prior to spot weld. First and foremost, the specimens were cut according to the American Welding Society (AWS) dimension. The standard dimension for each plate to be spot welded is 100 mm in length, 20 mm in width and the overlap for the lap joint is of 20 mm. The thickness of each plate is 1 mm. The dimension was cut as shown in Fig. 1(a) using a shearing machine for all the testing. Whereas, a dimension of 20 mm × 20 mm × 1 mm as shown in Fig. 1(b) was cut specifically for chemical composition using arc spark spectrometer testing. There are many parameters that can control the weld quality. The main three parameters that have been varied in this project were welding current, welding time and holding time. TABLE 1 shows the parameters and its value that have been used to conduct the experiment.

After the spot welding is conducted, the nugget diameter is measured by using the vernier caliper. Nugget is referring to a pool of molten metal that quickly cools and solidifies into a round joint after the welding processed the overlapping pieces of metal at small points by application of pressure and electric current. The nugget measurement is crucial and it is a standard in the welding world since it is useful to determine whether the welding process is experiencing any deformity in order to determine the strength of the weld itself.

Then, the tensile test was conducted as it provides qualitative information such as tensile strength, yield strength and ductility. The static tensile test samples were prepared according to ANSI/AWS/SAE/D8.9-97 standard. Force was continuously applied with a speed of 2 mm/min until the specimen fractures. Later, the strength value can be calculated and types of failure mode was recorded from the failed samples. In term of hardness, Vickers microhardness testing was used more than any other hardness test largely due to the required calculations being independent of the size of the indenter. The applied load for this test is 9.807 N with a dwell time of 10 seconds.

Taguchi approach

There are four steps involved, namely selection of suitable orthogonal array (OA), Signal-to-noise (S/N) ratio, analysis of variance (ANOVA) and confirmation test. Type of OA choosen in this project is L9, which has three parameters with three levels. There is no noise factor identified. S/N ratio was calculated by using the formula as in Eq. (1). Then, the mean graph and S/N graph were plotted using software Minitab 17. From here the optimum parameter values can be obtained. ANOVA also will be calculated using Minitab 17. Final step is the confirmation step, the repetition of the predicted test result to validate the conclusion made by the previous steps. The S/N ratio of the predicted result is actually the optimum value of parameters



(a) (b)

Fig. 1. (a) RSW single plate dimension (b) AES sample dimension

TABLE 1

Process Parameters with their values at three levels

Thickness of metal sheet	Symbol	Process Parameter	Unit	Level 1	Level 2	Level 3
1.0 mm	A	Welding Current	kA	4	5	6
	B	Welding time	sec	2	5	10
	C	Hold Time	sec	5	10	20

that was calculated using Eq. (2). This result was then compared with the experimental result by running an experiment using the optimum parameters value.

$$\eta = -10 \log_{10}\left(\sum \frac{\frac{1}{y^2}}{n}\right) \quad (1)$$

Where n is the number of tests, and y is the experimental value of the ith quality characteristic, and η is the S/N ratio [2].

$$\acute{\eta} = n + \sum_{i=0}^{n}\left(\eta i - \eta m\right) \quad (2)$$

where ηm is the total mean of S/N ratios, ηi is the mean of S/N ratio at level, and n is the number of main welding parameters that significantly affect the performance [2].

3. Results and discussion

3.1. Chemical composition analysis

TABLE 2 shows the result of chemical composition of galvanized steel obtained by conducting arc spark spectrometer testing. It has been found that the steel being used is of standard AISI 1023. A carbon content of 0.152 wt% shows the steel is made up of low-carbon steel. The amount of carbon present in the material may affect the welding that the joint becomes hard and brittle.

TABLE 2

Chemical composition of investigated galvanized steel by arc spark spectrometer testing

Element	Composition (wt%)
Fe	98.700
C	0.152
Si	0.017
Mn	0.214
P	0.017
S	0.029
Cr	0.025
Mo	0.124
Ni	0.018
Cu	0.014
Al	0.395

3.2. Nugget diameter analysis

The nugget diameter size is the key physical attribute that controls spot welded materials mechanical properties and failure mode. For all the experiment number 1 until 9, the nugget size has reached the required minimum nugget diameter size. It should be more than 3.5 times to 4 times to its thickness [9]. Therefore, the galvanized steel sheet used in this experiment has more than 3.5 mm of nugget diameter size where the thickness of the plate is 1mm. Typically, the measured size of weld nugget is between 4 mm to 8 mm for all the conducted experiments. Besides, size of the nugget diameter affects the type of failure that occurs during tensile testing. The two types of failure that observed in this project are interfacial failure and partial pull-out with tearing. Full pull-out failure does not occur mainly because the current applied in this project is not sufficient enough to cause this failure. Interfacial mode (nugget fracture) is the dominant failure mode for small diameter spot welds and nugget pullout mode (sheet fracture) is dominant for large diameter spot welds [9].

Increasing nugget diameter will leads to failure mode of in the form nugget pull-out. Whereas, smaller nugget diameter faces interfacial failure with tearing as can be observed during experiment number 1, 2, 3 and 7. During the tensile testing, the steel plates with current values of 5 and 6 kA experienced severe tearing with pull-out. The pull-out failure with tearing is to be initiated near the middle of the nugget circumference in the galvanised steel sheet and then propagated by necking along the nugget circumference until the upper sheet is torn off. Apart from this, the interfacial failure can be related to the lower hardness of the weld nugget which provides lower resistance to crack propagation. Its small nugget size experiences much higher shear stress at the nugget interface [9]. TABLE 3 shows nugget diameter relative to the mode of failure. The type of failure mode occurred during tensile testing can be observed in Fig. 2.

TABLE 3

Nugget diameter with respect to failure mode

Experiment	Current (kA)	Welding Time (s)	Holding Time (s)	Nugget Diameter (mm)	Failure Mode
1	4	2	5	±5.475	Interfacial failure
2	4	5	10	±5.645	Interfacial failure
3	4	10	20	±5.965	Interfacial failure
4	5	2	10	±5.200	Partial pull-out with tearing
5	5	5	20	±6.550	Partial pull-out with tearing
6	5	10	5	±6.600	Partial pull-out with tearing
7	6	2	20	±5.650	Interfacial failure
8	6	5	5	±7.850	Partial pull-out with tearing
9	6	10	10	±6.475	Partial pull-out with tearing

As welding time and holding time is increasing from the value of 2, 5, 10 s and 5, 10, 20 s respectively with a constant current value of 4 kA, the nugget diameter is increasing as well. Although the applied current value is the lowest among the three levels, the increasing welding time and holding time significantly affects the heat flow to the joint and therefore increasing the nugget diameter.

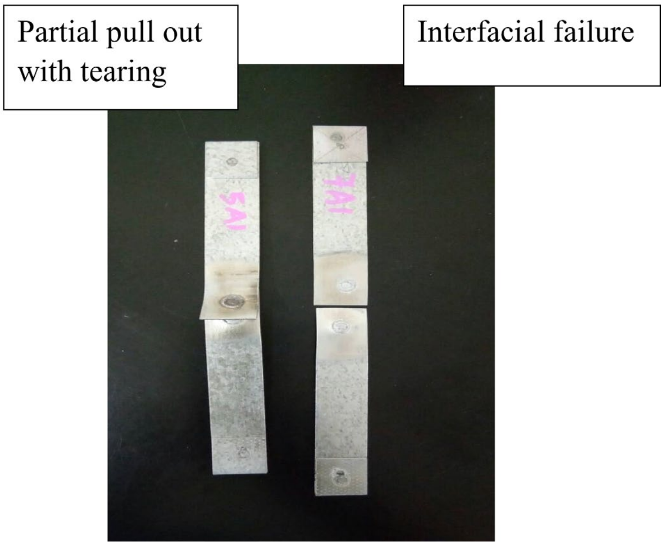


Fig. 2. Types of failure mode

Whereas, when the third level of welding time of 2 s and level two holding time of 10 s used for a current of 5 kA, the nugget diameter is found to be the lowest which is about 5.2 mm. This is partly due to the very short welding time that makes the current flow very shortly to the plates. Increasing the welding time to 5 s and holding time to 20 s at 5 kA current further increases the nugget diameter size. It is recommended to use a higher holding time during spot welding of galvanised steel as it has a higher strength than low carbon steels. Nugget diameter reaches a value of 6.6 mm in this 5 kA current when a higher welding time of 10 seconds and the shortest holding time of 5 s were used. Highest nugget diameter was achieved among all the experiments when third level current of 6 kA, welding time of 5 s and holding time of 5 s were used. Increasing current means more heat has been supplied to the welding plates that increase fusion zone (FZ) size and fusion penetration depth [10].

3.3. Effect of welding parameters on tensile strength and hardness

Both results of tensile strength and hardness values were plotted in Fig. 4 and Fig. 5. From Fig. 4, the highest average tensile strength of 512.987 MPa was observed at experiment number 4 when the current has a value of 5 kA, welding time of

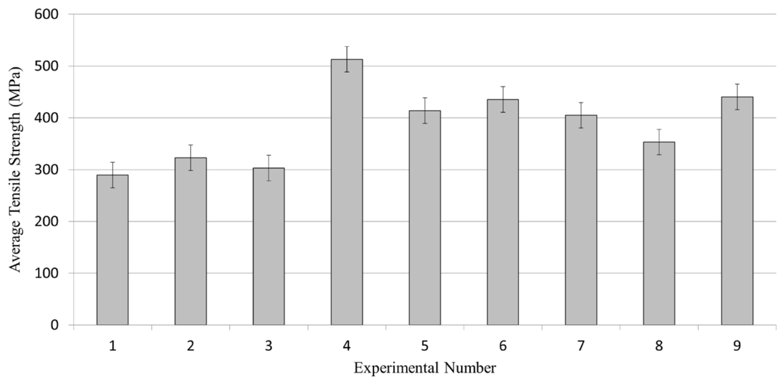


Fig. 4. Average tensile strength (MPa) based on the experimental number

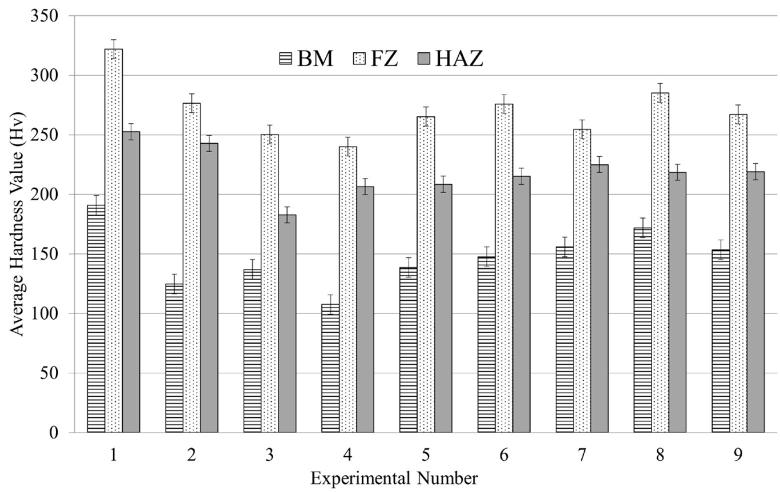


Fig. 5. Bar graph of average hardness value of each zone based on experimental number

2 s and holding time of 10 s. The second highest average tensile strength of 440.439 MPa was observed at experiment number 9 with a current value of 6 kA, welding time of 10 s and holding time of 10 s followed by 435.513 MPa at experiment number 6 with a current of 5 kA, welding time of 10 s and holding time of 5 s. The lowest tensile strength was observed at experiment number 1 with a current value of 4 kA, welding time of 2 s and holding time of 5 s. Lowest current value with shorter welding time and holding time provides less heat input to the joint at where the coalescence of metals is not strong enough. High current, short welding time and high holding time are expected to yield a high tensile strength. It is known fact that the heat input in the resistance spot welded joints increases with increase in the weld current [11]. However, the weld current must be sufficiently low to prevent excessive heating of the electrode and to prevent molten metal expelled from the weld zone [12].

Fig. 5 shows the microhardness distribution where it is almost the same for all the conducted experiments. The weld nugget or FZ has higher values compared to base metal (BM) and heat affected zone (HAZ). Basically, the hardness value for all the experiments at FZ is within the range of 240.1 HV to 322 HV. Whereas, the hardness value at HAZ and BM are within the range of 182.8 HV to 252.6 HV and 124.8 HV to 190.9 HV respectively. The highest hardness value at FZ was observed in the experiment number 1 that has a hardness value of 322 HV followed by HAZ of 252.6 HV and BM of 190.0 HV. The hardness ratio of FZ to failure location is around 1.7. This highest value at FZ is similar to an experiment conducted by [9] that has an average hardness value of 335 HV and a hardness value of the BM of 140 HV. The highest hardness of FZ is largely due to a martensitic structure is expected at the FZ relative to the BM [13]. Besides that, hardness of the metal is usually an indication of its ductility although ductility of resistance weld is determined by these factors which are composition of BM and effect of high temperature as well as subsequent rapid cooling on the composition [11].

3.4. Optimization by using taguchi approach

For Taguchi approach, L9 orthogonal array (OA) design was selected. Taguchi uses the S/N ratio to measure the quality characteristic deviating from the desired value. The quality characteristics studied are tensile strength and hardness values. Since, high tensile strength and hardness values are desired, higher-the-better S/N ratio formula was used as shown in Eq. (1). The S/N ratio for each level is summarised in c 4. As shown response curve in Fig. 3 of S/N ratio with respect to tensile strength indicates the welding current to be the most significant parameter that controls the weld tensile strength. Whereas, welding time and holding time are comparatively less significant in this regard.

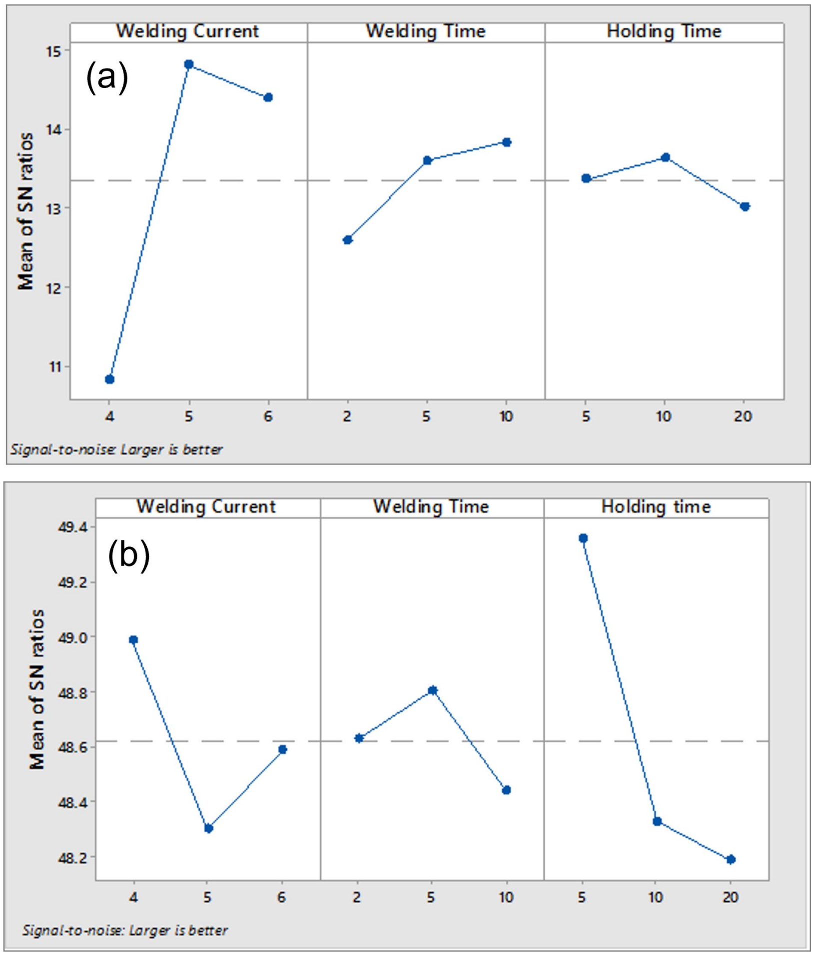


Fig. 3. S/N ratio graphs for (a) tensile strength and (b) hardness value

TABLE 4

S/N ratios for the tensile strength and hardness measurements

Experiment	Current (A)	Welding Time (s)	Holding Time (s)	Tensile Strength (kN)	S/N ratio (dB)	Hardness Value (Hv)	S/N ratio (dB)
1	4	2	5	3.17	10.0	322.00	50.2
2	4	5	10	3.65	11.2	276.50	48.8
3	4	10	20	3.62	11.2	250.25	48.0
4	5	2	10	5.34	14.6	240.10	47.6
5	5	5	20	5.42	14.7	265.30	48.5
6	5	10	5	5.75	15.2	275.80	48.8
7	6	2	20	4.57	13.2	254.60	48.1
8	6	5	5	5.54	14.9	285.20	49.1
9	6	10	10	5.70	15.1	267.20	48.5

The optimum level of current of tensile strength is found to be at level 2 with a S/N ratio of 14.81 dB, followed by level 3 welding time of 13.83 dB and then level 2 holding time of 13.64 dB. On the other hand, the response curve of S/N ratio with respect to hardness value shows that the holding time to be the most significant parameter that controls the hardness of spot welded plate followed by welding current and welding time. The optimum level of holding time is at level 1 with a mean S/N ratio of 49.37 dB then, level 1 of welding current with a mean S/N ratio of 49.00 dB and level 2 of welding time of 48.80 dB. Response table for tensile strength and for hardness value was tabulated in TABLE 5 and TABLE 6.

According to ANOVA, the most effective parameters with respect to tensile strength is welding current, welding time and holding time. Based on TABLE 7, the highest percentage of contribution is from welding current with a percentage of 86.85%, followed by welding time with 7.59% and holding time with 1.61%. This indirectly shows that the decision on selecting value of current is a critical step as it a factor that effect significantly the tensile strength of a spot welded material. Whereas, for hardness value on TABLE 8, holding time is having highest contribution of 46.16%, followed by welding current and welding time having contributions of 39.07% and 11.58% respectively.

TABLE 5

Response table for S/N ratio for tensile strength

Process Parameter	Units	S/N Ratio (dB)			Total Mean S/N (dB)	Max-Min	Rank
		Level 1	Level 2	Level 3			
Welding Current	A	10.81	14.81*	14.40	13.34	4.00	1
Welding Time	Sec	12.59	13.60	13.83*		1.24	2
Holding Time	Sec	13.36	13.64*	13.02		0.62	3

Note: * Optimum level

TABLE 6

Response table for S/N ratio for hardness

Process Parameter	Units	S/N Ratio (dB)			Total Mean S/N (dB)	Max-Min	Rank
		Level 1	Level 2	Level 3			
Welding Current	A	49.00*	48.30	48.57	48.62	0.70	2
Welding Time	Sec	48.63	48.80*	48.43		0.37	3
Holding Time	Sec	49.37*	48.30	48.20		1.17	1

Note: * Optimum level

TABLE 7

Results of ANOVA for tensile strength

Process Parameters	Degree of Freedom	Sum of square	Variance	F-ratio	Contribution Percentage (%)
Current	2	29.3810	14.6905	108.94	86.85
Weld Time	2	2.5659	1.2830	9.514	7.59
Hold Time	2	0.5430	0.2715	2.0133	1.61
Error	2	0.2697	0.13485	—	3.95
Total	8	32.7596	—	—	100

TABLE 8

Results of ANOVA for hardness value

Process Parameters	Degree of Freedom	Sum of square	Variance	F-ratio	Contribution Percentage (%)
Current	2	0.7479	0.3740	0.7206	46.16
Weld Time	2	0.2058	0.1029	0.1983	11.58
Hold Time	2	2.5239	1.2620	2.4315	39.07
Error	2	1.038	0.519	—	3.19
Total	8	4.5156	—	—-	100

TABLE 9

The confirmation results of tensile strength (S/N ratios for the optimal parameter)

	Initial process parameters	Optimal process parameters		Improvement in S/N ratio (dB)
		Predicted	Experiment	
Level	$A_1B_1C_2$	$A_2B_3C_2$	$A_2B_3C_2$	
Tensile Strength (kN)	3.65	6.03	6.14	2.49
S/N ratio (dB)	11.2	15.6	15.8	4.6

TABLE 10

The confirmation results of hardness value (S/N ratios for the optimal parameters)

	Initial process parameters	Optimal process parameters		Improvement in S/N ratio (dB)
		Predicted	Experiment	
Level	$A_1B_3C_3$	$A_1B_2C_1$	$A_2B_3C_2$	
Tensile Strength (kN)	250.25	313.7	320.0	69.75
S/N ratio (dB)	48.0	49.93	50.1	2.1

As shown in TABLE 9, the improvement in S/N ratio of tensile strength is about 4.6 dB more than the initial process parameters. Whereas, the improvement in S/N ratio for hardness value is shown in TABLE 10 which is about 2.1 dB more than the initial process parameters. Basically, the confirmation test has proved that it is possible to increase the tensile strength and hardness by using the proposed statistical method.

4. Conclusions

The galvanized material is used to coat metal pieces to reduce the risk of rust. However, the coating material contains zinc which makes it difficult to spot weld, nonetheless, it is possible and can be done. The complicated behavior of this process has been optimized their RSW process parameters to get good quality weld.

i) The optimum value of parameters for the tensile test analyzed by using Taguchi method is welding current of 5 kA, welding time of 10 s and holding time of 10 s.
ii) The optimum value of parameters for the hardness test analyzed by Taguchi method is welding current of 4 kA, welding time of 5 s and holding time of 5 s.
iii) Based on the nugget diameter, there are two types of failure modes occur which are interfacial failure and partial pull-out with tearing. Interfacial failure occurs when the nugget diameter is smaller (less than 6.0 mm) whereas, pull-out failure occurs when the nugget diameter is larger (more than 6.0 mm).

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