Proceedings of the 4th International Congress APMAS2014, April 24-27, 2014, Fethiye, Turkey

Application of Taguchi Method to Investigate the Effect of Nucleus Diameter on Mechanical Properties of Automotive Sheets in Electrical Resistance Spot Welding

Ö. Savaş*
Yildiz Technical University, Naval Architecture and Maritime Faculty, 34349, İstanbul, Turkey

In this study, the effects of nucleus diameter on tensile-peel strength in electrical resistance spot welding were investigated. Taguchi design approach has been employed to the experimental planning, the $L_{27}(3^{13})$ orthogonal array. The larger-the-better and the nominal-the-best response criteria were selected to obtain the optimum conditions for nucleus diameter and tensile-peel strength, respectively. In addition, the effects of five parameters, electrode pressure, clamping time, welding current, welding time, and holding time, were examined in this way. Results showed that the tensile-peel strength was related with nucleus diameter, and that welding current and welding time were the most effective parameters for improvement of the strength of weld joints.

DOI: 10.12693/APhysPolA.127.921
PACS: 81.20.Vj

1. Introduction

Electrical Resistance Spot Welding (ERSW) is a joining process, based on the electrical resistance of the components and generation of the heat when a current is passed through. It is used in production of automobiles, truck cabins and rail vehicles [1]. Galvanized steel sheets, having good welding ability and corrosion resistance, are widely used in automobile bodies [2].

The mechanical performance of the welding joints of ERSW is mainly determined by nucleus geometry such as nucleus diameter (d_n), height (h_n) and size ratio (h_n/h_d). Major factors on nugget geometry and mechanical properties are, in particular, welding current, electrode pressure, welding time, clamping time, holding time, electrode diameter, etc. [3, 4].

Luo Yi et al. [5] predicted nugget diameter and tensile shear (T-S) strength of weld joints by developing a mathematical model. They used experimental study on commercially galvanized steel sheet widely used in car fabrication. They selected input parameters as preheating current, welding current, welding time and welding pressure. The results showed that a more accurate prediction is obtained on nugget size and mechanical properties of weld joints by using the optimized models.

Thakur et al. [6] have studied optimization of tensile shear strength of RSW (resistance spot welding) for galvanized steel by using Taguchi method. They reported that the highly effective parameters on tensile strength were identified as welding current and welding time, whereas electrode force and electrode diameter were less effective factors. The results also indicated that it is possible to increase tensile strength of welt joints significantly by optimization of the parameters by Taguchi technique.

Eşme [7] has studied optimization of welding parameters on the tensile shear strength in the (RSW) process by using Taguchi experimental approach. The results showed that the highly effective parameters on T-S strength were determined as welding current and electrode force. In this study, Taguchi approach was effectively used for optimization of welding parameters in RSW process.

In the present work, Taguchi design approach has been employed to examine the effects of nucleus diameter on T-S strength in electrical resistance spot welding. Additionally, this technique is used to obtain an optimal experimental prescription to determine the final T-S strength of the welding joints.

2. Experimental work

Galvanized DP 600 steel sheet was used in the experiments. Its composition is given in Table I. The thickness of the steel sheet and the galvanized layer are 1.2 mm and 7 μm, respectively [8, 9].

Chemical composition of workpiece materials. TABLE I

C	Si	Mn	Cr	Al	Cu	Mo	balance
0.054	0.158	1.840	0.097	0.027	0.021	0.155	97.647

An ERSW machine, controlled current and timer, was used in experimental works. Workpiece materials were welded by the machine with changing electrode force, welding current, holding time and cooling water flow rate during experiments, with fixed electrode diameter of 15 mm sphere. After welding workpieces, in order to determine the joints strengths, all trials of T-P tests were

*e-mail: osavas@yildiz.edu.tr

exposed to a 50 kN load on computerized universal testing machine. The tensile speed was kept constant at a crosshead of 10 mm/min. The nucleus diameters were measured by means of an optical microscope as seen in Fig. 1.

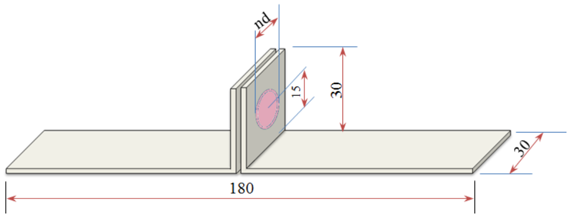

Fig. 1. The sizes of T-P test specimens [3] .

The present experiments were designed to apply the Taguchi's methods to establish the effects of nucleus diameter on T-P strength. Taguchi's method has been used for a wide range of industrial applications worldwide since it is a simple, efficient and systematic approach to optimize designs for performance, quality and cost [10, 11]. Five parameters (factors), designated for this study, and their levels are given in Table II.

TABLE II

Process parameters and their levels.

Factors	Col.	Lev.1	Lev.2	Lev.3
Electrode pressure [kN]	A	3	4	5
Clamping time, period [1/50 s]	B	10	15	20
Welding current [kA]	C	6	10	14
Welding time, period [1/50 s]	D	10	15	20
Holding time, period [1/50 s]	E	10	15	20

Tests were carried out consecutively from trial 1 to trial 27 as seen in Table III. Welding data, electrode pressure, clamping time, welding current, welding time, and holding time, were obtained from the experimental layout. At the end of each trial, the average T-P strength and the nugget size ratio were measured. Signal-to-noise (S/N) ratio was calculated by using the values of the measurements. The previous studies have reported that an optimal nucleus diameter is needed to obtain the maximum strength of welding joints [2, 3, 7]. So, the nominal-the-better quality characteristics, represented by Eq. 1, were considered.

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

The larger-the-better quality characteristics was considered, since the performance was measured in terms of the T-P strength, a property which is generally expected to be as high as possible, as represented by Eq. 2.

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

Here n is the number of measurements in a trial and y is the value of a measurement in a trial. Analysis of variance statistical method (ANOVA) which employs Eq. 3–7 [10, 11], was prepared to determine the effect and the optimal combination of the parameters by using the signal-to-noise (S/N) ratio values.

TABLE III

$L_{27}(5^3)$ orthogonal design array, measured nucleus diameter (d_n), T-P strength and S/N ratios.

	Factor level					d_n [mm]		T-P str. [MPa]	
Exp. No	A	B	C	D	E	Mean	S/N ratio	Mean	S/N ratio
1	1	1	1	3	2	8.50	1.22	56.25	3.50
2	1	1	2	3	2	9.85	1.03	50.63	3.41
3	1	1	3	3	2	10.25	1.30	39.11	3.18
4	1	2	1	1	3	6.35	0.65	53.59	3.46
5	1	2	2	1	3	6.65	0.88	49.22	3.38
6	1	2	3	1	3	10.95	0.96	25.31	2.81
7	1	3	1	2	1	7.65	1.14	46.04	3.33
8	1	3	2	2	1	7.70	1.11	49.32	3.39
9	1	3	3	2	1	10.50	0.91	42.34	3.25
10	2	1	1	1	1	6.10	0.65	44.43	3.30
11	2	1	2	1	1	8.00	1.30	47.19	3.35
12	2	1	3	1	1	10.50	1.13	51.67	3.43
13	2	2	1	2	2	8.25	1.62	48.28	3.37
14	2	2	2	2	2	7.85	1.50	55.01	3.48
15	2	2	3	2	2	11.25	0.80	42.76	3.26
16	2	3	1	3	3	8.75	2.09	47.86	3.36
17	2	3	2	3	3	8.50	2.00	57.50	3.52
18	2	3	3	3	3	12.50	0.47	56.56	3.51
19	3	1	1	2	3	7.45	1.13	49.32	3.39
20	3	1	2	2	3	9.50	1.45	41.51	3.24
21	3	1	3	2	3	11.45	0.76	35.00	3.09
22	3	2	1	3	1	7.25	0.84	50.26	3.40
23	3	2	2	3	1	9.25	2.29	47.14	3.35
24	3	2	3	3	1	9.75	1.68	47.08	3.35
25	3	3	1	1	2	550	0.53	27.00	2.86
26	3	3	2	1	2	8.55	1.77	53.13	3.45
27	3	3	3	1	2	10.80	0.97	34.00	3.06

$$SS_T = \left[\sum_{i=1}^{N}(S/N)i^2\right] - \frac{T^2}{N}. \quad (3)$$

$$SS_A = \left[\sum_{i=1}^{K_A}\left(\frac{Ai^2}{N_{A_i}}\right)\right] - \frac{T^2}{N}. \quad (4)$$

$$\nu_{\text{Total}} = N - 1. \quad (5)$$

$$V_{\text{Factor}} = \frac{SS_{\text{Factor}}}{\nu_{\text{Factor}}}. \quad (6)$$

$$F_{\text{Factor}} = \frac{V_{\text{Factor}}}{V_{\text{Error}}} \quad (7)$$

Here, SS_T is the sum of squares due to total variation, N is the total number of experiments, SS_A represents the sum of squares due to factor A, K_A is the number of levels for factor A. A_i stands for the sum of the total i-th level of the factor A, n_{A_i} is the number of samples for i-th level of factor A. T is the sum of total (S/N)

ratio of the experiments, ν_{Total} is the degrees of freedom, V_{Factor} is the variance of the factors, SS_{Factor} represents the sum of squares of the factor and F_{Factor} is the F ratio of the factor.

3. Results and discussion

Table III shows the average value of the nucleus diameter and T-P strength measured for each welding sample. Their S/N ratios are also presented in the adjacent columns, respectively. As seen from Table III, the nucleus diameters have varied between 6.1 mm and 12.50 mm. The highest nucleus diameter was obtained from trial 18, whereas the lowest value was measured from trial 4. As seen (Table III), the T-P strength has varied between 25.31 MPa and 57.50 MPa.

TABLE IV

Analysis of variance (ANOVA) for nucleus diameter. SS – sum of squares, ν – degrees of freedom, V - variance, F – factor.

	Factors	SS	ν	V	F
A	Electrode pressure	0.39	2	0.19	1.12
B	[a]Clamping time	0.10	2	0.05	0.28
C	[b]Welding current	1.17	2	0.59	3.41
D	[b]Welding times	0.94	2	0.47	2.72
E	[a]Holding times	0.02	2	0.01	0.07
	Total	2.50	6	0.42	
	Error (e)	3.44	20	0.17	

[a] pooling, [b] At least 90% confidence (2.59)

Table IV and Table V show the analysis of variance tables (ANOVA) which were prepared using Eq. 3–7. According to the ANOVA for the nucleus diameter, the high contribution and variance of factors C and D indicate that the welding current and welding times are significant with at least 90% confidence. The electrode pressure (A) is the effective factor. Clamping time (B), holding times (E) have less influence on the diameter of the nucleus. Similarly, according to the ANOVA for T-P strength, the high contribution and variance of factors C and D indicate that the welding current and the welding times are significant with at least 90% confidence, whereas, the clamping time (B) and holding time (E) have less significant influence on the T-P strength. In order to demonstrate the effect of the parameters C, D and A, the factor associated with B and E is pooled (insignificant factors, ignored due to their low significance). Table IV and V show that welding current and welding times are significant, whereas electrode pressure, clamping time and holding times are less effective parameters when both nucleus diameter and T-P strength of the weld is considered. The results are similar to those obtained by Aslanlar et al. [2, 3, 12], who reported that welding current and welding time were significant factors influencing the T-P strength of weld joints in the ERSW.

In order to obtain an optimal combination for the nucleus diameter (d_n) and T-S strength, S/N response graph derived by using the average S/N values of each

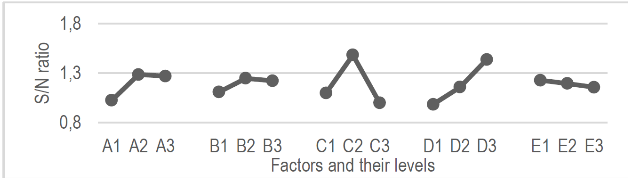

Fig. 2. Response graph for the nucleus diameter (d_n).

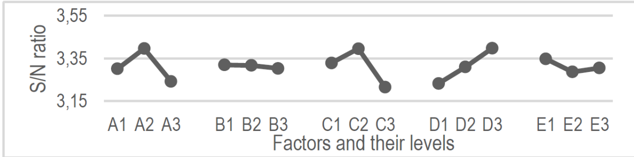

Fig. 3. Response graph for the tensile-peel strength.

factor level is given in Fig. 2 and Fig. 3, respectively. The figures reveal the optimal combination of experimental parameters and the corresponding values of each factor. Figure 2 indicates A_2, B_2, C_2, D_3, E_1 are the optimal combinations for obtaining nominal nucleus diameters (d_n). On the other hand, Fig. 3 shows that optimal combinations, A_2, B_1, C_2, D_3 and E_1, were required for obtaining high T-S strength of the weld joints. Considering influential factors, A_2, C_2 and D_3, both nominal nucleus diameter and higher T-S strength of weld joints can be obtained with the same combinations as seen in Fig. 2 and 3. These results indicate that the strength of welding is related with the diameter of the nucleus. In addition, a nominal nucleus diameter is required to obtain strength of weld joints. These results are in good agreement with previously reported results [3, 6, 7].

According to the Taguchi approach, to compare the results with the expected conditions, it is necessary to perform an experiment for verification. In this study, the less influencing factors (pooling) on the nucleus diameter and the T-S strength were ignored.

Results from the verification experiment. TABLE VI

Description	T-P strength [MPa]	Nucleus diameter [mm]
Optimum condition	$A_2B_1C_2D_3E_1$	$A_2B_2C_2D_3E_1$
Pooled factors	B and E	B and E
Estimated average S/N ratio	3.56	1.82
Estimated S/N ratio range	$3.48 < \mu < 3.64$	$1.61 < \mu < 2.03$
Exp. average S/N ratio	3.51	2.00
Estimated average value	60	8.10
Estimated value range	$55 < \mu < 66$	$8.02 < \mu < 9.48$
Exp. average value	57	8.50

It has been estimated that at the optimum condition, the strength should be between 55 MPa and 66 MPa as seen Table VI. Since the suggested optimum conditions (A_2, C_2, and D_3) have already been included in the original set of trials (see Table III), there was no need to carry out an extra validation trial. According to the results obtained from trial 17, the average of the strength was 57.50 MPa, which lays well within the calculated strength range. Similarly, the optimum condition for the nucleus diameter has been estimated to be between 8.02 mm and 9.48 mm. According to the result obtained from the trial 17, the nucleus diameter was 8.50 mm, which also remains within the calculated nucleus diameter range. This validates the confidence of the current study.

4. Conclusions

In this study, the effects of nucleus diameter on tensile-peel strength in electrical resistance spot welding were examined. Taguchi's technique has been used for the experimental planning. In the light of the obtained results, the present study can be concluded as follows:

- The most influential parameters on tensile-peel strength and the nucleus diameter were the welding current, welding time and electrode pressure. Whereas, clamping time and holding time were less effective factors. As the heat needed for resistance welding processes is produced by welding current and its duration under electrode pressure the present results stand logical and are also in good agreement with previous studies.

- Results also indicate that there is a relationship with the welding strength and the nucleus diameter. A nominal nucleus diameter which is 8.30 mm is required to obtain the highest strength of a weld joint. After extending this critical diameter, the strength decreases, because the electrodes sink into the material as a result of increasing welding current and duration and also the pressure applied to the electrodes. At the nominal nucleus diameter, the highest average tensile-peel strength of 57.50 MPa was obtained with an optimal combination of the factors of 9 kA welding current, 20 s welding time and 4 kN electrode pressure.

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