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Effect of some welding parameters on nugget size in electrical resistance spot welding

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Abstract. In this study, the effects of weld parameters on nugget size and tensile-shear strength of welding joint in electrical resistance spot welding of galvanized DP 600 steel sheets having 1.2 mm were investigated. Taguchi design method has been employed to examine the effects of five parameters of welding current, electrode pressure, welding time, clamping time and holding time by using the L_{27} (5^3) orthogonal array. Results showed that the most effective parameters on tensile shear strength and the nugget size ratio (hn/dn) were found as welding current and welding time, whereas electrode pressure, clamping time and holding time were less effective factors. Max. 545 MPa strength was obtained through proposed optimum conditions by Taguchi technique.

Keywords: resistance spot welding; nugget size ratio; tensile shears strength; Taguchi method

1. Introduction

Electrical Resistance Spot Welding (ERSW) is the most popular joining process for fabricating sheet metal assemblies. It has low cost, high speed and suitability for automation. Thus, it is an attractive choice for auto-body assemblies such as automobiles, truck cabins and rail vehicles (Vural 2004). Galvanized steel sheets are widely used in automobile bodies to have good weld ability and corrosion resistance (Aslanlar *et al*. 2007).

Resistance spot welding (RSW) is an electrical resistance process, based on the electrical resistance of the components to generate heat when a current is passed through them. Spot welding may be performed manually, robotically or by a dedicated spot welding machine. High current intensity and low voltage for welding process is required that a local pool of molten metal is formed, joining the two parts. The amperage can be selected in the range 1 000-1 00 000 A. and the voltage in the range 1-30 V (Lantz 2000). The heat generated (Q) is proportional to the square of the current (I2), the resistance of the components (R) and the time for which the current is passed (t) at the electrical spot welding process as represented by Eq. (1) (Jenney and Brien 2001).

$$Q = I^2 . R . t \tag{1}$$

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where Q = heat generated, Joules (J); I = current, amperes (A), R = resistance of the components, ohms (Ω); t = time duration of current, seconds (s).

In general, the quality of a resistance spot weld is defined by its nugget geometry, grain size and crystal orientation in the fusion region, which mainly determines the mechanical performance of the weld. In present research (Liu *et al*. 2010, Vural and Akkus 2004, Aslanlar 2006), the phenomenon of nugget geometry and the effect of welding parameters on shape, diameter (dn), height (hn), size satio (hn/hd) of weld nuggets are studied.

Obtaining good welding quality starts with a good process design that decreases the variables encountered in welding process. Previous studies has made to establish an optimal levels welding parameters for obtaining the weld strength, weld quality, and productivity. Effect of some welding parameters on nugget geometry and mechanical properties is the welding current, electrode pressure, welding time, clamping time and holding time. In the studies of optimization of RSW process, it is determined that welding current, welding time and electrode force are prime effective factors on the weld joints (Hamidinejad *et al*. 2012, Xu *et al*. 2007, Eşme 2009, Qiu *et al*. 2010).

In the present work, effects of some parameters such as the welding current, electrode pressure, welding time, clamping time and holding time on nugget size and tensile-shear strength properties in the welded joints of RSW was investigated. Taguchi's experimental design has been set to optimize some important parameters affecting on nugget size and the final tensile-shear strength of the weld joints.

2. Experimental

2.1 Materials and methods

The materials used in experiment were commercially available galvanized DP 600 steel sheet, widely used in car fabrication. Its composition was given in Table 1. The thickness of its is 1.2 mm and galvanized layer is 8 μ. Tensile-shear tests specimens were prepared according to the ASTM E8 standard by the laser cutting process. The sizes of tests specimen is shown in Fig. 1 (Aslanlar 2006, Aslanlar *et al*. 2013).

Table 1 Chemical composition of workpiece materials

C	Si	Mn	Cr	Al	Cu	Mo	balance
0.0544	0.158	1.840	0.0967	0.0277	0.0212	0.155	97.647

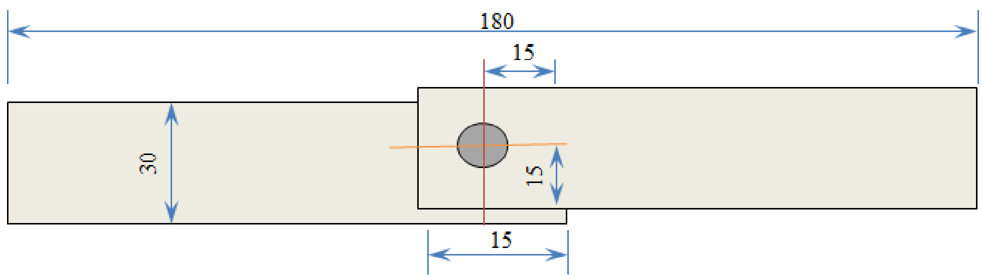

Fig. 1 The sizes of tensile-shear test specimens (Aslanlar 2006)

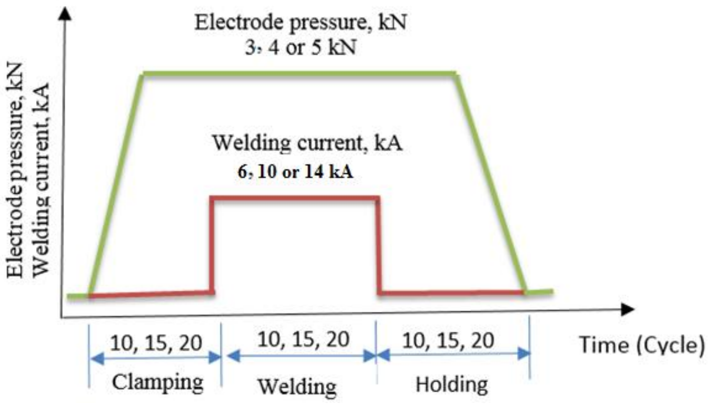

Fig. 2 Basic welding cycle for spot welding

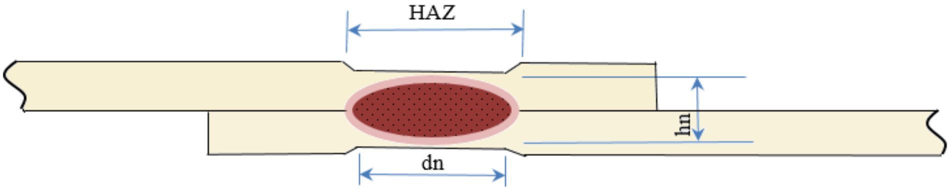

Fig. 3 Weld nugget geometry

A current and timer controlled electrical resistance spot welding machine was used in experimental works. It has 120 kVA capacity and pneumatic application mechanism. Part were welded by electrical resistance spot welding by changing electrode force, welding current, holding time and fixing electrode diameter having 15 mm sphere, cooling water flow rate during experiments. The welding period applied in experiments was shown in Fig. 2 (Aslanlar *et al*. 2013).

After welding parts, all trials were exposed to tensile-shear tests by in a 50 kN computerized universal testing machine in order to determine the joint strengths. The tensile speed was kept constant at a crosshead of 10 mm/min in room temperature during test. The Nugget size, height (hn) and diameter (dn), were measured by means of an optical microscope as seen Fig. 3.

2.2 Design of experiments

Taguchi technique is a statistical methods to improve the quality of manufacture by extending the application of fractional factorial design to the use of orthogonal array. Taguchi's method has been used for a wide range of industrial applications worldwide duo to the simple, efficient and systematic approach to optimize designs for performance quality and cost (Ross 1988, Lochner and Matar 1990). In this study, the present experiments were designed to apply the Taguchi's methods to establish the effects of five welding parameters on the extent of tensile-shear strength and the nugget sizes. The five design parameters (factors) and their levels are given in Table 2.

The welding such as welding time, holding time from the experimental lay out as seen from the

Table 2 Process parameters and their levels

Factors	Symbols	Level 1	Level 2	Level 3
Welding current, kA	A	6	10	14
Electrode pressure, kN	B	3	4	5
Welding times, period	C	10	15	20
Clamping time, period (1/50 s)	D	10	15	20
Hold times, period	E	10	15	20

$L_{27}(5^3)$ orthogonal array (Table 3) were carried out in the order from trial 1 to trial 27. Each trial was repeated at least three times. The average tensile-shear strength and the nugget size ratio were measured. A signal-to-noise (*S*/*N*) ratio was calculated by using the average values of the measurements. The larger-the-better and the nominal–the-best quality characteristics were considered as represented by Eqs. (2) and (3) respectively.

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

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

Where *n* is the number of measurements in a trial and y is the value of measurement in a trial. Analysis of variance statistical method (ANOVA) employs Eqs. (4)-(8) (Ross 1988, Lochner and Matar 1990), was prepared to determine the effect and the optimal combination of the parameters by using the signal-to-noise (*S*/*N*) ratio values.

$$SS_T = \left[\sum_{i=1}^{N} (S/N)i^2 \right] - \frac{T^2}{N} \quad (4)$$

$$SS_A = \left[\sum_{i=1}^{K_A} \left(\frac{Ai^2}{n_{A_i}} \right) \right] - \frac{T^2}{N} \quad (5)$$

$$v_{Total} = N - 1 \quad (6)$$

$$V_{Factor} = \frac{SS_{Factor}}{v_{Factor}} \quad (7)$$

$$F_{Factor} = \frac{V_{Factor}}{V_{Error}} \quad (8)$$

where, 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_{Ai} is the number of samples for *i*th level of factor *A*. T is the sum of total (*S*/*N*) ratio of the experiments, v_{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

Table 3 shows the average value of nugget size and tensile shear strength measured from each sample. The average values of nugget height, diameter were measured from three different regions of each sample to define nugget geometry. As seen from table, the highest nugget height was obtained from trial 16, whereas the lowest value was measured from trial 21. Table 3 indicates that the nugget diameter varied between 5.25 mm and 12.25 mm. The highest nugget diameter was obtained from trial 26, whereas the lowest value was measured from trial 7.

As seen from Table 3, the tensile shear strength was varied between 88 MPa and 471 MPa. The highest the strength was obtained from trial 12 which were associated with 10 kA welding current, 3 kN electrode pressure, 20 period welding times, 10 period clamping time and 15 period holding time, On the other hand, the lowest values obtained from trials 7 were associated with 6 kA of welding current, 5 kN electrode pressure, 10 period welding times, 20 period clamping time and 15 period holding time.

The nugget diameter (dn) or nugget height (hn) is not enough to explain the effect of welding nucleus on tensile-shear of joints (Fig. 4). Therefore, nugget size ratio (hn/dn) and tensile shear strength can be used in optimization deign (Aslanlar 2006, Anık and Gulbahar 1989). Calculated *S*/*N* ratios for the nugget size ratio and tensile shear strength were also presented in Table 3 respectively.

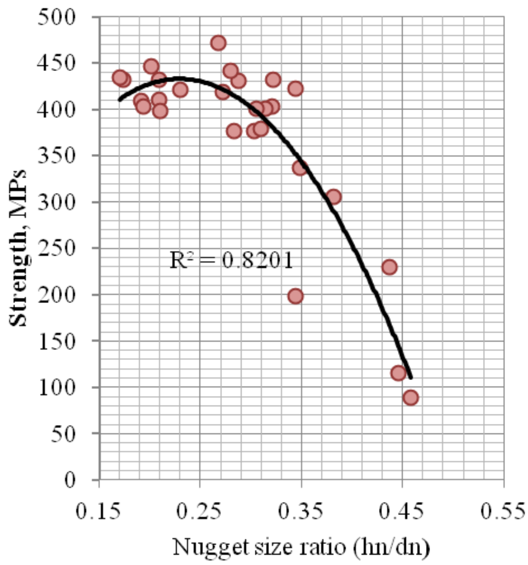

Fig. 4 The effect of nucleus size ratio on tensile-shear strength

The exchange of the shear strength with nugget size ratio (hn/dn) is given in Fig. 4. The tensile shear strength rises up to a maximum value with nugget size ratio increment and then the strength value starts to decrease. This result indicates that an optimum nugget size ratio is needed to obtain the maximum strength as reported in previous studies with optimization of welding joint (Aslanlar 2006). So, the nominal-the-better quality characteristics were considered since the performance was measured in terms of the nugget size ration, property which is generally expected to be as nominal as possible as represented by Eq. (2).

Table 3 L_{27} (53) orthogonal design array, measured the nugget size and tensile-shear strength and calculated *S*/*N* ratios for hn/dn and tensile-shear strength

Exp. No	Parameters					Nugget size				Tensile-shear strength	
	A	B	C	D	E	Height (hn), mm	Diameter (dn), mm	hn/dn	*S*/*N* ratio	Strength. MPa	*S*/*N* ratio
1	1	1	1	2	3	2.44	5.575	0.45	0.17	115.10	4.12
2	1	1	2	3	1	2.45	7.075	0.35	0.99	336.67	5.05
3	1	1	3	1	2	2.38	7.75	0.31	1.50	378.80	5.16
4	1	2	1	1	1	2.4	5.55	0.44	0.25	230.05	4.72
5	1	2	2	2	2	2.38	7.875	0.30	2.03	377.08	5.15
6	1	2	3	3	3	2.4	8.475	0.28	2.54	376.62	5.15
7	1	3	1	3	2	2.40	5.25	0.46	0.16	88.53	3.89
8	1	3	2	1	3	2.39	6.975	0.34	1.07	198.96	4.60
9	1	3	3	2	1	2.39	6.375	0.38	0.57	305.21	4.97
10	2	1	1	2	3	2.36	6.875	0.34	1.14	422.45	5.25
11	2	1	2	3	1	2.25	7.050	0.32	1.34	432.55	5.27
12	2	1	3	1	2	2.4	9.025	0.27	1.60	471.46	5.35
13	2	2	1	1	1	2.38	7.450	0.32	1.42	403.70	5.21
14	2	2	2	2	2	2.39	7.625	0.31	1.79	400.47	5.21
15	2	2	3	3	3	2.37	8.250	0.29	2.72	431.41	5.27
16	2	3	1	3	2	2.49	8.175	0.31	1.97	400.94	5.21
17	2	3	2	1	3	2.51	9,000	0.28	2.10	441.20	5.29
18	2	3	3	2	1	2.48	9.125	0.27	2.11	419.01	5.24
19	3	1	1	2	3	2.28	10.925	0.21	0.81	432.52	5.27
20	3	1	2	3	1	1.95	9.750	0.20	0.72	446.72	5.30
21	3	1	3	1	2	1.85	10.625	0.17	0.46	434.84	5.28
22	3	2	1	1	1	2.36	10.250	0.23	1.08	420.78	5.25
23	3	2	2	2	2	2.08	10.875	0.19	0.64	409.32	5.22
24	3	2	3	3	3	2.13	12.250	0.17	0.50	431.77	5.27
25	3	3	1	3	2	2.18	10.450	0.21	0.81	410.52	5.23
26	3	3	2	1	3	2.17	11.225	0.19	0.66	403.28	5.21
27	3	3	3	2	1	2.19	10.500	0.21	0.80	398.75	5.20

Table 4 shows the analysis of variance table (ANOVA) which was prepared using Eqs. (4)-(8). The average values of *S/N* ratio for different levels of each trial are also given in Table 4 According to the ANOVA, the high contribution and variance of factors *A* and *C* indicate that the welding current and welding times are significant at least 99% confidence, respectively. The electrode pressure (B), Clamping time (D), holding times (E) have less influence on the nugget size ratio (hn/dn). In order to demonstrate the effect of the parameters of *A* and *C*, the factor associated with Clamping time (D) and Holding times (E) are pooled (insignificant factors ignored) due to low significance. The result is similar to that obtained by Aslanlar 2006, Aslanlar *et al*. 2008, have reported that the welding current and welding times are significant factor on the resistance spot welding (RSW).

Using the average *S/N* value of each factor level, an *S/N* response graph and response table were derived which is given in Fig. 5, respectively. In relation to the principles of Taguchi's method, these results indicate the high nugget size ratio (hn/dn). Therefore, Fig. 5 shows the optimal combination of the factor levels and corresponding the high value of each parameter level. These are A2, B2, C3, D3 and E3 for obtaining a nominal nugget size ratio (hn/dn).

The larger-the-better quality characteristics was considered since the performance was measured in terms of the tensile-shear strength, a property which is generally expected to be as high as possible as represented by Eq. (3). prepared the analysis of variance (ANOVA) table by

Table 4 Analysis of variance (ANOVA) for the nugget size ratio (hn/dn)

	Factors	Sum of squares (SS)	Degrees of freedom (v)	Variance (V)	F(factor)
A	Welding current	5.57	2	2.78	10.09[#]
B	Electrode pressure	1.03	2	0.52	1.87
C	Welding times	1.47	2	0.74	2.67[$]
D	Clamping time	0.20	2	0.10	0.36[e]
E	Holding times	0.34	2	0.17	0.62[e]
	Total	8.07	6.00	1.35	
	Error (e)	5.52	20	0.28	

[e] pooling, [#]At least 99% confidence (5.78), [&]At least 95% confidence (3.49), [$] At least 90% confidence (2.35)

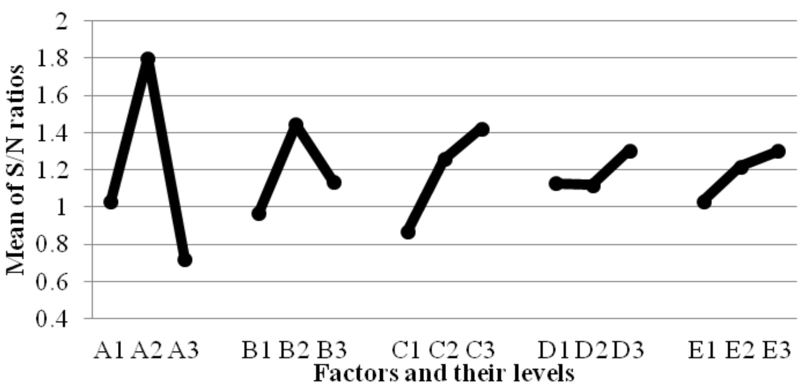

Fig. 5 Response graph for the nugget size ratio (hn/dn)

Table 5 Analysis of variance (ANOVA) for the tensile shear strength

	Factors	Sum of squares (SS)	Degrees of freedom (v)	Variance (V)	F(factor)
A	Welding current	1.46	2	0.73	12.30[#]
B	Electrode pressure	0.16	2	0.08	1.33
C	Welding times	0.46	2	0.23	3.87[&]
D	Clamping time	0.01	2	0.01	0.11[e]
E	Hold times	0.04	2	0.02	0.30[e]
	Total	2.08	6	0.35	
	Error (e)	1.19	20	0.06	

[e] pooling, [#]At least 99% confidence (5.85), [&]At least 95% confidence (3.49), [$]At least 90% confidence (2.59)

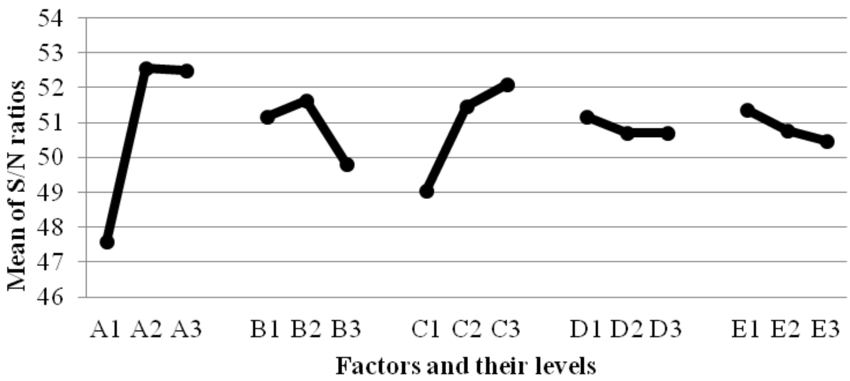

Fig. 6 Response graph for the tensile shear strength

Table 6 Results from the confirmation experiment

Description	Shear strength, MPa	nugget size ratio (hn/dn)
Optimum condition	$A_2B_2C_3D_1E_1$	$A_2B_2C_3D_3E_3$
Pooled factors	*D* and *E*	*D* and *E*
Estimated average *S*/*N* ratio	5.45	2.30
Estimated *S*/*N* ratio range	$5.33 < \mu < 5.58$	$2.03 < \mu < 2.57$
Exp. average *S*/*N* ratio	5.47	2.44
Estimated average value	532	0,30
Estimated value range	$464 < \mu < 617$	$0.293 < \mu < 0.286$
Exp. average value	545	0.281

using *S*/*N* ratios is seen in Table 5. According to the ANOVA, the high contribution and variance of factors *A* and *C* indicate that the welding current and the welding times are significant at least 99% and 95% confidence respectively, Whereas, the clamping time (D) and hold times (E) have less significant influence on the strength. In order to demonstrate the effect of the parameters of *A*, *B* and *C*, the factor associated with *D* and *E* is pooled (insignificant factors ignored) due to low

Table 7 Results of validation trial

Parameters					Nugget size				Tensile-shear strength	
A	B	C	D	E	Height (hn), mm	Diameter (dn), mm	hn/dn	*S*/*N* ratio	Strength, MPa	*S*/*N* ratio
2	2	3	1	1	2.30	8.30	0.28	2.44	545.03	5.47

significance.

According to the principles of the Taguchi method, this study defines the high shear strength with a high *S*/*N* ratio. Therefore, Fig. 6 reveals the optimal combination of experimental parameters and the corresponding values of each factor. These are *A*2, *B*2, *C*3, *D*1 and *E*1 for obtaining the highest shear strength.

According to the Taguchi approach, to compare the results with the expected conditions, it is necessary to perform a confirmation experiment. In this study, insignificant factors (pooling) were ignored. In order to obtain optimum the combination of the factor levels the following Eqs. (9)-(11) have been used (Ross 1988, Lochner and Matar 1990).

$$\mu_{Strength} = \overline{A2} + \overline{B2} + \overline{C3} - 2\overline{T} \quad (9)$$

$$\mu_{hn/dn} = \overline{A1} + \overline{D1} - \overline{T} \quad (10)$$

$$\mu \pm \sqrt{\frac{F_{(p)} V_e}{n}} \quad (11)$$

where μ is estimated average *S*/*N* values, $F_{(p)}$ is *F* ratio, V_e is error variance, *n* is number of tests under given condition.

Using Eqs. (9)-(11), it has th been estimated that at e optimum condition, the shear strength should be between 464 MPa and 617 MPa as seen Table 6. Since the suggested optimum condition (*A*2, *B*2, *C*3, *D*1 and *E*1) has not already been included in the original set of trials (see Table 3), there was need to carry out an extra validation trial. Results of validation trial which was made at the suggested optimum condition are given in Table 7. According to the results, the average shear strength was 545 MPa which well lies within the calculated shear strength range. Similarly, the optimum condition for the nugget size ratio (hn/dn) has been estimated that it should be between 0.286 mm/mm and 0.293 mm/mm. According to the result obtained from the validation trial, *S*/*N* ratio of the nugget size ratio (hn/dn) was 2.44, which also stay within the calculated the *S*/*N* ratio of 2.03 and 2.57. This validates the confidence of the current study.

Tables 4-6 show the welding current and the welding times are significant, whereas electrode pressure, clamping time and holding times are less influence parameters on weld of both nugget size and tensile-shear strength. Figs. 5-6 reveal same optimal combination of experimental parameters (*A*2, *B*2 and *C*3) to obtain both nugget size and strength for effectiveness factors. Here, clamping time (*D*) and holding times (*E*) have not been considered for less influence parameters. These results indicate that the strength of welding is related with nugget size. In addition, a nominal nugget size is required to obtain strength of weld joints. These results are in good agreement with previously reported results (Aslanlar *et al*. 2007, Eşme 2009, Vural *et al*. 2006). For this study, results from the confirmation test indicate that nominal nugget size having 2.3

heights and 8.3 diameters are suggested to obtain the highest tensile shear strength (545 MPa) in the seen Table 7.

4. Conclusions

This work has presented an investigation on the optimization and the effect of welding parameters on the tensile shear strength and nugget size ratio of Electrical Resistance Spot Welding. The levels of importance of the welding parameters on the tensile shear strength and nugget size ratio are determined by using Taguchi technique.

- Based on the method, the highly effective parameters on tensile shear strength and the nugget size ratio (hn/dn) were found as welding current and welding time, whereas electrode pressure, clamping time and holding time were less effective factors.
- The results showed that welding current was about three times more important than the second effective factor (welding time) to obtain high tensile shear strength and nugget size ratio. The highest tensile shear strength was average 545 MPa with the confirmation test which was obtained with the optimal combination of the factors as 9 kA welding current, 20 period welding time, 4 kN electrode pressure, 10 period clamping time and 10 period holding time.
- These results indicate that the strength of welding is related with nugget geometry. A nominal nugget size having 2.3 heights and 8.3 diameters is required to obtain the highest strength of weld joints. Max. 545 MPa strength was obtained through proposed optimum conditions by Taguchi technique.

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