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RSW Process Parameters Optimization by Taguchi Method

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Abstract:*The paperpresents experimental investigation studies that were conducted under varying Resistance spot welding parameters such as electrode force, welding current and welding time in order to establish their influence on spot weld quality. The quality characteristics are shear tensile strength and direct tensile strength of the spot welded joint has been considered. The process parameters were optimized to improve the nugget quality characteristics. The approach is based on Taguchi method, the signal-to-noise (S/N) ratio and the analysis of variance (ANOVA) are employed to study the performance characteristics in RSW process.The experimental data was extracted as per the the pattern of L_9 Orthogonal Array(OA).The data was analysed by using the signal-to-noise (S/N) ratio to get optimum level of spot welding parameters combination.Analysis of variance (ANOVA) and F- test has been used for determining most significant parameters affecting the spot weld quality characteristics. Confirmation tests with optimal levels of RSW process parameters are conducted to validate the test results. Experimental results have shown that the responses in RSWprocess can be improved significantly through this approach.*

Key words:*Resistance spot welding (RSW), Orthogonal Array (OA), S/N ratio, ANOVA, Tensile strength.*

I. Introduction

The Resistance spot welding process was introduced almost a hundred years ago. Since then, it has found extensive use in nearly all industries which need to join sheet metal parts together. In the automobile industry, Resistance Spot Welding (RSW) is widely used for its low cost, high speed, simple mechanism and applicability for automation. In particular, its use in the automotive industry is of great importance, since every car includes approximately 5000 spot welds in its assembly process [1]. Spot welds are very susceptible to various types of loading conditions. Therefore they are prone to failure, if not designed properly, during their service life time. Therefore it is very important to understand the behaviour of spot welds and their failure characteristics.The spot weld is made by a combination of heat, electrode force, and weld time. As the name implies, it uses the resistance ofthe materials to the flow of current that causeslocalized heating between the parts to be joined [2]. It is desirable to have the maximum temperature at the interface of the parts to be joined. Therefore, the resistance of the workpieces and the contact resistance between the electrodes and work should be kept as low as possible with respect to the resistance between the faying surfaces. This could be achieved by controlling the contact area, electrode materials, and dimensions, applied pressure, and surface quality of the workpieces [3].

Heat obtained at the end of the spot welding also raises the temperature of both electrodes and workpieces. Consequently, micro-structural change might be seen around the spot welding zone due to the distributed heat. The heat affected zone (HAZ) should be as small as possible in a well-qualified spot weld [4, 5]. On the other hand, excessive heat in the electrodes reduces the electrode cap life and deteriorates the spot weld quality. Hence, the electrodes are cooled via water circulation through channels opened inside them. The related studies have shown that both water temperature and flow rate affect the electrode life and weld quality [6]. Also, the applied pressure and timing are important for the spot weld quality and electrode life [7, 8].

The qualities of the spot welded joints are defined by the mechanical properties and size of the heat affected zone. The weld strength is measured by a number of standardized destructive tests, which subject the spot weld to different types of loading. Some of these are tension-shear, direct tension, torsion, impact, fatigue, and hardness. Controlling the spot welding parameters plays an important role on the quality of the spot weld. The stiffness and the operating strength of sheet metal parts are strongly influenced by the spot welding parameters and location of the spot welding [9].Therefore, it is very important to select the spot welding process parameters for obtaining optimal spot weld strength. Usually, the desired spot welding process parameters are determined based on experience or from a handbook. However, this does not ensure that the selected welding process parameters can produce the optimal or near optimal spot weld strength for that particular welding machine and environment.

Literature reports that work has been done on various aspects of modeling, simulation, and process optimization in the resistance spot welding process. Detailed analysis has been made to establish relationships between spot welding parametersspot weld strength, spot weld quality, and productivity to select spot welding parameters leading to an optimal process. Martin et al. [10] proposed Artificial Neural Network (ANN) for quality control by ultrasonic testing in resistance spot welding; Mukhopadhyayet al. [11] investigated the effect of pre-strain on the strength of spot welded joints; Kong et al. [12] developed a 3D model based on the predicted constitutive material laws coupled with a Gurson fracture model to simulate the deformation of spot welded joints; Martin et al. [13] developed a tool capable of reliably predicting the tensile shear load bearing capacity (TSLBC) in spot welding of 304 austenitic stainless steels; Yoon et al. [14] investigated optimal welding conditions in resistance spot welding of 7075-T6 aluminum alloy sheets by the tensile-shear strength tests and the Taguchi method; and Esmeet et al.[15] reported the selection of process parameters for spot welding of steel sheets using the Taguchi method.

In this study, the use of the Taguchi method to determine the spot welding process parameters with the optimal tensile shear strength and direct tensile strength is reported. This is because the Taguchi method is a systematic application of design and analysis of experiments for the purpose of designing and improving product quality at the design stage [16, 17]. In recent years, the Taguchi method has become a powerful tool for improving productivity during research and development so that high quality products can be produced quickly and at low cost [18].

II. Taguchi Method

Taguchi's techniques have been used widely inengineering design [19, 20]. TheTaguchi method contains system design, parameterdesign, and tolerance design procedures to achieve arobust process and result for the best product quality[21, 22]. The main trust of Taguchi'stechniques is the use of parameter design [23], which is an engineering method for product orprocess design that focuses on determining the parameter(factor) settings producing the best levels of a qualitycharacteristic performance measurewith minimumvariation. Taguchi method has become a powerful tool for improving productivity during research and development so thathigh quality products can be produced quickly and at low cost.Taguchi designs provide a powerful andefficient method for designing processes that operateconsistently and optimally over a variety of conditions.To determine the best design, it requires the use of astrategically designed experiment, which exposes theprocess to various levels of design parameters.

By using the Taguchi techniques, industries areable to greatly reduce product development cycle time for both design and production, therefore saving costsand increasing profit.Taguchi proposed that engineering optimization of a process or product should be carriedout in a three-step approach: system design, parameter design, and tolerance design. In system design, theengineer applies scientific and engineering knowledge to produce a basic functional prototype design. Theobjective of the design is to optimize the settings of the process parameter values for improving performancecharacteristics and to identify the product parameter values using the optimal process parameters.

The parameter design is the key step in the Taguchi method for achieving high quality without increasing cost.The steps included in the Taguchi parameter design are: selecting the proper orthogonal array (OA) according tothe numbers of controllable factors (parameters); running the experiments based on the OA; analysing the data;identifying the optimum conditions; and conducting confirmation runs using the optimal levels of theparameters. The main effects indicate the general trend of influence of each parameter. Knowledge of thecontribution of individual parameters is the key for deciding the nature of the control to be exercised on aproduction process[24].Taguchi recommends the use of the loss function to measure the deviation of the quality characteristic from thedesired value. The value of the overall loss function is further transformed into a signal-to-noise (S/N) ratio. Usually, there are three categories of the quality characteristic in the analysis of the S/N ratio, i.e. the lower-the-better, thelarger-the-better, and the more-nominal-the-better. The S/N ratio for each level of process parameters is computedbased on the S/N analysis. Regardless of the category of the quality characteristic, a larger S/N ratio corresponds to abetter quality characteristic. Therefore, the optimal level of the process parameters is the level with the highest S/Nratio. Furthermore, a statistical analysis of variance (ANOVA) is performed to see which process parameters arestatistically significant. The optimal combination of the process parameters can then be predicted.Finally, a confirmation experiment is conducted to verify the optimal process parameters obtained from theprocess parameter design.

III. Experimental Details

Low carbon steel (eg. CR3) is extensively used for deep drawing of motor car bodies, motor cycle parts, and other domesticapplications. RSW is still the first choice to join Low Carbon steel in auto body assembly line because of high efficiency and low cost. Therefore, the present work was planned to optimize the resistance spot welding parameters of cold rolled (CR3) low carbon steel sheets with different thicknesses. The specimens were prepared by cutting the workpiece material into thesuitable dimensions and then cleaned and abraded to prevent high contact resistance which is created due to an oxidelayer [25]. The resistance spot weld should have shear strength equal to the base metal shear strength and should exceed the strength of a rivet or a fusion plug weld of the same cross sectional area. Shear strength is normally accepted as the criteria for resistance spot weld specifications, although other methods may be used.The chemical composition (percentage by weight) and the mechanical properties of the workpiece material given in Table 1.

Percentage of Composition(%)	C	Mn	P	S
	0.10	0.45	0.030	0.025
MechanicalProperties (at room temperature)	Yield strength (MPa)	Tensile strength (MPa)	Percent Elongation	Hardness (HB)
	220 Max.	350 Max.	34	57

Table 1: Chemical analysis and Mechanical properties of Workpiece (CR3) materials (IS 513: 2008**)**

Experimental data was used to compute performance characteristics of parametric combination for spot welding through calculation of signal-to-noise (S/N) ratio. Through S/N ratio, a set of optimum welding parameters was obtained. Using analysis of variance (ANOVA) predominant process parameters for spot welding were investigated.RSWparametersselected are welding current, electrode force and welding time. Level of each process parameter identified to predict RSW characteristics of spot weld strength was chosen in an available range for spot welding. Squeeze time (5 cycles, 1 cycle = 0.02 sec) and hold (5 cycles) times were kept constant for all the experiments.Under Taguchi system having 3 parameters with 3 levels can be performed with 9 experiments. Therefore, in RSW process **L_9**orthogonal array was selected. The tension shear test and direct tension test experiments were performed on the specimens according to welding standards of the Resistance Welders Manufacturer Association (RWMA). The configuration and dimensions of the specimens used throughout the work are given in Table 2. The specimen samples and their testing are shown in Figure 1&2.

Thickness(t) mm	Width (w)mm	Length (l) mm	Contacting overlap mm
0.8	40	120	40
1.0	40	120	40

Table 2: Workpiece dimensions

In this study, copper was used as an electrode material and it was kept constant during the experiment. The electrode shape and corresponding dimensions of the electrodes was maintained unchanged for each experimental run to prevent the effect of electrode damage on the nugget formed.

3.1 Design the Orthogonal Array (OA)

Using OAs significantly reduces the number of experimental configurations to be studied [26]. The effect of many different parameters on the performance characteristic in a process can be examined by using the orthogonal array experimental design proposed by Taguchi. Once the parameters affecting a process that can be controlled have been determined, the levels at which these parameters should be varied must be determined. Determining what levels of a variable to test requires an in-depth understanding of the process, including the minimum, maximum, and current value of the parameter. If the difference between the minimum and maximum value of a parameter is large, the values being tested can be further apart or more values can be tested. If the range of a parameter is small, then less value can be tested or the values tested can be closer together. In the present study, three-level process parameters, i.e. electrode force, welding current and welding time, are considered. The value of the welding process parameter at the different levels is listed in Table 3. In Taguchi method for 3 parameters with 3 levels of 8 degree of freedom L_9 orthogonal array was selected. The pattern of parameter based **L_9**orthogonal array was shown in Table 4.

Thickness of metal sheets	Symbol	Process Parameter	Unit	Level 1	Level 2	Level 3
0.8 mm & 1.0 mm	A	Electrode Force	kN	1	1.5	2
	B	Welding Current	kA	3	3.5	4
	C	Welding Time	sec	1	2	3

Table 3: Process parameters with their values at three levels for both 0.8 & 1.0 mm thickness lap joint sheets

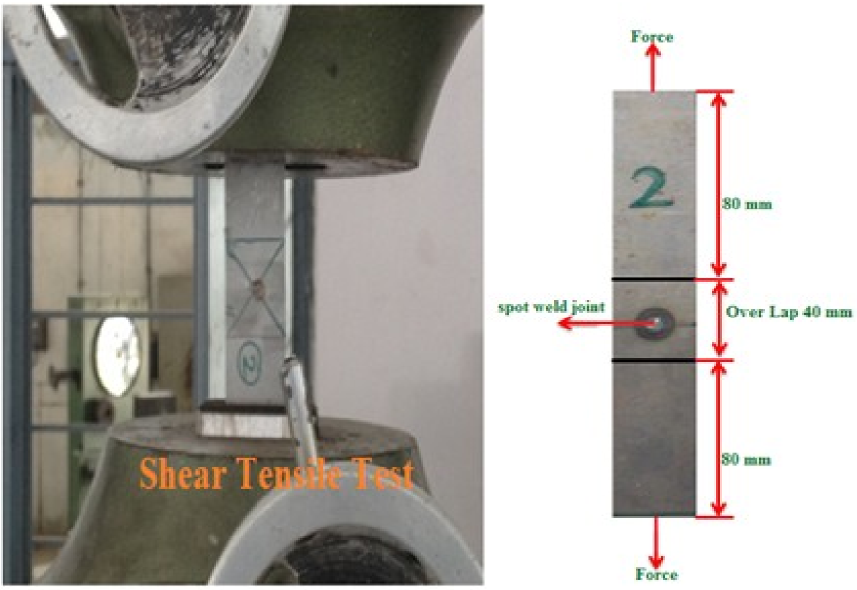


Figure 1: Specimen sample for Shear tensile strength testing by UTM

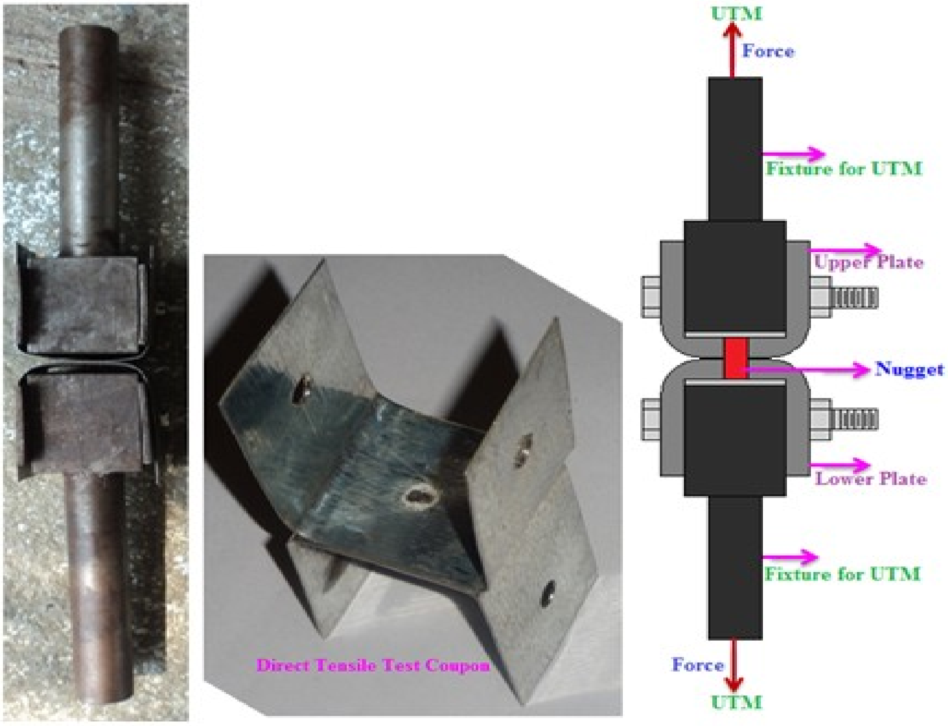


Figure 2: Specimen sample attached with fixture for direct tensile strength test

3.2 Analysis of S/N Ratio Based On Taguchi Method

Taguchi uses the S/N ratio to measure the quality characteristic deviating from the desired value. There are several S/N ratios available, depending on the type of characteristic;

1. Lower-is-Better (LB)
2. Nominal-is-Better (NB)
3. Higher-is-Better (HB).

$$S/N\ (\eta) \quad = \quad \text{useful output/harmful output}$$

The goal of this work was to produce high shear tensile strength and high direct tensile strength Resistance spot welded joint. Higher values represent better or improved strength of the resistance spot weld joint. Therefore, a higher-is-better quality characteristic S/N ratio [26] was implemented and introduced in this study. The equation for calculating S/N ratio for higher-the-better characteristic (in decibels) is;

$$\eta = -10\log_{10}\left(\frac{1}{N}\sum_{i=1}^{r}\frac{1}{y_i^2}\right) i = 1,2,\ldots r(1)$$

Where **'N'** is the number of tests, and **'y_i'** is the experimental value of the ith quality characteristic, and **'η'** is the S/N ratio. The **'η'** corresponding to each experiment of **L_9**(OA) as calculated and given in Table 4.

The effect of each welding process parameter on the S/N ratio at different levels can be separated out because the experimental design is orthogonal. The S/N ratio for each level of the welding process parameters is summarized in Table 4. In addition, the total mean of the S/N ratio for the **9** experiments is also calculated and listed in Table 5. Figure 3 & 4 shows the S/N ratio graphs. Basically, the larger the S/N ratio, the better is the quality characteristic for the shear tensile strength and direct tensile strength.

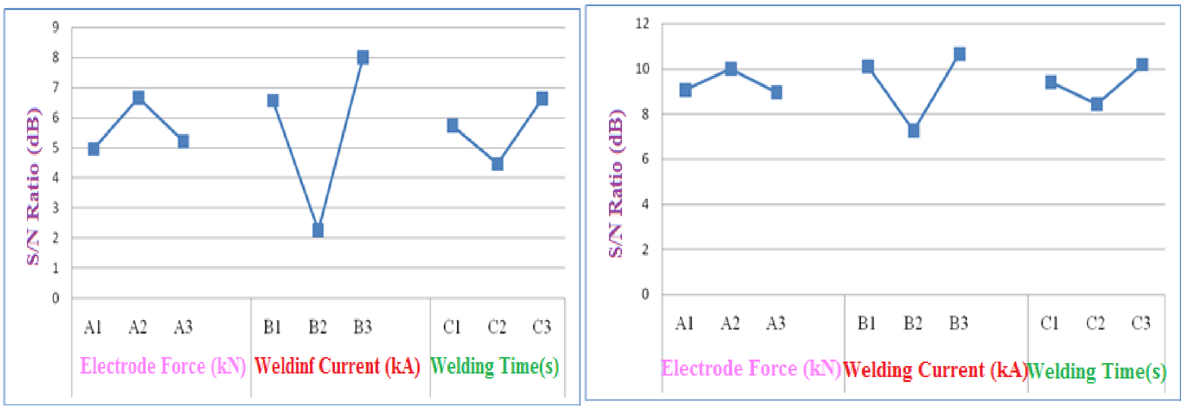
Exp.No .	Process Parameter Level			0.8 mm thickness				1.0 mm thickness			
	Electrode Force (kN)	Welding Current (kA)	Weld Time Sec	Direct Tensile Strength (kN)	S/N Ratio dB	Shear Tensile Strength (kN)	S/N Ratio dB	Direct Tensile Strength (kN)	S/N Ratio dB	Shear Tensile Strength (kN)	S/N Ratio dB
1	1	3	1	2.940	9.4	1.910	5.6	2.910	9.3	3.010	9.5
2	1	3.5	2	2.110	6.5	1.100	0.8	2.110	6.5	4.120	12.3
3	1	4	3	3.680	11.3	2.650	8.5	3.810	11.6	4.330	12.7
4	1.5	3	2	3.120	9.9	2.150	6.6	3.340	10.5	3.500	13.8
5	1.5	3.5	3	2.590	8.3	1.560	3.9	2.550	8.1	4.920	13.8
6	1.5	4	1	3.900	11.8	2.970	9.5	4.270	12.6	4.400	12.8
7	2	3	3	3.560	11.0	2.380	7.5	3.520	10.9	2.890	9.2
8	2	3.5	1	2.250	7.0	1.270	2.1	2.250	7.0	3.720	11.4
9	2	4	2	2.780	8.9	2.000	6.0	3.480	10.8	3.400	10.6

Table 4: S/N Ratios for the Shear & Direct Tensile Strength Measurements

Thickness	Process parameter	Units	S/N Ratio (dB)			Total Mean S/N (dB)	Max-Min
			Level 1	Level 2	Level 3		
0.8 mm (Shear Tensile strength)	Electrode Force	kN	4.96	6.66^a	5.2	5.60	1.7
	Welding current	kA	6.56	2.26	8^a		5.74
	Welding time	sec	5.73	4.46	6.63^a		2.17
0.8 mm (Direct Tensile strength)	Electrode Force	kN	9.06	10^a	8.96	9.34	1.04
	Welding current	kA	10.09	7.26	10.66^a		3.4
	Welding time	sec	9.40	8.43	10.19^a		1.76

Note:^{a}Optimum level

Table 5: S/N Responses for the Shear & Direct Tensile Strength of 0.8 mm sheets



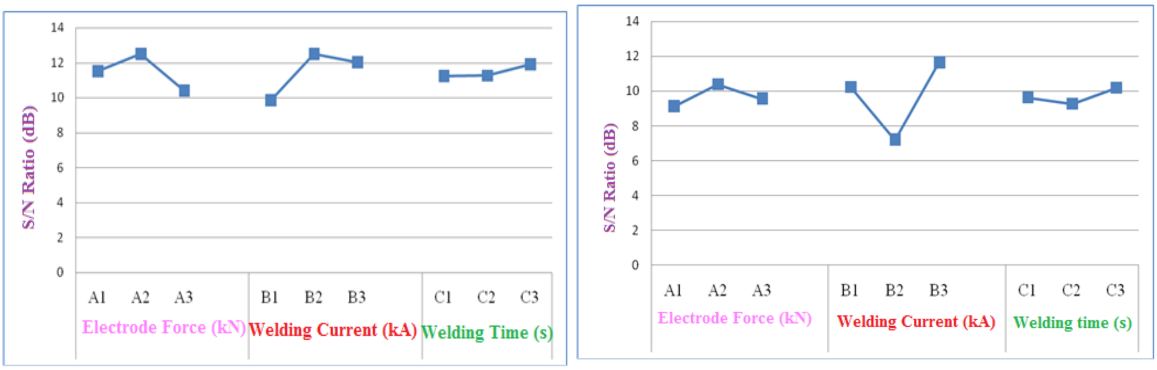
(a) **(b)**

Figure3:S/N ratio graphs for Shear (a)& Direct Tensile Strength (b) of 0.8mm thickness

Thickness	Process parameter	Units	S/N Ratio (dB)			Total Mean S/N (dB)	Max-Min
			Level 1	Level 2	Level 3		
1.0 mm (Direct Tensile strength)	Electrode Force	kN	9.133	10.4^{a}	9.566	9.69	1.267
	Welding current	kA	10.233	7.2	11.666^{a}		4.466
	Welding time	sec	9.633	9.266	10.199^{a}		0.933
1.0 mm (Shear Tensile strength)	Electrode Force	kN	11.5	12.5^{a}	10.4	11.46	2.1
	Welding current	kA	9.86	12.5^{a}	12.03		2.64
	Welding time	sec	11.23	11.26	11.9^{a}		0.67

Note:^{a}Optimum level

Table 6: S/N Responses for the Direct& Shear Tensile Strength of 1.0 mm sheets



(a) **(b)**

Figure4: S/N ratio graphs for Shear (a)&DirectTensile Strength (b) of 1.0 mm thickness

3.3Analysis of variance (ANOVA)

ANOVA is a statistically based, objective decision-making tool for detecting any differences in the average performance of groups of items tested. ANOVA [27-29] helps in formally testing the significance of all main factors by comparing the mean square against an estimate of the experimental errors at specific confidence levels. ANOVA is performed to find out the factors which have a significant effect on the sensitivity of the process and their contribution on quality characteristics; tensile shear strength and direct tensile strength of the Resistance spot welding joint.

The results of ANOVA for the welding outputs are presented in Tables 7, 8, 9 and 10. Statistically, F-test provides a decision at some confidence level as to whether these estimates are significantly different [26-33]. Larger F-value indicates that the variation of the process parameter makes a big change on the performance.

According to this analysis, the most effective parameters with respect to tensile shear strength and direct tensile strength is welding current, electrode force, and welding time. Percent contribution indicates the relative power of a factor to reduce variation. For a factor with a high percent contribution, a small variation will have a great influence on the performance. The percent contributions of the welding parameters on the tensile shear strength are shown in Tables 8 and 10. According to Tables 8 and 10, welding current was found to be the major factor affecting the tensile shear strength (78.815% for 0.8 mm and 59.63% for 1 mm), whereas welding time was found to be the second ranking factor (9.253% for 0.8 mm) and electrode force was32.854% for 1 mm. The percent contributions of other parametersare much lower as per their mentioned values in the Table 8 and Table 10 for 0.8 mm and 1.0 mm respectively.

Similarly, the percent contributions of the welding parameters on the direct tensile strength are shown in Tables 7 and 9. According to Tables 7 and 9, (and also shown in fig.5 through'pie' diagrams) welding current was found to be the major factor affecting the tensile strength (67.237% for 0.8 mm and 86.239% for 1 mm), whereas after error it was welding time was found to be the next ranking factor (12.478% for 0.8 mm) and electrode force was 5.474% for 1 mm. The percent contributions of other parameters are much lower as per their mentioned values in the Table 7 and Table 9 for 0.8 mm and 1.0 mm respectively.

Parameter	Process Parameters	Degree of Freedom	Sum of Square	Variance	F	Contribution Percentage
A	Electrode Force	2	1.948	0.974	1.585	2.591
B	Welding Current	2	19.908	9.954	16.2	67.237
C	Welding Time	2	4.695	2.347	3.821	12.478
Error		2	1.228	0.614		17.694
Total		8	27.782			100

Table 7: Results of ANOVA for Direct Tensile Strength of 0.8 mm thickness sheets

Parameter	Process Parameters	Degree of Freedom	Sum of Square	Variance	F	Contribution Percentage
A	Electrode Force	2	5.095	2.547	5.37	6.229
B	Welding Current	2	53.415	26.707	56.294	78.815
C	Welding Time	2	7.108	3.554	7.492	9.253
Error		2	0.947	0.473		5.703
Total		8	66.568			100

Table 8: Results of ANOVA for Shear Tensile Strength of 0.8 mm thickness sheets

Parameter	Process Parameters	Degree of Freedom	Sum of Square	Variance	F	Contribution Percentage
A	Electrode Force	2	2.486	1.243	4.605	5.474
B	Welding current	2	31.206	15.603	57.792	86.239
C	Welding Time	2	1.326	0.663	2.456	2.212
Error		2	0.539	0.269		6.075
Total		8	35.56			100

Table 9: Results of ANOVA for Direct Tensile Strength of 1.0 mm thickness sheets

Parameter	Process Parameters	Degree of Freedom	Sum of Square	Variance	F	Contribution Percentage
A	Electrode Force	2	6.619	3.309	32.023	32.854
B	Welding Current	2	11.846	5.293	57.306	59.63
C	Welding Time	2	0.846	0.423	4.095	3.278
Error		2	0.206			4.238
Total		8	19.52			100

Table 10: Results of ANOVA for Shear Tensile Strength of 1.0 mm thickness sheets

IV. Confirmation Tests

The purpose of the confirmation experiment is to validate the conclusions drawn during the analysis phase. The confirmation experiment is performed by conducting a test with a specific combination of the factors and levels previously evaluated. In this study, after determining the optimum conditions and predicting the response under these conditions, a new experiment was designed and conducted with the optimum levels of the welding parameters. The final step is to predict and verify the improvement of the performance characteristic. The predicted S/N ratio $\hat{\eta}$using the optimal levels of the welding parameters can be calculated as

$$\hat{\eta} = \eta_m + \sum_{i=0}^{n} (\bar{\eta}_i + \eta_m) \qquad (2)$$

Where $\eta_m$is thetotal mean ofS/N ratiois, $\bar{\eta}_i$is the mean of S/N ratio at the optimal level, and **'n'**is the number of main welding parameters that significantly affect the performance. The results of experimental confirmation using optimal welding parameters and comparison of the predicted tensile shear strength with the actual tensile shear strength using the optimal welding parameters are shown in Table 11. The improvement in S/N ratio from the starting welding parameters to the level of optimal welding parameters is 9.27 dB, 1.53 dB (shear tensile strength) and 5.65 dB, 6.26 dB (direct tensile strength) for 0.8 mm and 1 mm steel sheets, respectively. The raw data of shear tensile strength is increased by 2.09 kN, 0.8 kN times and direct tensile strength is increased by 1.94 kN, 2.24 kN for 0.8 mm and 1 mm, respectively. Therefore, the shear tensile strength and direct tensile strength is greatly improved by using the Taguchi method.

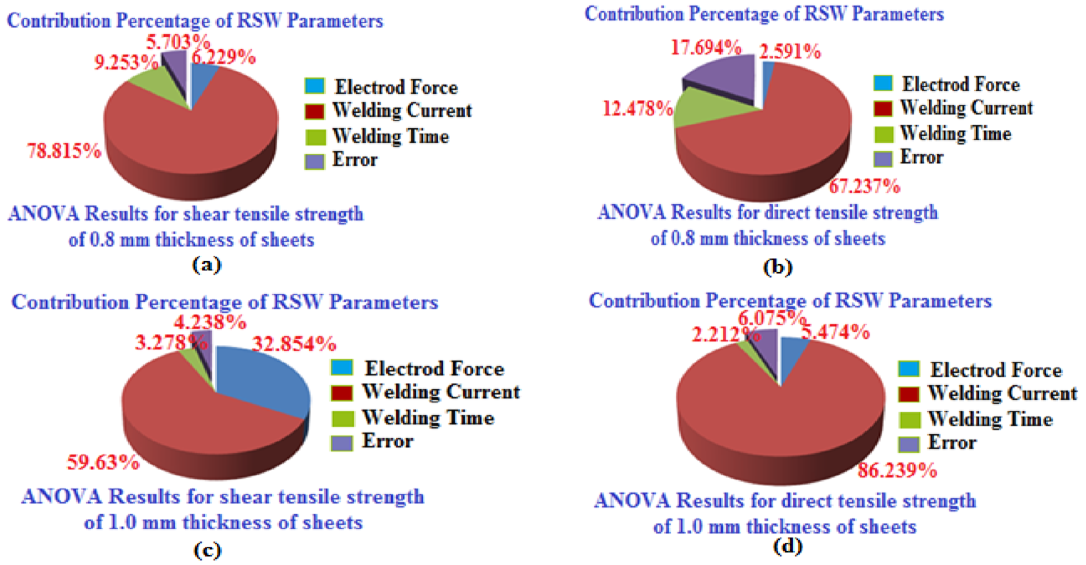


Figure 5: Contribution of RSW process parameters on quality characteristics

Thickness of the sheet		Initial process parameters	Optimal process parameters		Improvement in S/N ratio (dB)
			Predicted	Experiment	
0.8 mm	Level	$A_2B_1C_2$	$A_2B_3C_3$	$A_2B_3C_3$	
	Direct Tensile strength (kN)	2.110	4.062	4.050	1.94*
	S/N (dB)	6.5	12.17	12.15	5.65
	Level	$A_2B_1C_2$	$A_2B_3C_3$	$A_2B_3C_3$	
	Shear Tensile strength (kN)	1.100	3.190	3.190	2.09*
	S/N (dB)	0.8	10.07	10.07	9.27
1.0 mm	Level	$A_2B_1C_2$	$A_2B_3C_3$	$A_2B_3C_3$	
	Direct Tensile strength (kN)	2.110	4.398	4.350	2.24*
	S/N (dB)	6.5	12.86	12.76	6.26
	Level	$A_2B_1C_2$	$A_2B_2C_3$	$A_2B_2C_3$	
	Shear Tensile strength (kN)	4.120	4.992	4.920	0.8*
	S/N (dB)	12.3	13.96	13.83	1.53

Note: * Improvement in raw data

Table 11: The confirmation results of Direct & Shear Tensile strength (S/N Ratios for the Optimal Parameters)

V. Conclusions

This study has presented an experimental investigation on the optimization and the effect of RSW process parameters on the tensile shear strength and direct tensile strength of spot welded CR3 steel sheets. The level of importance of the RSW parameters on the quality characteristics are determined by ANOVA. Based on ANOVA method, the highly effective parameters on tensile shear strength were found as welding current and welding time and the highly effective parameters on direct tensile strength were found as welding current and welding time, whereas electrode force was less effective factor for 0.8 mm thickness of sheets. Similarly for 1.0 mm thickness of sheetsthe highly effective parameters on tensile shear strength were found as welding current and electrode force and the highly effective parameters on direct tensile strength were found as welding current and electrode force, whereas welding time was less effective factor.An optimum parameter's combination for the maximum tensile shear strength and direct tensile strength was obtained by using the analysis of signal-to-noise (S/N) ratio. The confirmation tests indicated that it is possible to increase tensile shear strength significantly by using the proposed statistical technique. The experimental results confirmed the validity of the used Taguchi method for enhancing the welding performance and optimizing the welding parameters in resistance spot welding operations. Further study could consider on different materials, different thicknesses and more factors (e.g. Electrode geometry, etc.) in the research to see how the factors would affect the present and other quality characteristics such as fatigue strength, peel strength etc.

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