Process Parameter Optimization of Spot Welding of AISI 1081 Low Carbon Steel

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ABSTRACT

This experimental study is based on an investigation of the effect and optimization of welding parameters on the tensile shear strength in the Resistance Spot Welding (RSW) process. The experimental studies were conducted under varying forces, currents, and times. The settings of welding parameters were determined by using the Taguchi experimental design of the L9 Orthogonal array method. The combination of the optimum welding parameters has determined by using the analysis of the Signal-to-Noise (S/N) ratio. The confirmation test performed shows that it is possible to increase the tensile shear strength of the joint by the combination of the suitable welding parameters. Hence, 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.

Keyword: - *Resistance Spot Welding (RSW), Tensile strength, Taguchi method, S/N ratio, Optimization.*

I. INTRODUCTION

A. Basic Introduction

Spot welding is a resistance welding method used to join two to four overlapping metal sheets which are up to 3 mm thick each. Two copper electrodes are simultaneously used to clamp the metal sheets together and to pass current through the sheets. When the current is passed through the electrodes to the sheets, heat is generated due to the higher electrical resistance where the surfaces contact each other. As the heat dissipates into the work, the rising temperature causes a rising resistance, and the heat is then generated by the current through this resistance. The surface resistance lowers quickly, and the heat is soon generated only by the resistance of the material. The water-cooled copper electrodes take away the surface heat quickly since copper is an excellent conductor. The heat in the centre has nowhere to go, as the metal of the workpiece is a poor conductor of heat by comparison. The heat remains in the centre, melting the metal from the centre outward. As the heat dissipates throughout the workpiece in less than a second the molten, or at least plastic, the state grows to meet the welding tips. When the current is stopped the copper tips cool the spot weld, causing the metal to solidify under pressure. Some coatings, such as zinc, cause localized heating due to its high resistance and may require pulsation welding to dissipate the unwanted surface heat into the copper tips. It is used extensively in the automotive industry— cars can have several thousand spots.

B. Principle

Resistance welding is accomplished when the current is caused to flow through electrode tips and the separate pieces of metal to be joined. The resistance of the base metal to electrical current flow causes localized heating in the joint, and the weld is made. The resistance spot weld is unique because the actual weld nugget is formed internally with relation to the surface of the base metal shows a resistance spot weld nugget compared to a gas tungsten-arc (TIG) spot weld. The gas tungsten-arc spot is made from one side only. The resistance spot weld is normally made with electrodes on each side of the workpiece. Resistance spot welds may be made with the workpiece in any position. The resistance spot weld nugget is formed when the interface of the weld joint is heated due to the resistance of the joint surfaces to electrical current flow. In all cases, of course, the current must flow or the weld cannot be made. The pressure of the electrode tips on the workpiece holds the part in close and intimate contact during the making of the weld. Remember, however, that resistance spot welding machines are not designed as force clamps to pull the workpieces together for welding.

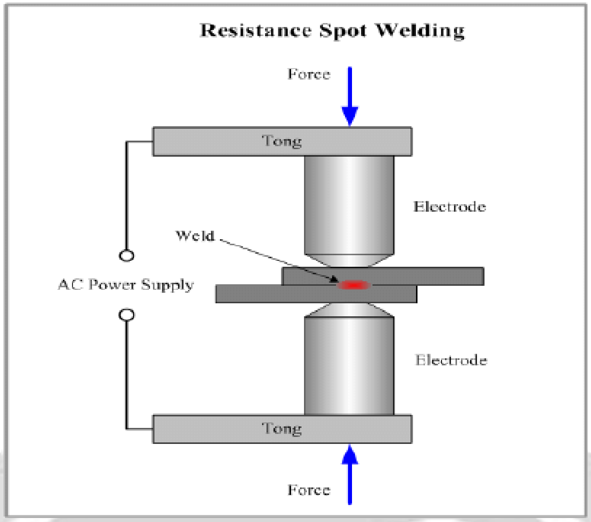

Figure 1: Resistance Spot Welding Process

C. Heat Generation

A modification of Ohm's Law may be made when watts and heat are considered synonymous. When current is passed through a conductor the electrical resistance of the conductor to current flow will cause heat to be generated. The basic formula for heat generation may be stated:

$H = I^2R$

Where

H = Heat

I = Welding Current

R = Resistance

The secondary portion of a resistance spot welding circuit, including the parts to be welded, is a series of resistances. The total additive value of this electrical resistance affects the current output of the resistance spot welding machine and the heat generation of the circuit. The key fact is, although the current value is the same in all parts of the electrical circuit, the resistance values may vary considerably at different points in the circuit. The heat generated is directly proportional to the resistance at any point in the circuit.

- SQUEEZE TIME − Time between pressure application and weld.
- HEAT OR WELD TIME − Weld time cycles.
- HOLD TIME − Time that pressure is maintained after the weld is made.
- OFF TIME − Electrodes separated to permit moving of material for the next spot.

The resistance spot welding machines are constructed so minimum resistance will be apparent in the transformer, flexible cables, tongs, and electrode tips. The resistance spot welding machines are designed to bring the welding current to the weldment in the most efficient manner. It is at the weldment that the greatest relative resistance is required. The term "relative" means about the rest of the actual welding circuit.

There are six major points of resistance in the work area. They are as follows:

i. The contact point between the electrode and the top workpiece.
ii. The top workpiece.
iii. The interface of the top and bottom workpieces.
iv. The bottom workpiece.
v. The contact point between the bottom workpiece and the electrode.
vi. The resistance of electrode tips.

D. Time Factor

Resistance spot welding depends on the resistance of the base metal and the amount of current flowing to produce the heat necessary to make the spot weld. Another important factor is time. In most cases, several thousands of amperes are used in making the spot weld. Such amperage values, flowing through a relatively high resistance, will create a lot of heat in a short time. To make good resistance spot welds, it is necessary to have close control of the time the current is flowing. Time is the only controllable variable in most single impulse resistance spot welding applications. Current is very often economically impractical to control. It is also unpredictable in many cases. Most resistance spot welds are made in very short periods. Since the alternating current is normally used for the welding process, procedures may be based on a 60 cycle time (sixty cycles = 1 second). Control of time is important. If the time element is too long, the base metal in the joint may exceed the melting (and possibly the boiling) point of the material. This could cause faulty welds due to gas porosity. There is also the possibility of the expulsion of molten metal from the weld joint, which could decrease the cross-section of the joint weakening the weld. Shorter weld times also decrease the possibility of excessive heat transfer in the base metal. Distortion of the welded parts is minimized, and the heat-affected zone around the weld nugget is substantially smaller.

D. Electrode Force

The effect of pressure on the resistance spot weld should be carefully considered. The primary purpose of pressure is to hold the parts to be welded in intimate contact at the joint interface. This action assures consistent electrical resistance and conductivity at the point of the weld. The tongs and electrode tips should not be used to pull the workpieces together. The resistance spot welding machine is not designed as an electrical “C” clamp! The parts to be welded should be in intimate contact before the pressure is applied. Investigations have shown that high pressures exerted on the weld joint decrease the resistance at the point of contact between the electrode tip and the workpiece surface. The greater the pressure, the lower the resistance factor. Proper pressures, with intimate contact of the electrode tip and the base metal, will tend to conduct heat away from the weld. Higher currents are necessary with greater pressures and, conversely, lower pressures require less amperage from the resistance spot welding machine. This fact should be carefully noted particularly when using heat control with the various resistance spot welding machines.

E. Electrode Tips

Copper is the base metal normally used for resistance spot welding tongs and tips. The purpose of the electrode tips is to conduct the welding current to the workpiece, to be the focal point of the pressure applied to the weld joint, to conduct heat from the work surface, and to maintain their integrity of shape and characteristics of thermal and electrical conductivity under working conditions. Electrode tips are made of copper alloys and other materials. The Resistance Welders Manufacturing Association (RWMA) has classified electrode tips into two groups:

Group A − Copper-based alloys

Group B − Refractory metal tips

The groups are further classified by number. Group A, Class I, II, III, IV, and V are made of copper alloys. Group B, Class 10, 11, 12, 13, and 14 are the refractory alloys. Group A, Class I electrode tips are the closest in composition to pure copper. As the Class Number goes higher, the hardness and annealing temperature values increase, while the thermal and electrical conductivity decreases. Group B compositions are sintered mixtures of copper and tungsten, etc., designed for wear resistance and compressive strength at high temperatures. Group B, Class 10 alloys have about 40 percent the conductivity of copper with conductivity decreasing as the number value increases. Group B electrode tips are not normally used for applications in which resistance spot welding machines would be employed.

II. LITERATURE REVIEW

Many researchers and academicians of international and national repute have probed into the topic of study of the effect of welding parameters whose name and work abstract has been given below:

Ugur Esme investigated the effect and optimization of welding parameters on the tensile shear strength in the resistance spot welding (RSW) process of SAE 1010 steel. The experimental studies were conducted under varying electrode forces, welding currents, electrode diameters, and welding times. The settings of welding parameters were determined by using the Taguchi experimental design method. The experimental results confirmed the validity of the used Taguchi method for enhancing the welding performance and optimizing the welding parameters in the resistance spot welding process [3].

M. Zhou, H. Zhang, and S. J. Hu. investigated A resistance spot weld’s strength is determined by the physical attributes of the weldment. However, it is extremely difficult to establish a universal relationship with experiments between the measurable attributes of a weld and the weld’s quality. A large number of variables and experimental uncertainty inhibit establishing such a relation. A computer simulation experiment was conducted in this study, using the concept of design of experiments, to overcome the shortcomings of traditional experimental investigations.

Quantitative relationships were established to link a weld's geometric and mechanical attributes to its strength under tensile-shear loading [6].

A.G. Thakur, T E Rao, M S Mukhedkar, and V. M. Nandedkar presented an experimental investigation for optimization of Tensile Shear (T-S) strength of RSW for Galvanized steel by using Taguchi method. RSW of galvanized steel is always difficult due to the tendency of zinc coating alloying with the electrode. The experimental studies were conducted under varying welding current, welding time, electrode diameter, and electrode force. Taguchi quality design concepts of L27 orthogonal array have been used to determine Strength to Noise(S/N ratio), Analysis of Variance (ANOVA), and F test value for determining the most significant parameters affecting the spot weld performance. The experimental results confirmed the validity of the used Taguchi method for enhancing welding performance and optimizing the welding parameter in the RSW process. The confirmation test indicated that it is possible to increase tensile shear strength significantly[4].

Naresh K. Sharma, Elizabeth A. Cudney, Kenneth M. Ragsdell, Kioumars Paryani studied the quality loss function developed by Genichi Taguchi considers three cases, nominal-the best,smaller-the-better, and larger-the-better. This research employs a term called target-mean ratio to propose a common formula for all three cases to bring about similarity among them. The target-mean ratio can take different values representing all three cases to bring consistency and simplicity in the model. Also, it eliminates the assumption of target performance at an infinite level and brings the model closer to reality[9].

A.G. Thakur and V. M. Nandedkar presented a systematic approach to determine the effects of process parameters on tensile shear strength on tensile shear strength of resistance weld joints of austenitic stainless steel AISI 304 using Taguchi method[7].

Resit Unal and Edwin B Dean presented an overview of the Taguchi methods for improving quality and reducing cost, describe the current state of applications, and its role in identifying cost-sensitive design parameters[10].

Min Jou presented the phenomena of how the changes in the controllable parameter of % heat input affect a measurable output signal indicative of strength and weld quality for various steel sheets used in the automotive industry[13].

Krupal Pawar studied the input parameters such as current (Amp), Voltage (V0), welding speed (mm/min), and gas flow rate (Lit/min) for study with tensile vigor as the replication factor. The result utilized for maximizing the tensile strength of AA7075-T73[14].

The objectives of present study are as follows:

- To determine the optimum process parameter combination of resistance spot welding process.
- To determine the importance and share of each parameter affecting the tensile shear strength.

III. METHODOLOGY

A. Overview of the Taguchi Method

Figure 2 provides a brief overview of the process followed by Taguchi's approach to parameter design (Phadke, 1989; Wille, 1990). The details of these steps are briefly described in the following sections.

a. Determine the Quality Characteristic to be Optimized.

The first step in the Taguchi method is to determine the quality characteristic to be optimized. The quality characteristic is a parameter whose variation has a critical effect on product quality. It is the output or the response variable to be observed. Examples are weight, cost, corrosion, target thickness, the strength of a structure, and electromagnetic radiation.

b. Identify the Noise Factors and Test Conditions

The next step is to identify the noise factors that can harm system performance and quality. Noise factors are those parameters that are either uncontrollable or are too expensive to control. Noise factors include variations in environmental operating conditions, deterioration of components with usage, and variation in response between products of the same design with the same input

c. Identify the Control Parameters and Their Alternative Levels

The third step is to identify the control parameters thought to have significant effects on the quality characteristic. Control (test) parameters are those design factors that can be set and maintained. The levels (test values) for each test parameter must be chosen at this point. The number of levels, with associated test values, for each test parameter defines the experimental region.

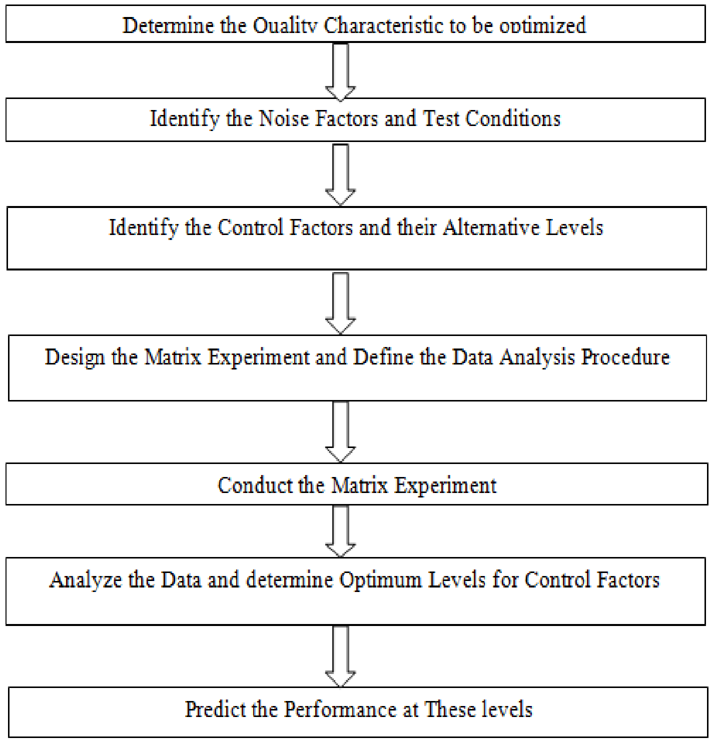

Figure 2 Flowchart of the Taguchi Method

d. Parameters in Resistance Welding

The principle of resistance welding is the Joule heating law where the heat Q is generated depending on three basic factors as expressed in the following formula:

$$Q=I^2Rt \qquad (1)$$

Where I is the current passing through the metal combination, R is the resistance of the base metals and the contact interfaces, and t is the duration/time of the current flow. The principle seems simple. However, when it runs in an actual welding process, there are numerous parameters, some researchers had identified more than 100, to influence the results of a resistance welding. To have a systematic understanding of the resistance welding technology, we have carried out a lot of experimental tests and summarized the most influential parameters into the following three types:

i. Welding Current

The welding current is the most important parameter in resistance welding which determines the heat generation by a power of square as shown in the formula. The size of the weld nugget increases rapidly with increasing welding current, but too high current will result in expulsions and electrode deterioration. The typical types of welding current applied in resistance welding including the single-phase alternating current (AC) that is still the most used in production, the three-phase direct current (DC), the condensation discharge (CD), and the newly developed middle frequency inverter DC. Usually, the root means square (RMS) values of the welding current are used in the machine parameter settings and the process controls. It is often the tedious job of the welding engineers to find the optimized welding current and time for each welding application.

ii. Welding Time

The heat generation is directly proportional to the welding time. Due to the heat transfer from the weld zone to the base metals and the electrodes, as well as the heat loss from the free surfaces to the surroundings, a minimum welding current as well as a minimum welding time will be needed to make a weld. If the welding current is too low, simply increasing the welding time alone will not produce a weld. When the welding current is high enough, the size of the weld nugget increases with increasing welding time until it reaches a size similar to the electrode tip contact area. If the welding time is prolonged, expulsion will occur or in the worst cases, the electrode may stick to the workpiece.

iii. Welding Force

The welding force influences the resistance welding process by its effect on the contact resistance at the interfaces and on the contact area due to the deformation of materials. The workpieces must be compressed with a certain force at the weld zone to enable the passage of the current. If the welding force is too low, expulsion may occur immediately after starting the welding current because the contact resistance is too high, resulting in rapid heat generation. If the welding force is high, the contact area will be largely resulting in low current density and low contact resistance that will reduce heat generation and the size of the weld nugget. In projection welding, the welding force causes the collapse of the projection in the workpiece, which changes the contact area and thereby the contact resistance and the current density. It further influences the heat development and the welding results.

e. Design the Matrix Experiment and Define the Data Analysis Procedure

The next step is to design the matrix experiment and define the data analysis procedure. First, the appropriate orthogonal arrays for the noise and control parameters to fit a specific study are selected. Taguchi provides many standard orthogonal arrays and corresponding linear graphs for this purpose (Taguchi and Konishi,1987). After selecting the appropriate orthogonal arrays, a procedure to simulate the variation in the quality characteristic due to the noise factors needs to be defined. A common approach is the use of Monte Carlo simulation (Phadke, 1989). However, for an accurate estimation of the mean and variance, Monte Carlo simulation requires a large number of testing conditions which can be expensive and time-consuming. As an alternative, Taguchi proposes orthogonal array-based simulation to evaluate the mean and the variance of a product's response resulting from variations in noise factors.

f. Conduct the Matrix Experiment

The next step is to conduct the matrix experiment and record the results. The Taguchi method can be used in any situation where there is a controllable process (Meisl, 1990; Phadke, 1989; Wille, 1990). The controllable process can be an actual hardware experiment, systems of mathematical equations, or computer models that can adequately model the response of many products and processes.

g. Analyze the Data and Determine the Optimum Levels

After the experiments have been conducted, the optimal test parameter configuration within the experiment design must be determined. To analyze the results, the Taguchi method uses a statistical measure of performance called the signal to noise (S/N) ratio borrowed from electrical control theory (Phadke, 1989). The S/N ratio developed by Dr. Taguchi is a performance measure to choose control levels that best cope with noise (Byrne and Taguchi, 1986; Phadke, 1989). The S/N ratio takes both the mean and the variability into account. In its simplest form, the S/N ratio is the ratio of the mean (signal) to the standard deviation (noise). The S/N equation depends on the criterion for the quality characteristic to be optimized. While there are many different possible S/N ratios, three of them are considered standard and are generally applicable in the situations below (Bryne and Taguchi, 1986; Phadke, 1989);

- Biggest-is-best quality characteristic (strength, yield),
- Smallest-is-best quality characteristic (contamination),
- Nominal-is-best quality characteristic (dimension).

Whatever the type of quality or cost characteristic, the transformations are such that the S/N ratio is always interpreted in the same way: the larger the S/N ratio the better.

h. Predict the Performance at These Levels

Using the Taguchi method for parameter design, the predicted optimum setting need not correspond to one of the rows of the matrix experiment. This is often the case when highly fractioned designs are used (Bryne and Taguchi, 1986; Phadke, 1989). Therefore, as the final step, experimental confirmation is run using the predicted optimum levels for the control parameters being studied.

IV. EXPERIMENTATION FOR OPTIMIZATION OF SPOT WELDING

A. Welding Parameters

In this project, three-level process parameters i.e. electrode force, welding current, and welding times are considered. The value of welding process parameters at three different levels is listed in table 1.

Thickness	Parameters	Unit	Level1	Level 2	Level 3
1mm	Electrode force	kN	1.37	1.76	2.15
1mm	Welding current	kA	8.3	9.6	10.5
1mm	Welding time	Cycles	15	17	19

Table1 Level of Parameters

B. Experimental Array

The effect of many different parameters on the performance characteristic in a compacted set of experiments 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 fewer values can be tested or the values tested can be closer together. Knowing the number of parameters and the number of levels, the proper orthogonal array can be selected. Using the array selector table shown below, the name of the suitable array can be found by looking at the column and row corresponding to the number of parameters and number of levels. Once the name has been determined (the subscript represents the number of experiments that must be completed), the predefined array can be looked up. These arrays were created using an algorithm Taguchi developed, and allows for each variable and setting to be tested equally.

Experiment	Electrode force (kN)	Welding current (kA)	Weld time (cycles)
1	1.37	8.3	15
2	1.37	9.6	17
3	1.37	10.5	19
4	1.76	8.3	17
5	1.76	9.6	19
6	1.76	10.5	15
7	2.15	8.3	19
8	2.15	9.6	15
9	2.15	10.5	17

Table 2 L9 Orthogonal Array

C. Material Selection

The chemical composition (percent by weight) and the mechanical properties of the workpiece material are given in Table 3.

Chemical Properties		Mechanical Properties	
Percentage composition (%)		Yield strength (Mpa)	215
C	0.055	Tensile strength(Mpa)	338
Mn	0.27	%Elongation	42
P	0.014	Hardness (HB)	50

Table 3 Properties of the Work Piece Material

The tension shear test experiments were performed on the specimens according to the welding standards of the Resistance Welders Manufacturer Association (RWMA) [23]. The configuration and dimensions of the specimens used throughout the work are given as- Thickness = 1 mm, Width = 30 mm, Length = 252 mm, Contacting Overlap = 30 mm

D. Details of Experimental Procedure

1) Preparing rectangular low carbon steel plates of size 252 mm X 30 mm X 1mm in shaping machine for performing the spot welding operation.
2) Cleaning the workpieces for any oil or dust
3) Checking and preparing the spot gun ready for performing the spot welding operation
4) Carrying out spot welding operation as per orthogonal array combination for each experiment
5) Checking and preparing the tensile testing machine ready for performing the tensile testing operation.
6) Placing the specimens in the jaws correctly
7) Applying the load.
8) Measuring the tensile shear strength of each specimen.

Specimen under Shear Test	Specimens after Shear Test

Figure 3 Images of Specimen Before and After Test

The tensile shear strength of different experiments as per L9 array is as shown in table 4.

Sr. No.	Electrode force	Welding current	Weld time	Tensile shear strength Mpa			
	kN	kA	cycles				
	A	B	C	Trial 1	Trail 2	Trail 3	Mean
1	1.37	8.3	15	89.5	91.85	93.84	91.73
2	1.37	9.6	17	112.85	111.37	111.78	112
3	1.37	10.5	19	119.39	124.61	122	122.14
4	1.76	8.3	17	107.5	111.8	108.9	109.4
5	1.76	9.6	19	107.35	105.8	107.25	106.8
6	1.76	10.5	15	141.28	141.99	136.94	140.07
7	2.15	8.3	19	147.6	149.75	153.25	150.2
8	2.15	9.6	15	105.4	106.75	100.48	104.21
9	2.15	10.5	17	192.04	190.35	190.61	191

Table 4: Tensile shear strength for L9 orthogonal array

V. RESULTS

a. The optimum process parameters were found using the Signal to Noise Ratio. The signal to noise ratio corresponding to the loss function for each experiment of *L9* was calculated. The S/N ratio for each experiment is tabulated in table 5. The S/N ratio for each level was calculated and tabulated in table 8. The level with the highest S/N ratio is the optimum level for that parameter as S/N ratio is the ratio of process average and the standard deviation. Therefore the optimum level for the parameter is that with the highest S/N ratio. Based on the above table data the optimum level for electrode force is level 3, the optimum level for welding current is level 3 and for welding time the optimum level is level 2 is marked with * and is shown in table 6

Sr.No.	Electrode force	Welding current	Weld time	T.S strength Mpa	S/N ratio for T-S strength
	kN	kA	Cycles	(mean)	
	A	B	C		
1	1.37	8.3	15	91.73	39.25
2	1.37	9.6	17	112	40.98
3	1.37	10.5	19	122.14	41.73
4	1.76	8.3	17	109.4	40.78
5	1.76	9.6	19	106.8	40.57
6	1.76	10.5	15	140.07	42.92
7	2.15	8.3	19	150.2	43.53
8	2.15	9.6	15	104.21	40.36
9	2.15	10.5	17	191	45.62

Table 5: S/N Ratios for the Tensile Shear Strength Measurements

	S/N Ratio		
Level	Electrode force	Welding current	Welding time
1	40.65	41.18	40.84
2	41.42	40.63	42.46
3	43.17	43.42	41.94

Table 6 Optimum Level of Welding Parameters

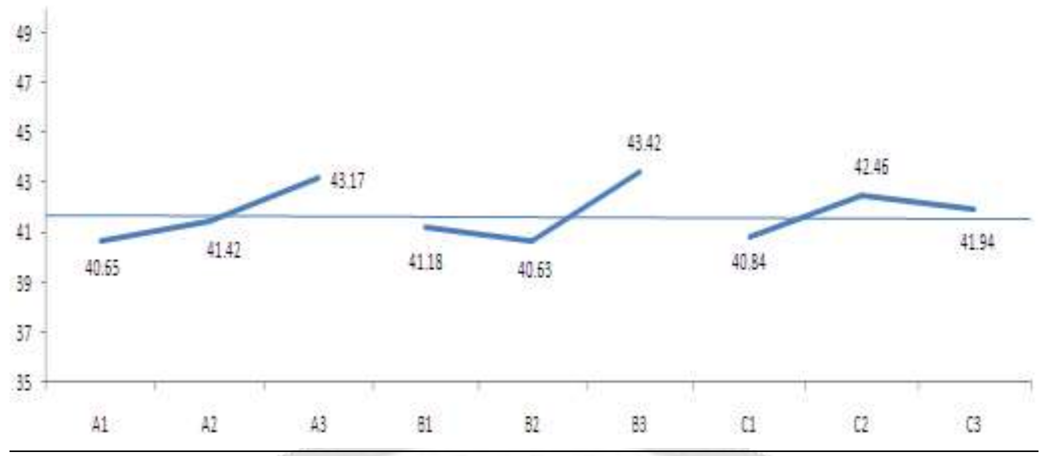

Figure 4 S/N Graph for Tensile Shear Strength

b. The above graph is the S/N ratio graph for tensile shear strength in which A1, A2, A3, B1, B2, B3, C1, C2, C3 represents the three levels of electrode force, welding current and welding time respectively. Basically, the larger the S/N ratio, the better is the quality characteristic for the tensile shear strength.

c. The mean tensile shear strength for each level of the welding process parameters was calculated using the same formula as for calculating the mean signal to noise ratio. The * mark shows the optimum level in Table 7.

	Mean Tensile Shear Strength		
Level	**Electrode force**	**Welding current**	**Welding time**
1	108.63	117.11	112
2	118.76	107.67	137.50*
3	148.50*	151.10*	126.38

Table 7: Mean Tensile Shear Strength for each parameter and level

d. The function of the confirmation test is to validate the conclusions drawn during the experimental phase. The confirmation test is performed by conducting a test with a specific combination of the factors and levels earlier evaluated. In this test, after determining the optimum levels using the S/N ratio, a new experiment was designed and conducted with the optimum levels of the welding parameters. The final step is to verify the improvement of the performance characteristic. The predicted tensile shear strength using the optimal levels of welding parameters can be calculated as

- Yopt = T/N + (Electrode force (opt) – T/N) + (Welding current(opt) – T/N) + (Welding time(opt) -T/N)
- Yopt =186.8 Mpa

Where, Yopt = Predicted optimum performance
T = Total number of observed values for all the experiment
N = Total number of observed values
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 8.

	Initial Process Parameter	**Optimal Process Parameter**	**Improvement in S/N ratio**

		Predicted	**Experimental**	
Level	**A1B1C2**	**A3B3C2**	**A3B3C2**	
T-S strength (Mpa)	175.67	186.8	191	0.73
S/N (dB)	44.89	45.42	45.62	

Table 8 Results of Test

The enhancement in S/N ratio from the starting welding parameters with level 1 of electrode force, level 1 of welding current and level 2 of the welding time to the level of optimal welding parameters with level 3 of electrode force, level 3 of welding current and level 2 of welding time is 0.73 dB. The tensile shear strength is increased by 8.72% from 175.67 Mpa to 191.00 Mpa. Therefore the tensile shear strength is improved to a great extent by using the Taguchi method.

e.A better understanding of the relative effect of the different welding parameters on the tensile shear strength (TS) was obtained by decomposition of variance, which is called analysis of variance (ANOVA). The total variance in the result is attributed among the parameters with the help of statistical methods which also helps in calculating the percentage significance of each factor. A factor scoring more percentage should be taken care of on a priority basis (sometimes some unavoidable constraints of time, money, etc.) do not permit optimization of every parameter and some of the parameters should be left as they are to their current levels. ANOVA helps to choose the parameters which badly need optimization and the parameters which can be left as they are which do not add much variance and scoreless percentage of significance. The relative importance of the welding parameters concerning the tensile shear strength was investigated to decide more accurately the optimum combinations of the welding parameters by using ANOVA. According to this analysis, the most effective parameters concerning tensile shear strength are welding current, electrode force, and welding time. Percent contribution indicates the comparative 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 9

Parameter	**Degree of Freedom**	**Factor Sum of Squares**	**Pure Sum of Squares**	**Contribution %**
Electrode force	2	2608.9	1863.72	24.81
Welding current	2	3151	2405.82	32.04
Welding time	2	1003.24	258.06	3.43
Error	2	745	2980.72	39.69
Total	8	7508.32		

. **Table 9:** Calculation results from ANOVA

Sr. No.	**Welding Parameters**	**Percentage Contribution**
1	Electrode force	24.81%
2	Welding current	32.04%
3	Welding time	3.43%

. **Table 10:** Percentage Contribution of Parameters

Percent contribution indicates the comparative 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. According to Table 14, the welding current was found to be the major factor affecting the tensile strength (32.04% for 1mm), whereas the electrode force was found to be the second-ranking factor (24.81% for 1mm). The percent contribution of welding time is much lower, being 3.43% for 1mm, respectively.

VII. CONCLUSIONS

This paper has presented an analysis of the optimization and the effect of welding parameters on the tensile shear strength of spot-welded low carbon steel sheets. The least number of experiments required to obtain maximum important information was determined by using the orthogonal array. An optimum parameter combination for the maximum tensile shear strength was obtained by using the analysis of the 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 level of importance of the welding parameters on the tensile shear strength is determined by using ANOVA. Based on the ANOVA method, the highly effective parameters on tensile shear strength were found as welding current and electrode force, whereas welding time was a less effective factor.

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