Optimization of Resistance Spot Weld Parameters using Grey Relational Analysis

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Abstract— Resistance spot welding approach in joining process which is widely accepted in the automotive industry to join steel parts of various thicknesses and types. The current practice in the automotive industry in determining the welding characteristics, which will be used in the welding process. This study concerns the employment of Taguchi Based grey relational analysis to determine the optimized joint characteristics in stainless steel & Mild steel joining of dissimilar materials. The joint characteristics, namely Electrode Force (KN), Weld Current (KA), Hold Time (Cycle) function of Average Tensile Shear Strength (kN), Average Weld Nugget Diameter (mm), Average Weld Indentation (mm). The experimentation in this work used a L9 orthogonal array with three factors with each factor having three levels. Taguchi Based grey relational analysis is employed to characterize the multiple quality characteristics of welded joint in terms of a relational grade. Analysis of variance (ANOVA) is then carried out to ascertain the relative influence of process parameters on the joint characteristics. The three factors used are welding current, weld time and electrode force. The three weld characteristics that were optimized are Average Tensile Shear Strength (kN), Average Weld Nugget Diameter (mm), Average Weld Indentation (mm). The analysis of variance (ANOVA) that was carried out showed that welding current gave the most significant contribution in the optimum welding schedule. The comparison test that was carried out to compare the current welding schedule and the optimum welding schedule showed distinct improvement in the increase of weld diameter and weld strength has well as decrease in electrode indentation.

Key words: Optimization, Multiple Quality Characteristics, Taguchi Based Grey Relational Analysis, Surface Roughness, Analysis of Variance

I. INTRODUCTION

Resistance spot welding process uses heavy current which is passed for a short period of time through the area of interface of metals and the application of pressure on the sheets to be joined. In resistance spot welding process flux is not used, and the use of filler metal is very rare[2]. Resistance welding operations are normally automatic and, therefore, all process parameters are pre-set and maintained constant. Heat generated in a localized area is enough to raise the temperature at interface, so that the parts can be joined with the application of pressure.

Spot welding operates based on four factors that are:

1) Amount of current that passes through the work piece.
2) Pressure that the electrodes applied on the work piece.
3) The time the current flow through the work piece.
4) The area of the electrode tip contact with the work piece.

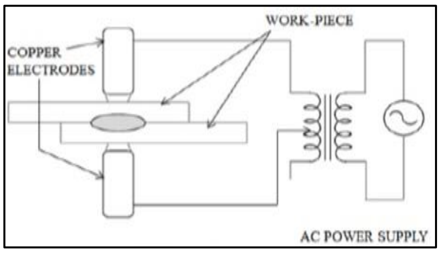


Fig. 1: Spot Weld

Resistance spot welding is getting significant importance in car, bus and railway bodies etc. due to automatic and fast process. The major factors controlling this process are current, time, electrode force, contact resistance, property of electrode material, sheet materials, surface condition etc. the quality is best judged by nugget size and joint strength. This study presents a systematic approach to determine effect of process parameters (electrode force, weld time and current) on tensile shear strength of resistance weld joint of mild steel using Taguchi method. A general introduction for principle, working and parameters of spot welding is given below. Resistance Spot Welding (RSW) is among the oldest of the electric welding method that used in the industry and it is useful and accepted method in joining metal.

II. LITERATURE REVIEW

- Thakur.et al.[15], focused to optimize tensile shear strength for galvanized steel using L27 orthogonal array method. On the basis of ANOVA, highly effective parameters are current and time, whereas force and diameter are less effective parameters. Using S/N ratio, tests indicate that tensile shear strength can be increased significantly (13.43%) by using the proposed statistical technique.
- Niranjan Kumar Singh .et al.[16] using Taguchi method conducted experiments in two phases on Austenition stainless steel grade 301 to find the effect of process parameters(welding current, weld cycle, hold time, cool cycle) on indentation as primary and initial measure of weld quality including tensile strength, nugget diameter and penetration.L32 orthogonal array and minitab 14 software was used for analysis. They found that the average indentation was 0.87mm and data followed normal distribution but after conducting Taguchi method, residuals followed normal distribution without any pattern with time and fitted value. The validity of Taguchi method was confirmed.
- Pandey. et al.[17] used taguchi method on low carbon cold rolled 0.9mm thick mild steel sheets to find the

effect of parameters on quality of weld strength. According to the results, current contribute 61%, holding time 28.7% and pressure 4% on tensile strength. For optimum result, current should be 6.8KA, pressure 0.79KPa, and holding time of 5 sec.

- Kadam. et al.[18] with the help of non-linear method like Genetic algorithm studied the effect of process parameters on nugget relation between responses and variable input parameters. They found that nugget dia. increases by increasing the number of generation. According to them with the help of Genetic algorithm, maximum value of nugget dia. can be obtained.
- Panchakshari. et al.[19] carried out a comparative study of responses on low carbon steel using three methods-Genetic algorithm, Design of experiment and Response surface method and cross validated the results by using D-optimal method. The results shows that weld cycle and welding current should be 12 cycles and 11.2KA respectively. Other parameters such as hold cycle, squeeze cycle, nugget dia., and weld strength must lie at range of 12 cycles, 30 cycles, 5.4mm and 290N/mm2 respectively.
- Arvinder Singh.et al.[20] used Taguchi L9 orthogonal array method to find the effect of process parameters(pressure, weld time, and welding current) on tensile strength of austenitic stainless steel AISI 316L.They found maximum tensile strength of 789.46N/mm2 at pressure 3.1KN,welding time 4ms and current 15KA
- Darshan Shah. et al.[21] used neural network-based systems to find the optimum process parameters for resistance spot welding and weld quality assessment. Input parameters used includes are welding current, sheet thickness and cycle time. Parametric analysis is carried out for the quality of the resistance spot welding, i.e. weld strength. This parametric analysis (ANOVA) using weld strength as quality indicator shows the percentage contribution of parameters individually, i.e. welding current as 49.81 %, thickness of 37.94 % and cycle time of 2.61 % and the error is of 9.62 %. It has been found that welds strength increases as welding current increases and weld strength decreases as thickness of the material increases.
- Pradeep M. et al.[23] present an approach to find out the optimum weld parameters in spot welding dissimilar material thickness. Parameters for welding of dissimilar thickness material are not available beyond 4mm.Low carbon steel have been used by them having a 0.8mm thick metal strips of cross-section 10 and 5 mm having a composition of 0.101 C,.33 Mg,0.011 S, and 0.019 P (wt.%).Taguchi approach has been used for the optimization of welding current and time using L9 orthogonal array. There result indicates optimum current as 3.5KA and time 10 cycles.
- Suresh R K.[24] reported a systematic approach to determine the effect of process variable(welding current, time, electrode size) on tensile shear strength properties using mild steel 1 mm thick,18mm wide and 150mm long sheets and copper electrodes. He used taguchi approach for design of optimization experiment. The input parameters used included welding current, welding time and electrode dia keeping squeezing time, hold time, electrode force, and sheet thickness as constant.L27 orthogonal array was selected for this study. A total of 27 experiments with mixed combination of inputs were carried out. The results indicated maximum tensile strength at current level of 17.5A, weld time of 15 sec. and electrode diameter of 3mm.ANOVA results showed the % contribution of current as 63.7%, weld time 28.7% for maximum tensile shear strength.
- Wuttipornpun [5] has determined an optimum welding condition to reduce welding spatter. The author has selected four independent variable namely electrical supply, thickness of material, welding angle and welding position and used a full factorial experiment. The conclusion of the work showed that electrical supply, welding angle and welding position are variables that affect the number of defective parts due to spatter.
- Balasubramaniam [6] has used regression analysis to optimize the welding current and weld time setting to achieve a minimum nugget diameter and a maximum tensile shear force. The work was carried out on the SPRC35 steel sheet. Subramaniam concluded the increase in welding current will lead to increase in nugget diameter and tensile shear strength.
- Hamedi et.al [7] has used artificial neural network (ANN) and genetic algorithm (GA) to optimize spot welding parameters required to minimize dimensional deviations or gaps in subassemblies. The ANN was used to produce relationships between the welding parameters and their respective produced assembly gaps. GA was later used to select the optimum welding parameters which gave the smallest dimensional deviation.
- Norasiah et.al [8] has looked into optimizing spot weld parameters in order to achieve a nominal weld diameter and smaller heat affected zone (HAZ) using Response Surface Methodology. Kim et.al [9] also has used Response Surface Methodology to determine the optimum spot weld parameters for TRIP steels. The work has developed a regression model to determine the response surface expressing the relationship between the input variables (welding current, welding time and welding force) and the output variables (shear strength and indentation).

III. TAGUCHI METHOD

Taguchi methods are statistical methods developed by Genichi Taguchi {5} to improve the quality of manufactured goods and more recently also applied to engineering,biotechnology, marketingand,advertising. Profe ssional statisticians have welcomed the goals and improvements brought about by Taguchi methods, particularly by Taguchi's development of designs for studying variation, but have criticized the inefficiency of some of Taguchi's proposals. The Taguchi method is a commonly adopted approach for optimizing design parameters. The method was originally proposed as a means of improving the quality of products through the application of statistical and engineering concepts. It is a method based on Orthogonal Array (OA) {8} experiments, which provides much-reduced variance for the experiment resulting is optimum setting of process control parameters. Orthogonal Array (OA) provides a set of well-balanced experiments (with less number of experimental runs) and Taguchi's signal-to-noise ratios (S/N), which are logarithmic functions of desired output, serves as objective function in the optimization process. This technique helps in data analysis and prediction of optimum results.

Taguchi method is a powerful tool for the design of high quality systems. It provides simple, efficient and systematic approach to optimize designs for performance, quality and cost. Taguchi method is efficient method for designing process that operates consistently and optimally over a variety of conditions. To determine the best design it requires the use of a strategically designed experiment. Taguchi approach to design of experiments in easy to adopt and apply for users with limited knowledge of statistics, hence gained wide popularity in the engineering and scientific community. The desired cutting parameters are determined based on experience or by hand book. Cutting parameters are reflected.

Steps of Taguchi method are as follows:

- Identification of main function, side effects and failure mode.
- Identification of noise factor, testing condition and quality characteristics.
- Identification of the main function to be optimized.
- Identification the control factor and their levels.
- Selection of orthogonal array and matrix experiment.
- Conducting the matrix experiment.
- Analyzing the data, prediction of the optimum level and performance.
- Performing the verification experiment and planning the future action.

A. *Orthogonal Arrays*

Taguchi has developed a system of tabulated designs (arrays) that allow for the maximum number of main effects to be estimated in an unbiased (orthogonal) manner, with a minimum number of runs in the experiment. Orthogonal arrays are used to systematically vary and test the different levels of each of the control factors. Commonly used OAs includes the L4, L9, L12, L18, and L27. The columns in the OA indicate the factor and its corresponding levels, and each row in the OA constitutes an experimental run which is performed at the given factor settings. Typically either 2 or 3 levels are chosen for each factor. Selecting the number of levels and quantities properly constitutes the bulk of the effort in planning robust design experiments. If there is an experiment having 3 factors which have three values, then total number of experiment is 27. Then results of all experiment will give 100% accurate results. In comparison to above method the Taguchi orthogonal array make list of nine experiments in a particular order which cover all factors. Those nine experiments will give 99.96% accurate result. By using this method number of experiments reduced to 9 instead of 27 with almost same accuracy.

B. *Signal to noise ratio and Pareto ANOVA approach*

The S/N ratio developed by Dr. Taguchi is a performance measure to choose control levels that best cope with noise. The S/N ratio {7} 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. There are three standard types of SN ratios depending on the desired performance response.

1) *Smaller the better (for making the system response as small as possible)*

$$SN_S = -10 \log \left(\frac{1}{n}\sum_{i=1}^{n} Y_i^2\right)$$

2) *Nominal the best (for reducing variability around a target)*

$$SN_T = 10 \log (Y^2/S^2)$$

3) *Larger the better (for making the system response as large as possible)*

$$SN_L = -10\log \left(\frac{1}{n}\sum_{i=1}^{n} 1/Y_i^2\right)$$

"Where *n* is the number of observations, y is the observed data".

These SN ratios are derived from the quadratic loss function and are expressed in a decibel scale. Once all of the SN ratios have been computed for each run of an experiment, Taguchi advocates a graphical approach to analyze the data. In the graphical approach, the SN ratios are plotted for each factor against each of its levels. Finally, confirmation tests should be run at the "optimal" product settings to verify that the predicted performance is actually realized.

C. *Grey Relational Method*

Following steps are important in grey relational analysis.

- Normalize all experimental turns' value.
- Perform operation of grey relational generating & to calculate grey relational coefficient (GRC).
- Averaging the value of grey relational coefficient (GRC) to determine grey relational grade (GRG).
- Perform ANOVA analysis with grey relational grade (GRG) and to find which parameter significantly affects experimental process.
- Select optimal level of parameters to determine optimal or prediction value.
- Conduct confirmation test and validate the prediction value.

IV. PROBLEM IDENTIFICATION

A. *Resistance Welding Parameters*

There are three main parameters which control the quality of resistance spot welding. Diagrammatically shown in figure:

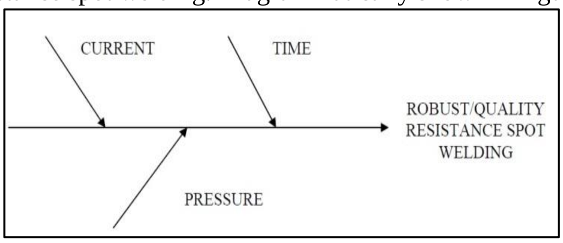


Fig. 2: Cause and effect diagram of main welding parameters

B. *Effect of Welding Current*

Current controls the heat which generated according to the equation $Q = I^2 Rt$. This shows that the current has more influence on the amount of heat generated Tensile shear strength increases rapidly with increasing current density. Excessive current density will cause molten metal expulsion (resulting in internal voids), weld cracking, and lower mechanical strength properties. Typical variations in shear strength of spot welds as a function of current magnitude are shown in Figure 2. In the case of spot welding excessive current will overheat the base metal and result in deep indentations in the parts and, it will cause overheating and rapid deterioration of the electrodes.

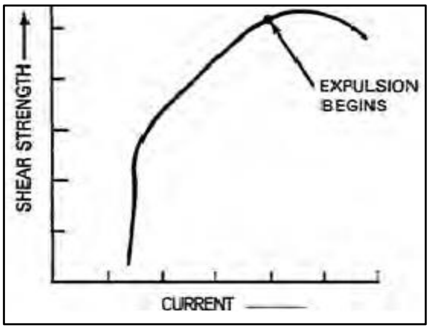


Fig. 3: Effect of welding current on spot weld shear strength

C. Effect of Weld Time

The rate of heat generation must be such that welds with adequate strength will be produced without excessive electrode heating and rapid deterioration. The total heat developed is proportional to weld time. During a spot welding operation, some minimum time is required to reach melting temperature at some suitable current density. Excessively long weld time will have the same effect as excessive amperage on the base metal and electrodes. Furthermore, the weld heat-affected zone will extend farther into the base metal. The relationship between weld time and spot weld shear strength is shown in Figure.3 assuming all other conditions remain constant. To a certain extent, weld time and amperage may be complementary. The total heat may be changed by adjusting either the amperage or the weld time. Heat transfer is a function of time and the development of the proper nugget size requires a minimum length of time, regardless of amperage

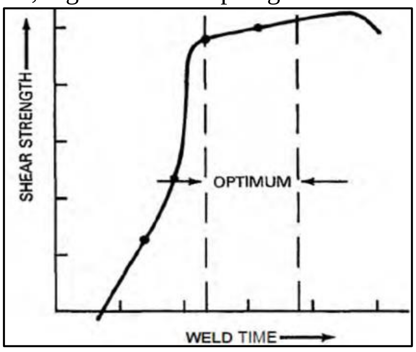


Fig. 4: Tensile-shear strength as a function of weld time

D. Effect of Welding Pressure

Welding pressure is produced by the force exerted on the joint by the electrodes. Electrode force is considered to be the net dynamic force of the electrodes upon the work, and it is the resultant pressure produced by this force that affects the contact resistance. As the pressure is increased, the contact resistance and the heat generated at the interface will decrease. To increase the heat to the previous level, amperage or weld time must be increased to compensate for the reduced resistance.

1) Types of Failure of the Welding Joint

There are two fracture modes of the spot welding joint have analysed, they are

- Interfacial mode (or nugget fracture): fracture of the weld nugget through the plane of the weld. The dominant failure mode for small diameter spot welds.
- Nugget pull-out mode (or sheet fracture): fracture of the sheet around the weld; the nugget remains intact. Dominant for large diameter spot welds.

V. Experiment and Data Collection

A. Experimental Setup

A batch of 100 mm×30mm×30 mm dissimilar sheets of Stainless steel & mild steel were selected. The chemical component of both steels is shown in “Table 1” & “Table 2”. The material of electrode is of copper.

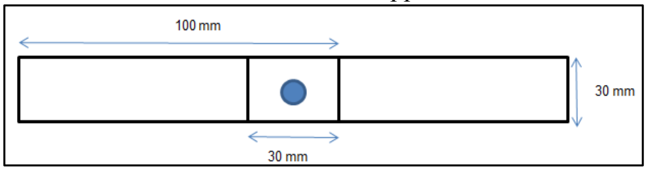


Fig. 5: Tensile shear test sample

C	Si	Mn	P	S
0.021	0.35	1.27	0.03	0.001
Cr	Ni	Mo	Ti	N
18.1	8.02	-	-	0.053

Table 1: Chemical composition of stainless steel sheets (weight %)

Component	C	Si	Mn	S	P
Wt%	0.16-0.18	0.40 max	0.70-0.90	0.40 max	0.40 max

Table 2: Chemical component of Mild steel

B. Method of Experiment

The Three main parameters in resistant spot welding are Electrode Force (KN), Weld Current (KA), Hold Time (Cycle). In order to produce good quality weld the above parameters must be controlled properly. The amount of heat generated in this process is governed by the formula,

$Q = I^2 R T$

Where

Q = heat generated, Joules

I = current, Amperes

R = resistance of the work piece, Ohms

T = time of current flow, second

C. Process Parameters

Parameters of the setting	
Control factor	Symbol
Electrode Force(KN)	Factor A
Weld Current(KA)	Factor B
Hold Time(CYCLE)	Factor C

Table 3: Process parameters

1) Selection of L9 Orthogonal Array

The input parameter is selected as Electrode Force (KN), Weld Current (KA), Hold Time (Cycle) Desired output parameters are average tensile shear strength (kN) average weld nugget diameter (mm), average weld indentation (mm). The input parameters are shown in “Table 3”.

Level	Force (KN)	Weld Current (KA)	Hold Time (Cycle)
	(A)	(B)	(C)
1	2	3	4
2	8	9	10
3	10	15	20

Table 4: Spot welding parameter of the setting

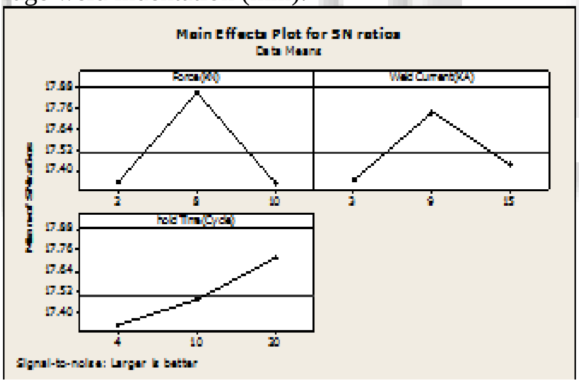
VI. RESULT

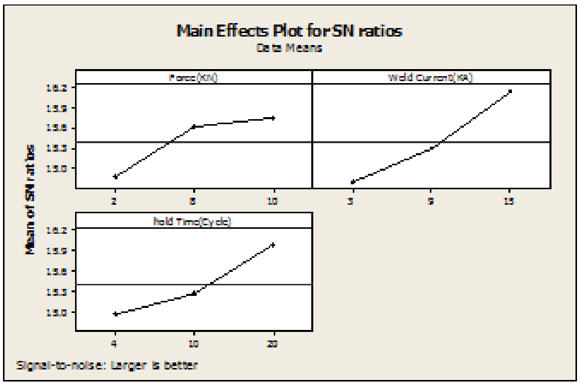
The experimentation was carried out using L9 orthogonal array in Taguchi Method as shown in Table .The outputs of this work were the weld tensile shear strength, weld nugget diameter and weld indentation. Tensile shear strengths for three test samples for each test were obtained by conducting a tensile test on a Universal Testing Machine. Optical microscope was used to measure the weld fusion zone in order to determine the weld nugget diameter. Weld indentations on each weld samples were measured using a digital dial gauge. The dial gauge was placed on the sample surface to get a measurement point. The gauge was later place on the surface of the spot weld to get another measurement point. The difference between the measurement points is computed as the weld indentation.

S. No.	F (KN)	Weld Current (KA)	Hold Time (Cycle)	Average Tensile Shear Strength (kN)	Average Weld Nugget Diameter (mm)	Average Weld Indentation (mm)
1	2	3	4	6.82	4.77	0.21
2	2	9	10	7.77	5.53	0.22
3	2	15	20	7.51	6.43	0.38
4	8	3	10	7.67	5.53	0.15
5	8	9	20	7.93	6.2	0.29
6	8	15	4	7.83	6.4	0.36
7	10	3	20	7.63	6.27	0.4
8	10	9	4	7.43	5.73	0.21
9	10	15	10	7.01	6.37	0.48

Table 5: Results in L9 Orthogonal

AvgStr = average tensile shear strength (kN), AvgD = average weld nugget diameter (mm), AvgI = average weld indentation (mm).





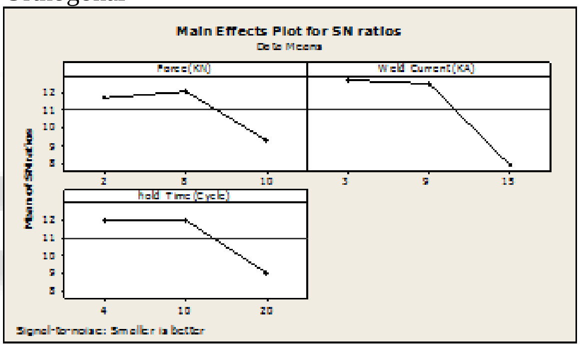


Fig. 6: SN Ratios

So in this thesis Spot weld parameters Electrode Force, Weld Current, Hold Time with different outputs of this work were the weld tensile shear strength, weld nugget diameter and weld indentation investigated employing Taguchi's design of experiments and optimized by S/N ratio.

The statistical analysis is done using MINITAB software for obtaining the main effect, interaction effect and graphs

A. Normalized Experimental Results

The normalized original sequence used in Table is as the following

- If a larger quality characteristics of the original data is better (larger-the-better)

$$x_i(k) = \frac{x_i(k) - \min\ x_i(k)}{\max\ x_i(k) - \min\ x_i(k)} \qquad (1)$$

- If a smaller quality characteristics of the original data is better (smaller-the-better)

$$x_i(k) = \frac{\max\ x_i(k) - x_i(k)}{\max\ x_i(k) - \min\ x_i(k)} \qquad (2)$$

Where xi(k) is the normalized original sequence after pre-processing, max $x_i(k)$ is the maximum value of

$x_i(k)$ and min $x_i(k)$ is the minimum value of $x_i(k)$. Table shown below the normalized values after data pre-processing using Grey relational analysis (1) and (2).

Test	Force (KN)	Current (KA)	Time (Cycle)	Avg Str	Avg Dia	Avg Ind
T1	2	3	4	0	0	0.82
T2	2	9	10	0.86	0.35	0.79
T3	2	15	20	0.62	0.8	0.3
T4	8	3	10	0.77	0.35	1
T5	8	9	20	1	0.65	0.58
T6	8	15	4	0.91	0.83	0.36
T7	10	3	20	0.73	0.68	0.24
T8	10	9	4	0.55	0.44	0.82
T9	10	15	10	0.17	1	0

Table 6: Normalized results using grey relational analysis

B. Deviation Sequences

Table given Below the deviation sequences, $\Delta_{0i(k)}$ which is the absolute value between $x_i(k)$ and $x_0(k)$

$$\Delta_{0i(k)}=|x_i(k)-x_0(k)| \quad (3)$$

Test	Force (KN)	Current (KA)	Time (Cycle)	Avg Str	Avg Dia	Avg Ind
T1	2	3	4	1	1	0.18
T2	2	9	10	0.14	0.65	0.21
T3	2	15	20	0.38	0.2	0.7
T4	8	3	10	0.23	0.65	0
T5	8	9	20	0	0.35	0.42
T6	8	15	4	0.09	0.17	0.64
T7	10	3	20	0.27	0.32	0.76
T8	10	9	4	0.45	0.56	0.18
T9	10	15	10	0.83	0	100

Table 7: Deviation Sequences

C. Determination of Grey Relational Coefficient and Grey Relational Grades

Table shows Below the calculations of Grey relational coefficients and Grey relational grades using (4) and (5) respectively.

$$\gamma(x_0^*, x_i^*(k)) = \Gamma_i = \frac{\Delta_{min} + \zeta.\Delta_{max}}{\Delta_{0i}(k) + \zeta.\Delta_{max}} \quad (4)$$

$$0 < \gamma(x_0^*(k), x_i^*(k)) \leq 1$$

ζ which is a distinguishing coefficient was given a value 0.5.

$$\Delta_{max} = \max_{\forall j \in i} \max_{\forall k} |x_0^*(k) - x_i^*(k)| \quad \Delta_{min} = \min_{\forall j \in i} \min_{\forall k} |x_0^*(k) - x_i^*(k)|$$

$$\gamma(x_0^*, x_i^*) = \frac{1}{n}\sum_{k=1}^{n} \gamma(x_0^*(k), x_i^*(k)) \quad (5)$$

Grey relational grades represented the level of correlation between the reference and the comparability sequences; the larger Grey relational grade means the comparability sequence exhibiting a stronger correlation with the reference sequence. Table shown below the average grey relation grade for each factor levels. Fig. shows the largest value of grey relational grades for factors A, B and C respectively. Therefore the welding schedule with force of 3 kN, time of 15 cycles and current of 9 kA is identified as the optimal welding schedule for welding.

TEST	Force (KN)	Current (KA)	Time (Cycle)	Avg Str	Avg Dia	Avg Ind	Grade	Rank
T1	2	3	4	0.33	0.33	0.73	0.47	8
T2	2	9	10	0.78	0.43	0.7	0.64	4
T3	2	15	20	0.57	0.71	0.42	0.57	6
T4	8	3	10	0.68	0.43	1	0.7	2
T5	8	9	20	1	0.63	0.54	0.72	1
T6	8	15	4	0.85	0.75	0.44	0.68	3
T7	10	3	20	0.65	0.61	0.4	0.55	7
T8	10	9	4	0.53	0.47	0.73	0.58	5
T9	10	15	10	0.38	1	0.33	0.57	6

Table 7: Grey Relational Coefficients and Grades

	Level		
Factor	1	2	3
A	0.56	0.7	0.6
B	0.53	0.64	0.61
C	0.57	0.64	0.6

Table 8: Average Grey Relational Grades For Different Factors And Levels

D. Analysis of Variance (ANOVA)

ANOVA was carried out to find which out of the three factors used in this work gives the most significant contribution in the spot welding.

Factor	DOF	SS	MS	% Contribution
A	2	0.004467	0.002233	21.5
B	2	0.0122	0.0061	58.7
C	2	0.002467	0.001233	11.9
Error	2	0.001645	0.001267	7.9
Total	8	0.020779		100

Table 8: ANOVA

VII. CONCLUSION

- The results find in this work drawn from experimental data evaluation. This work was conducted to study the use of Grey Based Taguchi Method to optimize the welding parameters for welding dissimilar material thicknesses and types. The conclusions of the work are as below:
- The optimum Resistance Spot welding parameters obtained in this work is a set of 3 kN of electrode force, time of 15 cycles and 9 kA welding current.
- ANOVA analysis that current provides the most significant contribution in this work to obtain optimized weld characteristics.
- The optimum welding schedule showed improvement in the weld characteristics compared to the welding schedules currently being used
- The advantages of Taguchi method in simplifying the experimentation was effectively utilized in this investigation for design and analysis for weld quality.

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