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Optimization of Resistance Spot Welding of 304 Steel Using GRA

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Abstract—Resistance spot welding (RSW) quality is mainly depends upon the parameters and their levels selected, like welding current, electrode force and welding time etc. So selection of optimal parameter levels plays an important role. Therefore, optimization of weld tensile strength and nugget diameter is selected for study. In this paper, use of Taguchi with Grey relational analysis (GRA) method to determine significant process parameters and their levels for optimal tensile shear strength (T-S) and nugget diameter (N-D) is reported. Taguchi based L27 (33) orthogonal array is selected for experimentation. Experiments are carried out on Stainless Steel 304. The level of importance of the welding parameters on the tensile shear strength and nugget diameter is determined by using analysis of variance (ANOVA) using Minitab 16 software. To improve the spot weld quality (i.e. T-S and N-D) multi objective process parameter optimization is performed using grey relational analysis.

Index Terms—Resistance Spot Welding (RSW), Tensile shear strength, Nugget diameter, Taguchi Method, Grey Relational Analysis

1. INTRODUCTION

Resistance spot welding process, in which coalescence of metal is produced at the faying surfaces by the heat generated at the joint by the contact resistance to the flow of electric current. The materials to be joined are brought together under pressure by a pair of electrodes. A high electric current passes through the workpiece between the electrodes. Due to contact resistance and joule heating, a molten weld nugget is formed in the work pieces. The amount of heat produced is a function of current, time and resistance between the workpieces. 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 theelectrodes and work should be kept as low as possible with respect to the resistance between the faying surfaces [1]. The principle of working is as shown in Fig.1.

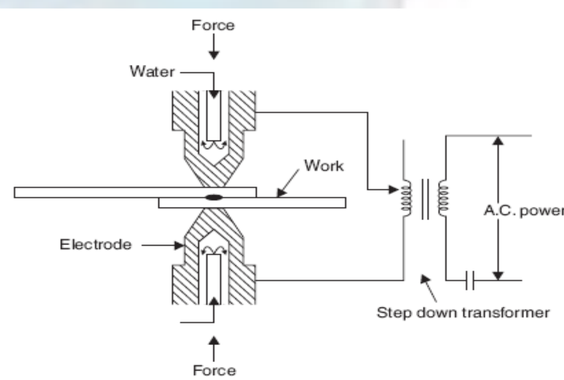

Fig. 1: Working Principle of Resistance Spot Welding

As the name implies, it uses the resistance of the materials to the flow of current that causes localized heating between the parts to be joined. Excessive heat in the electrodes reduces the electrode cap life and deteriorates the weld quality. Hence, the electrodes are cooled via water circulation through channels opened inside them [1]. The temperature and resistance obtained during resistance spot welding operation is as shown in Fig.2. Where R1, R2, R3 are the resistances at the Electrode tip and plate surface, Resistance of joining plates, Resistance at the interface of two plates respectively.

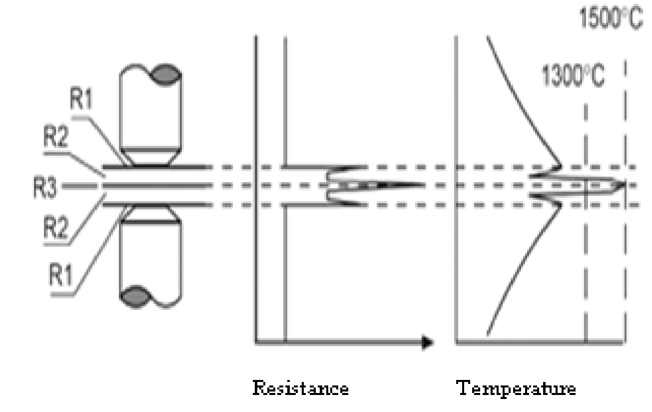

Fig. 2: Resistance and Temperature Distribution Curve

Resistance spot-welding is widely used as an efficient joining technology for assembling sheet metal components in the automotive industry. One priority of these industries is the production of high-quality spot welds to ensure the stability and safety of their products. One way to produce high-quality spot weld joints is to monitor the welding parameters such as voltage, welding current, electrode pressure, time, surface condition, etc. [2].

To predict the welding parameters accurately without consuming time, materials and labor efforts, there are various methods of obtaining the desired output variables through model development. Using appropriate statistical technique such as Taguchi Method (TM) and ANOVA, the number of unnecessary experiments can be reduced and the statistical significance of parameters can be safely identified.

There are many parameters which control the quality of resistance spot welding; Effect of these parameters is easily understood by cause and effect diagram as shown in Fig.3

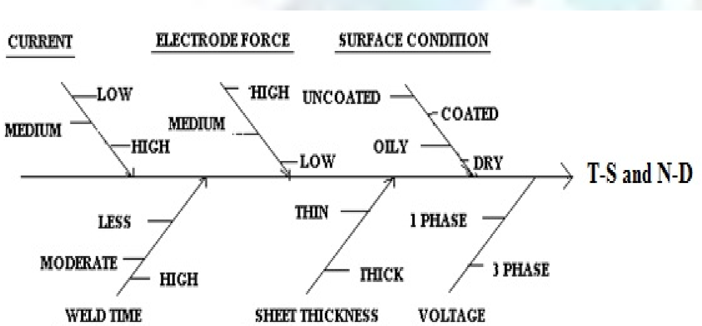

Fig.3: Cause and Effect Diagram for RSW

1.1 HEAT GENERATION IN RSW

There are three main parameters which affects the amount of heat generated in RSW namely, Welding current, contact resistance and weld time. 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 Eq.1.

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

Where, Q = Heat generated (J), I = Current (A)

R = Resistance of the work piece (Ω)

T = Time of current flow (Sec or Cycle).

2. EXPERIMENTAL WORK

The specimens were cut from a sheet metal and cut parallel to the rolling action of the sheets. The dimensions are 100 mm length (L) and 30 mm width (W), the overlap being equal to the width of the specimen. This overlap was chosen as per American Welding Society (AWS) recommendation as shown in Fig.4 [2]. The material used in the present work is Stainless Steel (304 grade) sheet of 1 mm thickness.

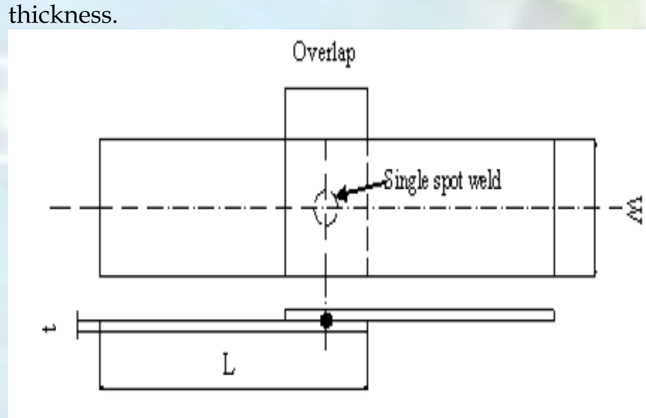

Fig.4: Specimen as per AWS

2.1 CHEMICAL COMPOSITION

The chemical composition for each element of the above material is listed in Table 1.

Table 1: Chemical composition of Stainless Steel

Content	C	Si	Mn	P	S	Cr	Mo	Ni	Fe
Value (%)	0.103	0.302	1.90	0.004	0.0082	19.05	0.079	8.08	70.3

2.2 SELECTION OF ORTHOGONAL ARRAY (OA)

Experiments were designed using Taguchi method which uses an orthogonal array (OA) to study limited number of experiments. In the present research three process parameters (factor) were chosen, all of them were set at three different levels shown in Table 2.

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Table 2: Process Parameters and Levels

Sr. No	Process Parameters	Parameter	Level 1	Level 2	Level 3
1	Welding Current (KA)	A	4.8	5.9	7
2	Electrode Force (KN)	B	0.490	0.539	0.588
3	Welding Time (cycle)	C	45	50	55

The selection of a particular OA is based on the number of levels of various factors. Here for experimentation L27 taguchi orthogonal array is selected for three process parameters and three levels of each. The photograph of spot welded specimen according to L27 Array is shown in Fig.5. Each experiment is carried out for three times to find effect of process parameters at different levels on performance characteristics.

Fig. 5: Photograph of Spot Welded Specimens

The tensile shear strength and nugget diameter tests are carried out on UTM and Dynascan optical profile meter as shown in Fig.6. Tensile strength and Nugget Diameter values for each run are noted in Table 3. These values are average of three experiments carried out at each parameter setting during experimentations.

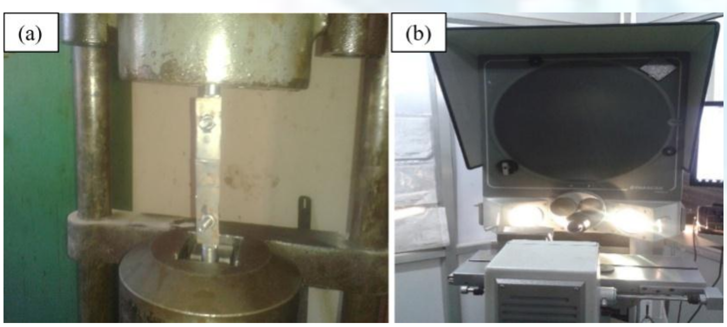


Fig. 6: Photograph of (a) Tensile Shear Test
(b) Nugget diameter measurement

2.3 ANALYSIS OF S/N RATIOS:

Taguchi recommends analyzing data using the S/N ratio that will offer two advantages; it provides guidance for selection of optimum level based on least variation around on the average value, which closest to target and also it offers objective comparison of two sets of experimental data with respect to deviation of the average from the target. The experimental results are analyzed to investigate the main effects.

Table 3: Orthogonal array with response variable data and S/N ratios

Sr. No	A	B	C	T-S (kN)	N-D (mm)	S/N Ratio	
						T-S	N-D
1	4.8	0.490	45	3.860	3.140	11.732	9.939
2	4.8	0.490	50	3.602	3.527	11.131	10.948
3	4.8	0.490	55	3.840	4.820	11.687	13.661
4	4.8	0.539	45	3.654	3.527	11.255	10.948
5	4.8	0.539	50	3.658	3.711	11.265	11.390
6	4.8	0.539	55	3.974	3.909	11.985	11.841
7	4.8	0.588	45	3.826	3.909	11.655	11.841
8	4.8	0.588	50	3.836	4.098	11.678	12.251
9	4.8	0.588	55	4.021	3.990	12.087	12.019
10	5.9	0.490	45	5.333	4.556	14.539	13.172
11	5.9	0.490	50	4.993	4.583	13.967	13.223
12	5.9	0.490	55	4.941	4.860	13.876	13.733
13	5.9	0.539	45	4.653	4.664	13.355	13.375
14	5.9	0.539	50	5.136	4.855	14.213	13.724
15	5.9	0.539	55	5.277	4.860	14.448	13.733
16	5.9	0.588	45	5.035	4.610	14.040	13.274
17	5.9	0.588	50	5.136	4.725	14.213	13.488
18	5.9	0.588	55	5.308	5.012	14.499	14.000
19	7.0	0.490	45	5.680	4.700	15.087	13.442
20	7.0	0.490	50	5.780	4.846	15.239	13.708
21	7.0	0.490	55	5.737	5.300	15.174	14.486
22	7.0	0.539	45	5.631	5.388	15.012	14.629
23	7.0	0.539	50	5.649	5.100	15.039	14.151
24	7.0	0.539	55	6.680	5.468	16.496	14.757
25	7.0	0.588	45	5.590	5.312	14.948	14.505
26	7.0	0.588	50	6.046	6.231	15.629	15.891
27	7.0	0.588	55	6.194	5.806	15.839	15.278

According to quality engineering the characteristics are classified as Higher the better (HB) and lower the better (LB). HB includes T-S strength and Nugget diameter which desires higher values. Similarly LB includes Heat Affected Zone (HAZ) for which lower value is preferred [3]. Results of S/N ratios are represented in Table 3 by using Eq.2.

Higher the better:

$$\eta = -10 \log \frac{1}{N} \sum_{i=1}^{n} \frac{1}{Y^2} \quad (2)$$

Lower the better:

$$\eta = -10\log\frac{1}{N}\sum_{i=1}^{n} Y^2 \quad (3)$$

Where, N= No. of experiments

Y= Response variable

2.4 Analysis of Variance (ANOVA):

ANOVA is carried out for finding most significant process parameters which will affect output quality characteristics. S/N values of response variables are used for obtaining ANOVA by using Minitab 16 software. Results are shown in Table 4 & 5 for T-S and N-D for higher the better characteristic. According to this analysis, the most significant parameter with respect to T-S and N-D is welding current. Whereas welding time and electrode force is least significant. 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 [3],[4].

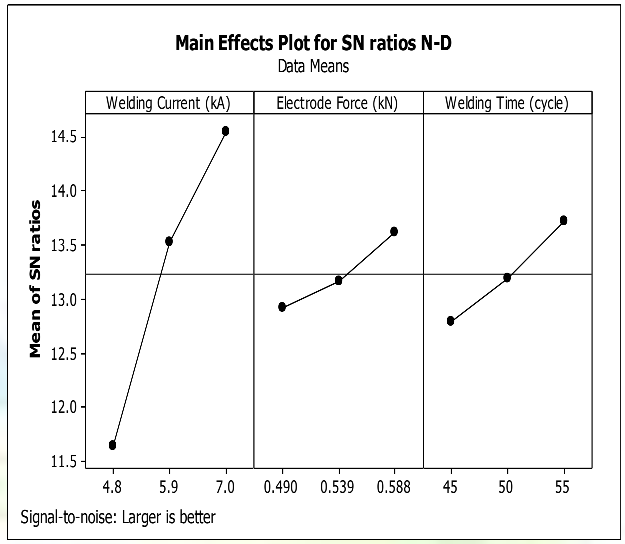
Table 4: ANOVA for Tensile -Shear Strength

Source	DOF	Seq SS	Adj MS	F	P	% C
A (kA)	2	66.574	33.287	261.34	0.000	94.21
B (kN)	2	0.2727	0.1364	1.07	0.362	0.39
C (cycle)	2	1.2711	0.6355	4.99	0.017	1.80
Error	20	2.5474	0.1274	-	-	3.60
Total	26	70.6652	-	-	-	100

Table 5: ANOVA for Nugget Diameter

Source	DOF	Seq SS	Adj MS	F	P	% C
A (kA)	2	38.689	19.3444	51.01	0.000	73.81
B (kN)	2	2.220	1.1098	2.93	0.077	4.23
C (cycle)	2	3.925	1.9627	5.18	0.015	7.49
Error	20	7.585	0.3792	-	-	14.47
Total	26	52.418	-	-	-	100

Fig. 7 (a) & (b) shows main effect plot for N-D and T-S. Here larger signal to noise ratio is considered as better one, hence values of plot at top positions indicate better results.



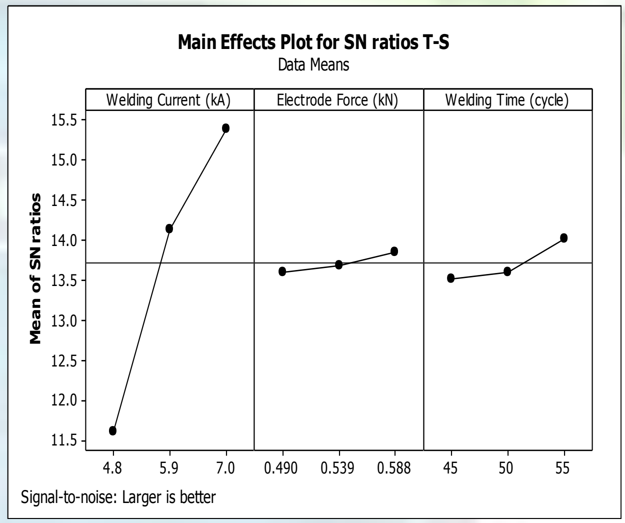


Fig. 7: Main Effects Plot of S/N Ratios for: (a) N-D Strength (b) T-S respectively

3 .GREY RELATIONAL ANALYSIS (GRA)

Taguchi can optimize single response only and unable to use, if the number of responses are more than one [5]. So, Grey Relational Analysis (GRA) method is used for multi response optimization. The multi response optimization converts multiple objectives into single objective [6].Hence grey relational analysis with Taguchi approach has been used to solve multi response optimization.

The optimization of multiple performance characteristics using GRA includes the following steps.

1. **Normalization of S/N ratio**

In GRA, normalization of S/N ratio is carried out for normalizing the raw data for analysis. A normalization of the S/N ratio in the range between zero and one is also called as the grey relational generation [7-8]. Normalization of data for larger-the-better, smaller-the-better and nominal-the-better characteristics are carried out for converting it into identical levels.

If smaller-the-better characteristic used in the original sequence, then it should be normalized as given by Eq.4.

$$x_i^*(k) = \frac{max x_i^0(k) - x_i^0(k)}{\max x_i^0(k) - min x_i^0(k)} \quad (4)$$

If larger-the-better characteristic used in the original sequence, then it should be normalized as given by Eq.5

$$x_i^*(k) = \frac{x_i^0(k) - \min x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)} \quad (5)$$

In this study both response variables are considered for larger-the-better characteristics. Therefore normalization is done by using Eq.5 and values are shown in Table 9.

For Experiment No.1, Tensile strength:

$$x_i^*(k) = \frac{(11.732) - (11.13)}{(16.496) - (11.13)} = 0.112$$

Nugget diameter:

$$x_i^*(k) = \frac{(9.94) - (9.94)}{(15.89) - (9.40)} = 0.000$$

All the sequences after normalization are denoted as x0*(k) and xi*(k) for reference sequence and comparability sequence, respectively. The larger value of normalized results indicates the better performance characteristic and the best-normalized results will be equal to one.

2. Deviation sequences

The deviation sequence which is represented by $\Delta_{oi}(k)$, is the absolute difference between the reference sequence $x_i^0(k)$ and the comparability sequence $x_i^*(k)$ after normalization. It is determined by using Eq.6

$$\Delta_{oi} k = |x_0^*(k) - x_i^*(k)| \quad (6)$$

For Experiment no.1, Tensile strength

$$\Delta_{oi}(1) = |1.000 - 0.112| = 0.888$$

Nugget diameter

$$\Delta_{oi}(1) = |1.000 - 0.000| = 1.000$$

3. Grey Relational Coefficient (GRC)

GRC for all the sequences gives the relationship between the ideal (best) and actual normalized S/N ratio. If the two sequences agree at all points, then GRC will be taken as 1. The GRC can be expressed by Eq.7 [9].

$$\gamma(x_0(k), x_i(k)) = \frac{\Delta_{min} + \zeta.\Delta_{max}}{\Delta_{0i}(k) + \zeta.\Delta_{max}} \quad (7)$$

Where,

$\Delta_{min} = min.min\Delta_{0,i}(k)$

$\Delta_{max} = max.max\Delta_{0,i}(k)$

$\Delta_{0i}(k)$Is the deviation sequence and
ζ = distinguishing coefficient, $\zeta \in (0,1)$. And for current research work, ζ is set as 0.5.

The Grey relational coefficient $\gamma(x_0^*(1).x_0^1(1))$ is calculated by using Eq.7 and subsequent values for all experiments are displayed in Table 9.

For Experiment No.1, Tensile strength:

$$\gamma(x_0^*(1).x_0^1(1)) = \frac{0.0000 + 0.5 \times 1.0000}{0.888 + 0.5 \times 1.0000} = 0.360$$

Nugget diameter:

$$\gamma(x_0^*(2).x_0^1(2)) = \frac{0.0000 + 0.5 \times 1.0000}{1.000 + 0.5 \times 1.0000} = 0.333$$

4. Grey Relational Grade (GRG)

The overall evaluation of the multiple performance characteristics is based on the GRG. The grey relational grade is an average sum of the GRC, and is calculated using Eq.8 [7-8].

$$\gamma(x_0, x_i) = \frac{1}{m}\sum_{i=1}^{m} \gamma(x_0(k), x_i(k)) \quad (8)$$

Where,
$\gamma(x_0, x_i)$is the Grey relational grade for the j_{th}experiment and m is the number of performance characteristics.
Grey relational grade (GRG) for experiment no 1 is calculated as,

$$\gamma(x_0, x_i) = \frac{0.360 + 0.333}{2} = 0.347$$

The order of experiments according to the magnitude of GRG is depicted in Table 9.

5. Prediction of GRG under optimum parameters

After evaluating the optimal parameter settings, the next step is to predict and verify the improvement of quality characteristics using the optimal parametric combination. The optimal Grey relational grade ηopt is predicted as follows [10-12].

$$\eta_{opt} = \overline{T} + (\overline{A}_{(1/2/3)} - \overline{T}) + (\overline{B}_{(1/2/3)} - \overline{T}) + (\overline{C}_{(1/2/3)} - \overline{T})$$

Where,
$\overline{T}$ = overall mean of the response
$\overline{A}_{(1/2/3)}, \overline{B}_{(1/2/3)}, \overline{C}_{(1/2/3)}$= Higher values of average response at the first or second or third levels of parameters A, B and C respectively.

$$\eta_{opt} = 0.451 + (0.715 - 0.451) + (0.580 - 0.451) + (0.592 - 0.451)$$

=0.98

The results of confirmation experiment obtained by grey relation analysis are as shown in Table 6.

Table 6: Result of Confirmation Experiment

Parameters	Initial Parameter Setting	Optimum Parameter level	
		Prediction	Experiment
	A3B3C2	A3B3C3	A3B3C3
A (kA)	7		7
B (kN)	0.588		0.588
C (cycle)	50		55
T-S (kN)	6.046		6.531
N-D (mm)	6.231		6.457
GRG	0.878	0.98	0.978
Improvement in Grey Relation Grade = 0.10			

Response Table for Means of GRG is as shown in Table 7, indicates the rank of the process parameters. Here, current is Rank 1 is most influencing parameter, rank 2 is Weld time and rank 3 is electrode force.

Table 7: Response Table for Means of GRG

Level	Welding Current (kA)	Electrode Force (kN)	Weld Time (cycle)
1	0.388	0.521	0.512
2	0.546	0.548	0.545
3	0.715	0.580	0.592
Min	0.388	0.521	0.512
Max	0.715	0.580	0.592
Delta	0.327	0.059	0.081
Rank	1	3	2

4 .ANOVA FOR GREY RELATIONAL GRADE

The results of GRG are considered as single response variable for obtaining most significant process parameter for multi response variables i.e. T-S and N-D. The Table 8 shows result of ANOVA obtained from GRG. The F-ratio value indicates the significance of process parameters. Larger the value of F-ratio represent most significance process parameter [11-12]. Here, Welding current is most significant process parameter followed by weld time and electrode force.

Table 8: ANOVA for GRG

Source	DOF	Seq SS	Adj MS	F	P	% C
A	2	125.42	62.713	131.9	0.000	86.77
B	2	2.834	1.416	2.98	0.074	1.97
C	2	6.771	3.3854	7.12	0.005	4.68
Error	20	9.508	0.4754	-	-	6.58
Total	28	144.53	-	-	-	100

The main effects of S/N ratios for GRG are shown in Fig. 8. Here, these values of parameters give best results of response variables. While the lower most values in the plot indicate the values of parameters for worst case results.

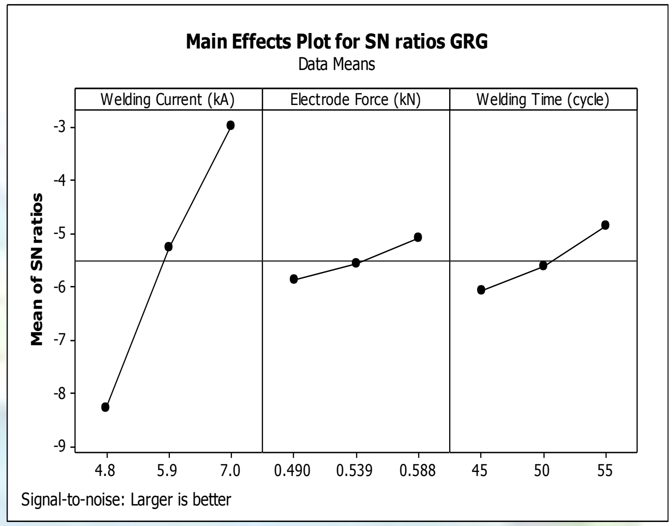


Fig. 8: Main Effects of S/N Ratios for GRG

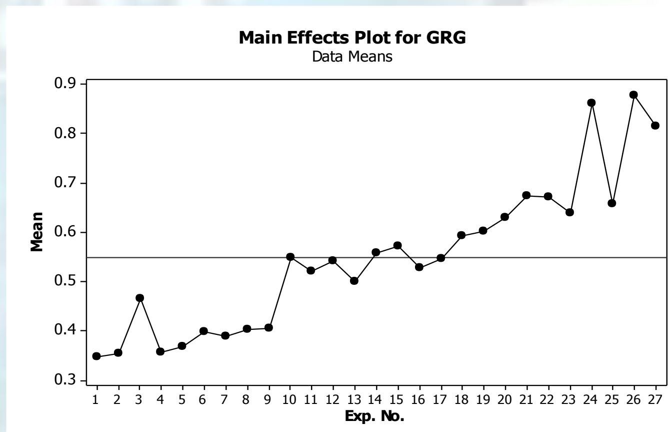


Fig. 9: Main Effects for GRG

Table 9: Grey Relational Analysis (GRA)

Sr No	A	B	C	S/N Ratio		Normalization		Deviation Sequence		Grey Relation Coefficient		GRG	Rank
				(T-S)	(N-D)	T-S	N-D	T-S	N-D	T-S	N-D		
1	4.8	0.490	45	11.732	9.939	0.112	0.000	0.888	1.000	0.360	0.333	0.347	27
2	4.8	0.490	50	11.131	10.948	0.000	0.169	1.000	0.831	0.333	0.376	0.355	26
3	4.8	0.490	55	11.687	13.661	0.104	0.625	0.896	0.375	0.358	0.572	0.465	19
4	4.8	0.539	45	11.255	10.948	0.023	0.169	0.977	0.831	0.339	0.376	0.357	25
5	4.8	0.539	50	11.265	11.390	0.025	0.244	0.975	0.756	0.339	0.398	0.368	23
6	4.8	0.539	55	11.985	11.841	0.159	0.320	0.841	0.680	0.373	0.424	0.398	22
7	4.8	0.588	45	11.655	11.841	0.098	0.320	0.902	0.680	0.357	0.424	0.390	24
8	4.8	0.588	50	11.678	12.251	0.102	0.388	0.898	0.612	0.358	0.450	0.404	20
9	4.8	0.588	55	12.087	12.019	0.178	0.349	0.822	0.651	0.378	0.435	0.406	21
10	5.9	0.490	45	14.539	13.172	0.635	0.543	0.365	0.457	0.578	0.523	0.550	13
11	5.9	0.490	50	13.967	13.223	0.529	0.552	0.471	0.448	0.515	0.527	0.521	17
12	5.9	0.490	55	13.876	13.733	0.512	0.637	0.488	0.363	0.506	0.580	0.543	15
13	5.9	0.539	45	13.355	13.375	0.415	0.577	0.585	0.423	0.461	0.542	0.501	18
14	5.9	0.539	50	14.213	13.724	0.574	0.636	0.426	0.364	0.540	0.579	0.559	12
15	5.9	0.539	55	14.448	13.733	0.618	0.637	0.382	0.363	0.567	0.580	0.573	11
16	5.9	0.588	45	14.040	13.274	0.542	0.560	0.458	0.440	0.522	0.532	0.527	16
17	5.9	0.588	50	14.213	13.488	0.574	0.596	0.426	0.404	0.540	0.553	0.547	14
18	5.9	0.588	55	14.499	14.000	0.628	0.682	0.372	0.318	0.573	0.612	0.592	10
19	7.0	0.490	45	15.087	13.442	0.737	0.589	0.263	0.411	0.656	0.549	0.602	7
20	7.0	0.490	50	15.239	13.708	0.766	0.633	0.234	0.367	0.681	0.577	0.629	9
21	7.0	0.490	55	15.174	14.486	0.754	0.764	0.246	0.236	0.670	0.679	0.675	4
22	7.0	0.539	45	15.012	14.629	0.723	0.788	0.277	0.212	0.644	0.702	0.673	5
23	7.0	0.539	50	15.039	14.151	0.729	0.708	0.271	0.292	0.648	0.631	0.640	8
24	7.0	0.539	55	16.496	14.757	1.000	0.810	0.000	0.190	1.000	0.724	0.862	2
25	7.0	0.588	45	14.948	14.505	0.712	0.767	0.288	0.233	0.634	0.682	0.658	6
26	7.0	0.588	50	15.629	15.891	0.838	1.000	0.162	0.000	0.756	1.000	0.878	1
27	7.0	0.588	55	15.839	15.278	0.878	0.897	0.122	0.103	0.803	0.829	0.816	3

Based on ranking order obtained from Table 9 and Fig.9, experiment no.26 is considered the best response value. Basically, larger the GRG, better will be corresponding characteristics.

5 .CONCLUSIONS

The objective of the current research work is to optimize spot welding process parameters like welding current, electrode force and welding time for tensile shear strength and nugget diameter as response variables. The conclusions based on multi objective optimization using Taguchi with GRA are Summarized as follows:

- The optimized input process parameters to get both maximum T-S and N-D values are A3B3C3 i.e. welding current 7 KA, Electrode force 0.588 KN and welding time 55 cycle.
- ANOVA shows that welding current is most significant process parameter among three input process parameters for both the response variables.
- The improvement of grey relational grade for optimal process parameter is found to be 0.10.

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