Multi objective optimization in tungsten inert gas (TIG) welding using grey relational analysis

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Abstract: Objective of the present work is to optimize the Hardness & Bending strength of a butt joint by analyzing welding process parameters: welding current, welding speed, gas flow rate & root gap in tungsten inert gas (TIG) welding. TIG welding helps in welding of difficult to weld materials (highly reactive materials) and now a days its application has been expanded to various metals like mild steels, stainless steels, and High speed steels etc. In the present work butt joint is created between dissimilar alloys of aluminum (AA5052) and aluminum (AA 6061) with aluminum filler material using Automatic TIG welding machine. Bending strength of butt joint is measured in 3 point bend fixture machine and hardness of butt joint is measured in Rockwell Hardness Testing machine. 16 experiments are performed and L-16 orthogonal array is constructed to design the experiment. Taguchi technique and Grey relational analysis are for optimization in MINITAB software. From the results it is found that welding current has the highest influence on hardness as well as bending strength.

Index Terms- **TIG, AA6061, AA5052, bending strength, hardness, Design of experiment (DOE), Taguchi, MINITAB, Optimum, ANOVA, 3 point bend fixture machine**.

1. INTRODUCTION:

Welding is a permanent joining process used to join different ferrous and nonferrous materials like metals and alloys at their mating surfaces by application of heat and or pressure. In some cases filler material is required to form a weld pool of molten metal which after solidification gives a strong bond between the materials. Weld ability of a material is determined by melting point, thermal conductivity, thermal expansion, electrical resistance, surface conditions etc.

In TIG welding process a non-consumable tungsten electrode connects to a power source and shielding gas pass through a welding gun. In most of the cases, Argon or Helium is used as shielding gas which has following functions:

1. Prevent the interaction of atmospheric gases with welding area.
2. Transfer of heat during welding.
3. Facilitate to start and maintain a stable arc due to low ionization potential.

The application of filler metal is optional depends upon the kind of weld. TIG welding is used in welding of difficult to weld materials like Aluminum and Magnesium. But the applications of TIG welding nowadays has been extended to variety of metals like MS, SS, HSS etc. to give high quality weld. **Fig. 1** shows the photographic view of Automatic TIG welding machine used in the present work.

Objectives

1. Analyze the effects of process parameters on hardness and bending strength of weld bead
2. Optimize the hardness and bending strength of weld bead.

16 experiments are carried out to create a butt joints between AA6061 and AA5052 pieces at various levels of process parameters: welding current, welding speed, gas flow rate and root gap in TIG welding process. Subsequently these weldments are tested for hardness and bending strength in Rockwell hardness tester (**Fig. 2**) and 3 point bend fixture Machine (**Fig. 3**) respectively. L 16 orthogonal array is constructed to design the experiments and optimized using Taguchi technique and grey relational analysis.

Figure 1: Automatic TIG welding Machine

In many industries like automobile primary concern is reduction of mass to improve the power to ratio of vehicle. Hence it has become predominant to focus on lightweight materials like aluminum and magnesium. Thermal conductivity of aluminum is also quite high which facilitates the conduction of heat away from the hot area. But Aluminum is a reactive metal that quickly forms an oxide layer on the surface and consequently strength of the weld area become weak. Therefore welding of aluminum by conventional arc welding process was very difficult before the advent of TIG. With the understanding of welding characteristics and by utilizing proper procedures aluminum and its alloys could be easily weld.

In this study aluminum alloys AA6061 and AA5052 are selected as the base material which comes under aluminum 6xxx series and 5xxx series. AA6061 has high strength, good toughness, good surface finish and good corrosion resistance to atmosphere and sea water. AA 5052 is non-heat treatable alloy, weldable and hardened by cold work. AA 5052 also has good forming characteristics and good corrosion resistance, including resistance to salt water.

Figure 2: Rockwell hardness Tester

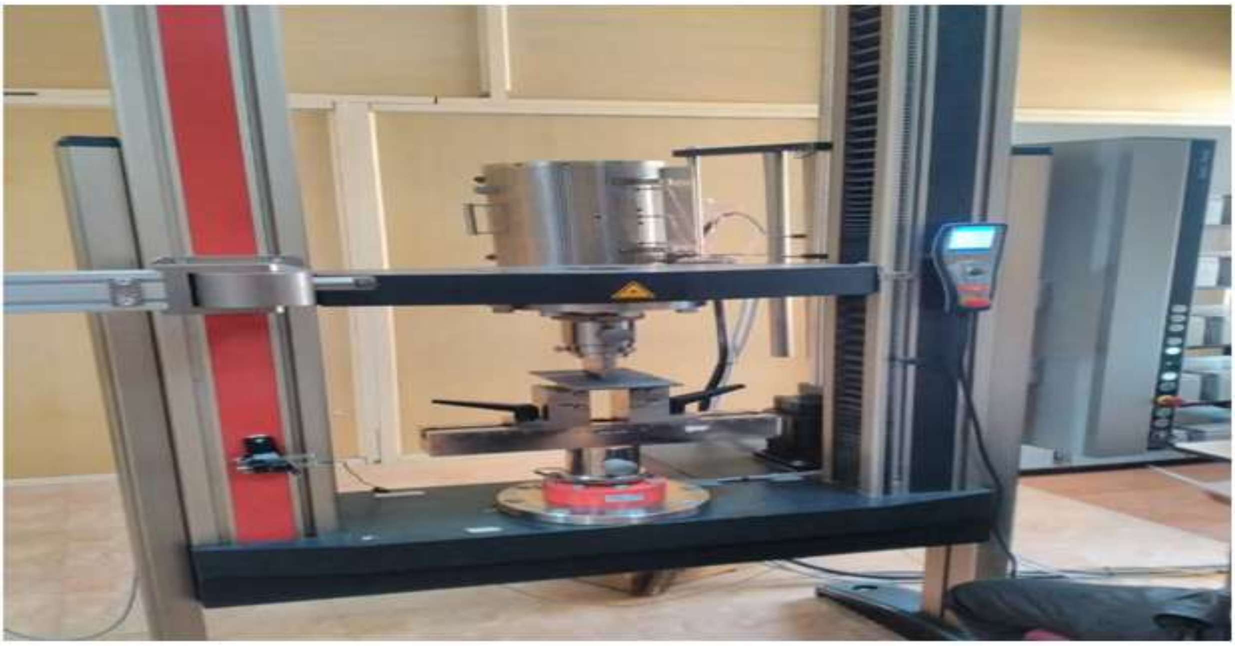

Figure 3: 3 point bend fixture machine

Thakur and Chapgaon [2] concluded that increasing welding current increases the deposition rate and bead height but reduces hardness.
Bahar [2] optimized the bending strength of a butt joint by analyzing welding process parameters: current, welding speed and gas flow rate in tungsten inert gas (TIG) welding and concluded that higher the welding current better will be bending strength.
Prakash et al. [3] dealt with the optimization of welding process variables in TIG welding and found that welding Current has the greatest influence on Tensile and Hardness in the welded sample of ASTM A29 followed by welding voltage and wire speed.
Esme et al. [4] investigated the multi-response optimization of tungsten inert gas welding (TIG) welding process to realize a favorable bead geometry.
Perumal et al. [5] investigated the effects of the different kinds of oxides fluxes (TiO2, SiO2, MnO2, CaF2) on weld bead penetration in TIG welding Process.
Lugade and Deshmukh [6] observed good joint strength is exhibited by all the joints which show that the welding of AISI 304L stainless steel sheet with A-TIG welding is possible without any joint preparation in single pass.
Hussain et al. [7] investigated the effect of welding speed on the tensile strength of the welded and concluded that tensile strength is higher with lower weld speed.
Choudhury et al. [8] observed that current as well gas flow rate have considerable influence on ultimate load in TIG welding.
Singh [9] designed the experiments to study the influence of welding process parameters on metal deposition rate and hardness of weldbead.
Yadav et al. [10] conducted a microstructure study was to find out the change in the microstructure of the Austenitic stainless steel for the optimum combination of parameters of the tested specimen in TIG welding process.

Optimization

In the present work optimization is carried out using Taguchi technique and Grey relational analysis. Taguchi technique identifies proper control factors to obtain the optimum results of the process.

Analysis of S/N ratio:

In Taguchi technique, the term ‘signal’ represents the desirable value for the output characteristic and the term ‘noise’ represents the undesirable value for the output characteristic. S/N ratios for different conditions are:

1. Nominal is the best characteristic

$$S / N = 10 \log_{10}\left(\frac{\bar{Y}}{S_y^2}\right) \quad ...(1)$$

2. Smaller is the best characteristic

$$S / N = -10 \log_{10}\left(\frac{\sum y^2}{n}\right) \quad ...(2)$$

3. Larger the better characteristics

$$S / N = -10 \log_{10}\left(\frac{1}{n}\sum\frac{1}{y^2}\right) \quad ...(3)$$

Where; n is the number experiments performed and y is the output response obtained by the experiment.

Grey Relational Analysis (GRA):

This technique transforms the multiple performance characteristics into single characteristics. The following steps are followed in GRA

- Experimental data are normalized in the range between zero and one.
- The grey relational coefficients are calculated from the normalized experimental data.
- The Grey relational gradeare computed by averaging the weighted grey relational coefficients corresponding to each performance characteristic.
- Then optimal levels of process parameters are selected.

In the analysis of grey relation for 'higher is better' response normalization done by equation (4) and for 'lower is better', normalization done by equation (5).

$$X_i^*(k) = \frac{X_i(k) - X_i\min(k)}{X_i max(k) - X_i\min(k)} \ldots(4)$$

$$X_i^*(k) = \frac{X_i max(k) - X_i(k)}{X_i max(k) - X_i\min(k)} \ldots(5)$$

Where;

Xi* (k) and Xi (k) are the normalized data and observed data, respectively, for i^{th} experiment using K^{th} response. The smallest and largest values $X_i(k)$ in the K^{th} response are $X_i$min(k) and Xi max(k), respectively.

After pre-processing the data, the grey relation coefficient (GRC) $\zeta_i(k)$ for the K^{th} response characteristics in the i^{th} experiment can be expressed as following:

$$\zeta i\ (k) = \frac{\Delta \min + \zeta\Delta\max}{\Delta i\ (k) + \zeta\Delta\max} \ldots(6)$$

where;

$X_0^i(k)$ = denotes reference sequence , $X^*_j(k)$ = denotes the comparability sequence

ς Є [0,1], is the distinguishing factor; 0.5 is widely accepted.

$\Delta_i = |X_0^*(k)-X_j^*(k)|$ = differnece in absolute value between $X_0^*(k)$ and $X_j^*(k)$

$\Delta_{min}=\min_{(j\in i)}\min_{(k)}|X_0^*(k)-X_j^*(k)|$ = smallest value ofΔ_i.

$\Delta_{max}=\max_{(j\in i)}\max_{(k)}|X_0^*(k)-X_j^*(k)|$ = largest value ofΔ_i.

After calculating GRC, the grey relational grade (GRG) is obtained as:

$$\gamma_i = \left(\frac{\sum w \times \zeta i\ (k)}{m}\right) \ldots(7)$$

where;

γ_i is the Grey Relational Grade, n is the number of responses, m is the number of run and w is the weight factor. Amount of influence of a response can be controlled in deciding the optimum machining parameters varying the value of w keeping in mind $\sum_1^n$ w should be equal to 1.

2. MATERIALS AND METHODS

Two plates are butt welded at different combination of process parameters by TIG welding. Details pertaining to dimension and material of plates, welding conditions etc are explained in this section. material of plates to be welded taken as aluminium(AA6061) and aluminum(5052) and each plate having dimension as 120mm×60mm×6mm. chemical compositions of AA6061 and AA5052 alloy is shown in **Table 1** and **Table 2** respectively.

Table1. Chemical composition of AA 6061

Al %	Si %	Fe %	Cu %	Mn %	Mg %	Cr %	Zn %	Ti %	Other %
95.85-98.56	0.4-0.8	0.7	0.15-0.4	0.15	0.8-1.2	0.04-0.35	0.25	0.15	0.15

Table 2: Chemical composition of AA 5052

Al %	Si %	Fe %	Cu %	Mn %	Mg %	Cr %	Zn %	Others %
95.75-96.65	0.25	0.4	0.1	0.1	2.2-2.8	0.15-0.34	0.1	0.15

Material used for filler: Aluminium filler material having diameter of 1mm is used @ 1m/min.

Shielding gas used: Argon

Electrode used: Ball shape Non consumable tungsten electrode having 3mm diameter is used.

Varied Parameters: Welding current, Welding speed, Gas flow rate and Root gap has varied for four levels as shown in **Table 3**. On the basis of these levels factors relationship, 16 combinations of these factors are considered (shown in **Table 4**) to generate L-16 orthogonal array.

Table 3: Levels of varying parameters

Parameters	**Levels**			
	L1	L2	L3	L4
Welding current, I (Amp)	130	150	170	190
Welding speed, S (mm/min)	120	130	140	150
Gas flow rate, GFR (mm^3/min)	19	20	21	22
Root gap, RG (mm)	1	1.5	2	2.5

Table 4: Combinations of input parameters for experiments

Ex.No	**I (Amp)**	**S (mm/min)**	**GFR (mm^3/min)**	**RG(mm)**	**Hardness**	**Bending Strength (N/mm^2)**
1	130	120	19	1.0	22	147.00
2	130	130	20	1.5	24	192.16
3	130	140	21	2.0	26	223.38
4	130	150	22	2.5	28	196.83
5	150	120	20	2.0	29	149.22
6	150	130	19	2.5	30	82.94
7	150	140	22	1.0	32	160.55
8	150	150	21	1.5	38	113.16
9	170	120	21	2.5	49	120.33
10	170	130	22	2.0	51	232.88
11	170	140	19	1.5	44	243.00
12	170	150	20	1.0	48	320.66
13	190	120	22	1.5	41	263.77
14	190	130	21	2.5	42	328.88
15	190	140	20	1.0	40	357.55
16	190	150	19	2.0	38	320.66

Corresponding to L 16 orthogonal array (given in Table 4) 16 welding experiments are performed (shown in Fig. 4) and subsequently tested for hardness and bending strength (values are given in Table 4).


Figure4a:I=130,S=120,GF=19,RG=1.0


Figure4b:I=130,S=130,GF=20,RG=1.5


Figure4c:I=130,S=140,GF=21,RG=2.0


Figure4d:I=130,S=150,GF=22,RG=2.5


Figure4e:I=150,S=120,GF=20,RG=2.0


Figure4f:I=150,S=130,GF=19,RG=2.5


Figure4g:I=150,S=140,GF=22,RG=1.0


Figure4h:I=150,S=150,GF=21,RG=1.5


Figure4i:I=170,S=120,GF=21,RG=2.5


Figure4j:I=170,S=130,GF=22,RG=2.0


Figure4k:I=170,S=140,GF=19,RG=1.5


Figure4l:I=170,S=150,GF=20,RG=1.0


Figure4m:I=190,S=120,GF=22,RG=1.5


Figure4n:I=190,S=130,GF=21,RG=2.5


Figure4o:I=190,S=140,GF=20,RG=1.0


Figure4p:I=190,S=150,GF=19,RG=2.0

Figure 4: Butt joints welded at different process parameters, I is welding current, S is welding speed, GF is gas flow rate and RG is root gap.

3. RESULTS AND DISCUSSIONS

From Table 4, values are fed in MINITAB software to analyze the main effect of S/N ratios and optimal conditions. **Fig. 5** shows the main effect plot for S/N ratios and **Table 5** presents the analysis of variance of hardness.

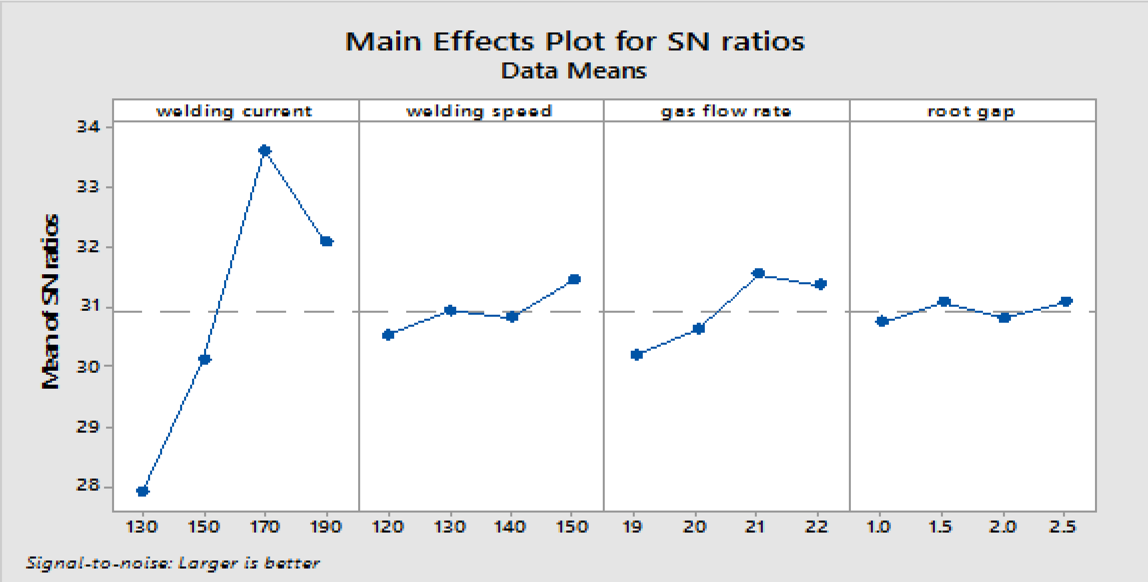

Figure 5: Main Effects plot for SN ratios of Hardness

Table 5: Analysis of variance for hardness

Analysis of Variance for Transformed Response

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
welding current	3	0.000864	89.56%	0.000864	0.000288	519.75	0.000
welding speed	3	0.000031	3.17%	0.000031	0.000010	18.42	0.020
gas flow rate	3	0.000060	6.27%	0.000060	0.000020	36.39	0.007
root gap	3	0.000008	0.82%	0.000008	0.000003	4.77	0.116
Error	3	0.000002	0.17%	0.000002	0.000001		
Total	15	0.000964	100.00%				

In the present study lager value of hardness is desirable and higher S/N ratios indicate optimal condition. Therefore optimal process parameters for hardness are evaluated from Fig. 5 and presented in **Table 6**. From Table 5, it is also clear that contribution of welding current is higher (89.56%) and contribution of root gap is negligible (0.82%). Error contribution is only 0.17% which indicates a robust design of experiment.

Table 6: optimal parameters for hardness

Parameter	Levels	values
welding current, I (A)	3	170
welding speed, S (mm/min)	4	150
Gas flow rate (mm^3/min)	3	21
Root gap (mm)	2	1.5

From Table 6 it can be inferred that welding speed should be high for optimum hardness. Like for hardness, similar analysis is performed for bending strength. **Fig. 6** shows the main effect plot for S/N ratios and **Table 7** presents the analysis of variance for bending strength.

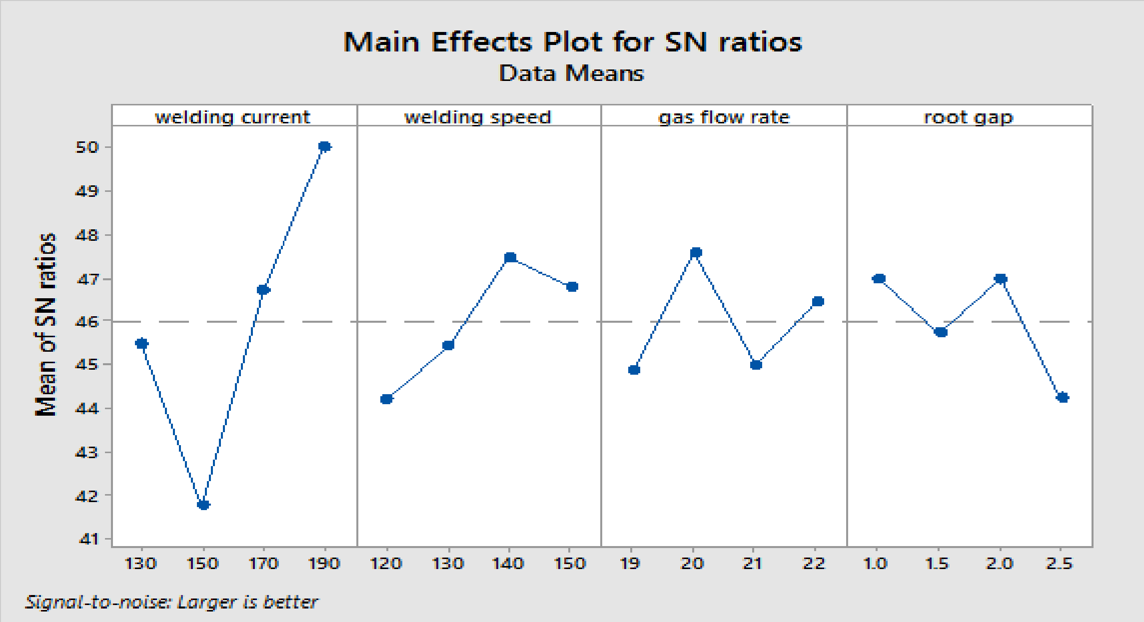

Figure 6: Main effect plot for SN ratios of bending strength

Table 7: ANOVA for bending strength

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
welding current	3	76882	70.73%	76882	25627.4	35.17	0.008
welding speed	3	14153	13.02%	14153	4717.7	6.47	0.080
gas flow rate	3	8846	8.14%	8846	2948.6	4.05	0.140
root gap	3	6632	6.10%	6632	2210.8	3.03	0.193
Error	3	2186	2.01%	2186	728.6		
Total	15	108699	100.00%				

In this communication lager value of bending strength is desirable and higher S/N ratios indicate optimal condition. Therefore optimal process parameters for toughness are evaluated from Fig. 6 and presented in **Table 8**. From Table 7, it is also clear that contribution of welding current is higher (70.73%) and contribution of root gap is lower (6.01%).

Table 8: Optimal parameter settings for bending strength

Parameter	Levels	values
welding current, I (A)	4	190
welding speed, S (mm/min)	3	140
Gas flow rate (mm^3/min)	2	20
Root gap (mm)	1	1

From Table 8 it can be inferred that welding current should be high for optimum bending strength while root gap should be lower.

Multi response optimization

In order to optimize hardness as well as bending strength, multi response optimization i.e Grey relational analysis is employed for which grey relational coefficients (GRC) and grey relational grades (GRG) are calculated and presented in **Table 9**.

Table 9: Grey relational coefficients for hardness & bending strength and grey relational grades

Exp. No	GRC (Bending strength)	GRC (Hardness)	GRG
1	43.3463	26.8485	0.3922

2	45.6733	27.6042	0.4492
3	46.9809	28.2995	0.4962
4	45.8818	28.9432	0.4811
5	43.4765	29.2480	0.4410
6	38.3753	29.5424	0.3876
7	44.1122	30.1030	0.4756
8	41.0743	31.5957	0.4883
9	41.6075	33.8039	0.6574
10	47.3426	34.1514	0.8150
11	47.7121	32.8691	0.6972
12	50.1209	33.6248	0.8722
13	48.4245	32.2557	0.6673
14	50.3407	32.4650	0.7906
15	51.0667	32.0412	0.8169
16	50.1209	31.5957	0.7292

Grey relational grades from Table 9 are analyzed in MINTAB for multi response optimization. **Fig. 7** shows the main effect plot for S/N ratios and **Table 10** presents the analysis of variance.

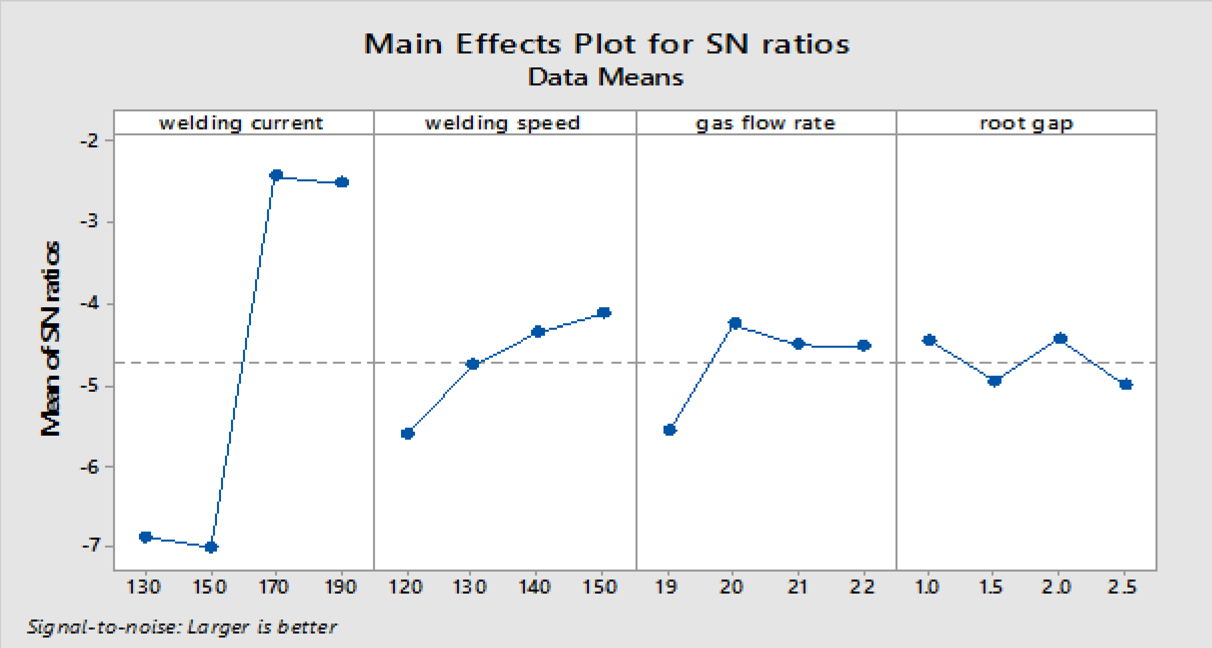

Figure 7: Main effects plot for SN ratios in multi response

Table 10: ANOVA for multi response

Analysis of Variance for Transformed Response

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
welding current	3	3.22415	87.06%	3.22415	1.07472	379.63	0.000
welding speed	3	0.22216	6.00%	0.22216	0.07405	26.16	0.012
gas flow rate	3	0.21188	5.72%	0.21188	0.07063	24.95	0.013
root gap	3	0.03672	0.99%	0.03672	0.01224	4.32	0.130
Error	3	0.00849	0.23%	0.00849	0.00283		
Total	15	3.70340	100.00%				

Since higher values of hardness and bending strength are desired therefore corresponding optimal process parameters for multi response are evaluated from Fig. 7 and presented in **Table 11**. From Table 10, it is also clear that contribution of welding current is higher (87.06%) and of root gap is lower (0.99%). Error contribution is only 0.34% which indicates a robust design.

Table 11: Optimal parameters for multi response

Parameter	Levels	values
welding current, I (A)	3	170
welding speed, S (mm/min)	4	150
Gas flow rate (mm^3/min)	2	20
Root gap (mm)	1	1

From Table 11, it can be inferred that for multi response optimization i.e optimization of hardness as well as bending strength, welding speed should be higher and root gap should be minimum.

4. CONCLUSION

1. Optimum parameter setting for hardness is obtained at 170 A of welding current, 150mm/min of welding speed, 21 mm^3/min of gas flow rate and 2.5 mm of root gap. The study found that the control factors had varying effects on the hardness, welding current having the highest contribution.
2. Optimum parameter setting for bending strength is obtained at 190 A of welding current, 140mm/min of welding speed, 20 mm^3/min of gas flow rate and 1 mm of root. The study found that welding current has the highest affect on bending strength.
3. By using grey relational analysis optimum parameter setting for multi response optimization (i.e optimization of bending strength with hardness) is obtained at 170 A of welding current, 150mm/min of welding speed, 20 mm^3/min of gas flow rate and 2 mm of root gap.

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