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Research Article

Taguchi-GRA Optimization of Shielded Metal Arc Welding Parameters for High Strength Low Alloy Steel

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Abstract – This research aims to enhance the quality of welding joints in industrial applications made from High Strength Low Alloy (HSLA) steel, by optimizing the welding parameters for Shielded Metal Arc Welding (SMAW). The quality of welds significantly impacts mechanical properties and is influenced by factors such as welding current, welding speed, and electrode diameter. Suboptimal values of these parameters can lead to defects, affecting mechanical characteristics adversely. In this study, we conducted nine experiments using the Taguchi orthogonal array L9 design and applied Grey Relational Analysis (GRA) for multi-response optimization. The optimized welding parameters, identified as 125 A current, 4 mm/s speed, and 4 mm electrode diameter, resulted in a notable 9% increase in Tensile Strength and a 3.20% improvement in hardness values, indicating significant enhancement in weld quality and joint integrity.

Keywords – SMAW, Welding, Taguchi, Grey Relational Analysis, Optimization

I. INTRODUCTION

Among other welding processes, the most common welding method used in industry is shielded metal arc welding (SMAW) [1], a type of fusion welding. Sometimes it is referred to as stick welding or just arc welding in everyday speech. This welding approach uses a non-continuous flux-coated electrode and a metal arc to create a simple, permanent joining process (an arc that transfers metal). A coated flux combusts during welding to protect, reinforce, and isolate the molten weld material. Due to its versatility, user friendliness, cost effectiveness, portability, and can operate on both alternating and direct current, shielded metal arc welding (SMAW) facilities are the most versatile in the metal industry. Shielded Metal Arc Welding (SMAW) can be carried out easily in any position with variety of electrodes. It is used in workshops and at site as well [2]. The process, however, is applied without any pressure. An illustration of the SMAW process is shown in Figure 1 [3].

In order to obtain the appropriate metallurgical and mechanical qualities, SMAW electrodes are used to weld almost 70% of all metal joints. Numerous low carbon steel electrodes, including basic low hydrogen (E7018), rutile (E6013), and cellulosic electrodes, are available for SMAW (E6010) [4]. In order to achieve an arc temperature of 5000°C, welding is usually done at a voltage between 15 and 45 V and a current between 10 and 500A. [5].

Different steel material are being used in manufacturing of industrial equipment and in construction industry, but high strength low alloy (HSLA) provides better corrosion resistance and high strength to weight ratio [6]. ASTM A 572 grade 50 finds extensive use in the construction of ships, bridges, oil/gas vessels, offshore constructions, agricultural and construction machinery, among other things [7].

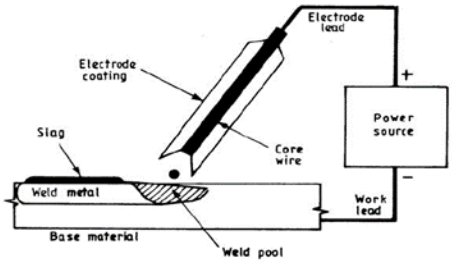

Fig. 1 SMAW process daigram

Five grades are available which differ due to carbon & alloy content and are termed as Gr 42, 50, 55, 60 and 65.

Sapakal and Telsang examined how voltage, current and weld speed impact the full penetration in Metal Inert Gas welding. For investigation, each parameter values were taken at two levels. Taguchi L9 orthogonal arrays is used to design number of experiments. For calculating the contribution of each factor on output variable, ANOVA is implied. The findings revealed that voltage had the most significant impact (84.42%), followed by speed (6.83%), on the outcome. This investigation did not examine interaction effects. Additionally, confirmation tests were carried out [8]. Kanchana et al. improved milling performance of TiAlN-coated carbide inserts using a Taguchi-based GRA technique. Nine experiments explored speed, depth of cut, and feed rate effects on temperature, abrasion, material removal rate, and cutting force. Cutting speed was identified as the key factor, highlighting the efficacy of Taguchi and GRA methods for optimizing milling processes [9]. Prabhu et al. utilized Taguchi coupled with GRA to enhance various quality response variables in grinding AISI D2 tool steel using a carbon nanotube-infused grinding wheel. Process factors included depth of cut, feed, and speed, aiming to minimize surface roughness and boost material removal rate (MRR). Regression models were employed, and ANOVA revealed the significant impact of feed on the grey relational grade [10]. Taguchi Based GRA technique for multi response optimization has been tremendously used in milling [11], forming [12], EDM [13].

Mechanical fabrication industries seek to improve welding methods to enhance welding joint quality by minimizing defects and achieving optimal mechanical properties through proper selection of welding parameters. Previous methods for parameter selection were based on suboptimal experience-based estimation, leading to increased focus on research and optimization. This study aims to maximize how welding settings affect response characteristics like hardness and tensile strength in high strength low alloy steel utilizing grey relational analysis (GRA) based on Taguchi experimental design. Nine experimental runs based on a L9 Taguchi orthogonal array were carried out in order to accomplish this goal and find the ideal parameter combination for the required response variables. Grey relational analysis (GRA) and Taguchi Signal-to-Noise ratios are used to evaluate the experimental results. Confirmatory experiments are used in the final phase of the study to validate the experimental data.

As per the author's knowledge, no previous research with selected variables has reported the optimization of SMAW process for ASTM A 572 Grade 50 using GRA to achieve desired responses with selected parameters. Hence, this study is a significant and valuable addition to the current literature.

II. MATERIALS AND METHOD

A. *Base Material*

In this research study, ASTM A 572 has been chosen as the base plate material for investigation and testing. Thickness of base metal is 12 mm.

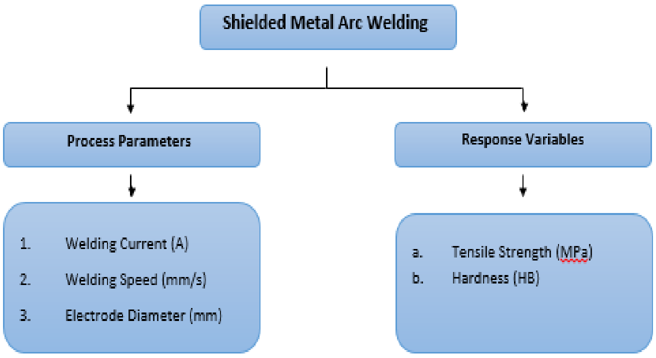

Fig. 2 SMAW Input and Output Variables

Table 1. Chemical composition of ASTM A 572 Grade 50.

Element	**C**	**Si**	**Mn**	**Cb**	**V**	**P**	**S**
Weight %	0.19	0.30	1.28	0.03	0.09	0.018	0.026

Welding Current

In shielded metal arc welding (SMAW), heat production is closely correlated with the welding current. The welding current plays a pivotal role in determining the amount of weld metal deposited. It measures the electrical current strength, directly impacting the melt-off rate of the electrode and the depth of penetration into the base material. In this study a range of 75 A to 125 A is selected for welding current.

Welding Speed

The pace at which the electrode travels along the welding path to unite two pieces is referred to as welding speed. High welding speeds, however, may result in insufficient filler metal deposition rates and poor weld quality. Conversely, a low welding speed can result in excessive heat input, leading to burn-through, distortion, and residual stresses. The right choice of welding speed is crucial for minimizing flaws and attaining desired weld quality. The selected welding speed in our study varied between 3 mm/s and 5 mm/s.

Electrode Diameter

The electrode diameter has a variety of effects on the stick welding process. Welding speeds, penetration, and heat levels are all accelerated by thicker electrodes. Conversely, thinner materials or situations requiring a smaller, more accurate weld are better suited for electrodes with a smaller diameter [15]. In our research, electrodes of sizes 2 mm, 3 mm, and 4 mm (designated as E7018) were utilized.

C. *Response Variables*

Response variables, which behave as independent variables are desirable characteristics or explanatory variables.

Tensile strength

The amount of resistance a material can withstand under stress before breaking or failing is known as tensile strength. This test's goal is to ascertain the maximum strength utilizing a universal testing device (UTM). The prepared specimen is loaded in the UTM during the tensile test, and the elongation caused by the applied force is measured.

Hardness

It is described as resistance to abrasion, scratching or indentation. The process of creating an indentation involves forcing an indenter into a substance for a predetermined amount of time. The penetration is then measured in terms of the indentation's diameter, diagonal and depth.

III. EXPERIMENTATION

A. *Experimental Design*

The Taguchi fractional factorial designs are used in the experimental design and the chosen orthogonal array is L9. Table 2 shows parameter selected for study along with their levels.

Minitab software version 19 is used to obtain the coded and un-coded design matrix as shown in Table 3.

B. *Experimentation*

On CNC flame cutting machine, 9 pieces of plate measuring 250 mm x 120 mm of thickness 12 mm were cut from large sheet.

Bevel angle of 30° is produced on each sample plate through portable bevel cutting machine. Electrodes were kept in holding oven at 100℃.

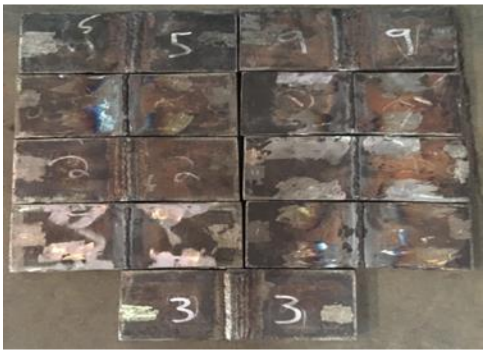

Fig. 3 Welded Samples

Table 2. SMAW parameters and levels

Parameters	**Units**	**Symbol**	**Level 1**	**Level 2**	**Level 3**
Welding Current	A	A	75	100	125
Welding Speed	mm/s	B	3	4	5
Electrode Diameter	mm	C	2	3	4

Table 3. Design Matrix

Exp. No	**Coded Matrix**			**Uncoded Matrix**			**Experimental Results**	
	A	**B**	**C**	**A**	**B**	**C**	**TS (MPa)**	**H (HB)**
1	1	1	1	75	3	2	554	135
2	1	2	2	75	4	3	546	148
3	1	3	3	75	5	4	549	141
4	2	1	2	100	3	3	565	140
5	2	2	3	100	4	4	568	150
6	2	3	1	100	5	2	557	150
7	3	1	3	125	3	4	562	155
8	3	2	1	125	4	2	539	159
9	3	3	2	125	5	3	564	153

Lincoln electric R3R-600-I welding plant has been used. All nine samples shown in Figure 3 were welded in Flat 1G position with constant inter-pass temperature of 150℃. Same welder, welding facility and electrode Company were used in order to preserve welding quality and reduce the likelihood of issues.

C. *Mechanical Testing*

Decision-makers are interested in mechanical testing qualities including impact strength, percent elongation, fatigue strength, tensile strength, hardness, elasticity and rupture stress. The results of mechanical testing aid researchers and engineers in determining if a material is suitable for mechanical applications. Tensile and hardness tests were carried out to gauge welded samples quality.

Tensile Testing

ASTM A370 was followed in the production of the tensile test specimens. A total of 9 sample, each measuring 50 mm in gauge length, are acquired. AutoCAD sketch and tensile specimen are shown in Figure 4 & 5 respectively. Tests were carried out using a Testometric universal testing machine (Model: FS500 AT).

Fig. 4 AutoCAD sketch of Tensile Specimen

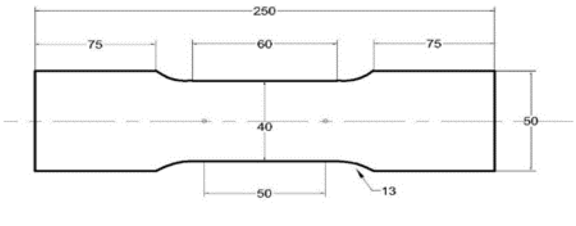

Fig. 5 Tensile Specimen

Hardness

Brinell hardness test is a method of measuring the hardness of a material by applying a constant load on its surface using a steel or tungsten carbide ball and measuring the size of the impression left. Portable brinell hardness tester in Figure 6 is used to get hardness values on flushed welding bead.

Fig. 6 Hardness Testing with Portable Hardness Tester

D. *Experimental Results*

Table 3 displays the experimental values for tensile strength and hardness of 9 experiments.

IV. INVESTIGATION AND OPTIMIZATION

A. *Taguchi Method*

The Taguchi method stands out as one of the most effective experimental techniques for determining the lowest number of tests to conduct within the permitted range of parameters and levels and to solve single response optimization problems.

Signal to noise (S/N) ratio is used for the optimal control factor settings that would produce a durable product or process and orthogonal arrays (OA) are employed for a well-balanced (minimum) experimentation layout [16].

B. *Grey Relational Analysis*

A mathematical method called grey relational analysis (GRA) is used to analyze and compare multiple, potentially incomplete and uncertain data sets. This method is rooted in the fundamentals of grey systems theory, enabling the assessment of information that lacks completeness, clarity, and certainty [12]. T-GRA finds significant use in multi-objective optimization, highlighting one of its key applications. [17][18].

Optimization methodology steps are shown in Figure 7.

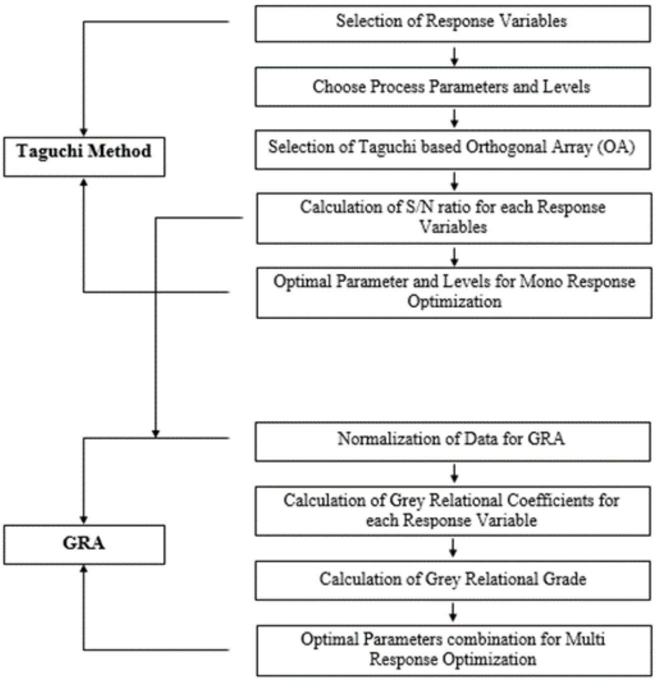

Fig. 7 T-GRA optimization steps

S/N Ratio

Our research study aims in minimization (smaller-the-better) of hardness and maximization (larger-the-better) of Tensile strength.

Eq (1) provides the formula for calculating the larger-is-better S/N ratio;

$$\mathrm{S/N\ ratio}(\eta) = -10\log_{10}\left(\frac{1}{n}\right)\sum_{i=1}^{n}\frac{1}{y_{ij}^2} \qquad 1$$

Eq (2) provides the formula for calculating the smaller-is-better S/N ratio;

$$\mathrm{S/N\ ratio}(\eta) = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} y^2 ij\right) \qquad 2$$

Normalization

Before using grey relational analysis or any other statistical technique, the data must be normalized. The normalization formulas for each category's data are listed below

The formula for the larger-is-better is shown in Eq 3.

$$Z_{ij=}\frac{y_{ij} - \min(y_{ij,}i = 1,2,\ldots,n)}{\max(y_{ij,}i = 1,2,\ldots,n) - \min(y_{ij,}i = 1,2,\ldots,n)} \qquad 3$$

The formula for the smaller-is-better in Eq 4.

$$Z_{ij=}\frac{\max(y_{ij,}i = 1,2,\ldots,n) - y_{ij}}{\max(y_{ij,}i = 1,2,\ldots,n) - \min(y_{ij,}i = 1,2,\ldots,n)} \qquad 4$$

Calculation of Grey Relational Coefficient

The normalized S/N ratio data acquired in step 2 are used to determine the grey relationship coefficient. The grey relational coefficient (GRC) calculation formula is shown in equation (5).

$$\gamma\left(y_0(k), y_j(k)\right) = \frac{\Delta\, min + \varsigma\, \Delta\, max}{\Delta_{0j}(k) + \varsigma\, \Delta\, max} \qquad 5$$

Grey Relational Grade Generation

A numerical representation denoting the degree of connection between the observed attributes and their optimal values. The weighted total of GRC is used to calculate GRG, which is displayed in Eq (6).

$$\overline{\gamma_j} = \frac{1}{n}\sum_{i=1}^{m}\gamma_{ij} \qquad 6$$

V. RESULTS AND DISCUSSION

A. *Probability Plots*

To assess the distribution of experimental data, probability graphs are employed, as illustrated in Table 3. The validation of the normalcy assumption is conducted through the Anderson-Darling test (ADT) [19]. Figure 8 shows the experimental data's responses lie in close proximity to the fitted line, suggesting that the data most likely has a normal distribution.

B. *ANOVA*

The analysis of variance (ANOVA) is used to examine the main influence of input factors on individual response at a 95% confidence level. In Table 4, the ANOVA findings for tensile strength and hardness are presented.

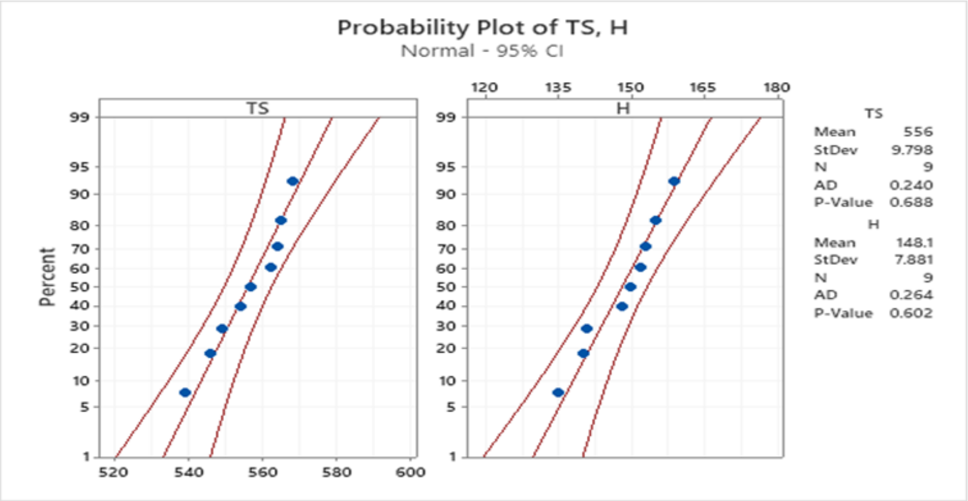

Fig. 8 Normal Probability Plots of Tensile Strength and Hardness

Table 4. ANOVA for individual responses

	Source	DoF	Adj SS	Adj MS	F-value	P-value	% Contribution
Tensile Strength	Welding Current	1	42.67	42.67	0.38	0.566	5.56
	Welding Speed	1	20.17	20.17	0.18	0.690	2.63
	Electrode Diameter	1	140.17	140.17	1.24	0.316	18.25
	Error	5	565.00	113.00			
	Total	8					
Hardness	Welding Current	1	308.167	308.167	10.05	0.025	62.02
	Welding Speed	1	32.667	32.667	1.06	0.349	6.57
	Electrode Diameter	1	2.667	2.667	0.09	0.780	0.54
	Error	5	153.389	30.678			
	Total	8					

Table 5. S/N ratio Response table

Signal to Noise Ratio Response Table					
Tensile Strength	Larger is better	**Level**	**WC**	**WS**	**ED**
		1	54.80	**54.97**	54.81
		2	**55.02**	54.82	54.94
		3	54.88	54.91	**54.96**
		Delta	0.21	0.15	0.15
		Rank	1	3	2
Hardness	Smaller is better	**Level**	**WC**	**WS**	**ED**
		1	**-43.00**	-43.11	-43.39
		2	-43.36	-43.69	**-43.34**
		3	-43.84	**-43.40**	-43.48
		Delta	0.84	0.58	0.14
		Rank	1	2	3

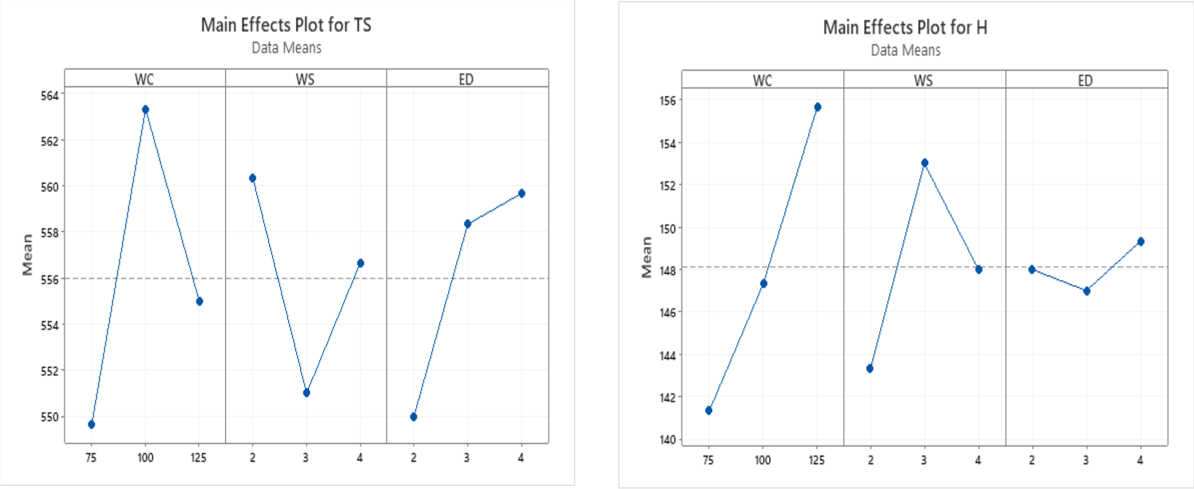

Fig. 9 Main Effect Plots of Tensile Strength and Hardness

Figure 9 shows main effect plots of means for tensile strength and hardness.

In Analysis of variance for Tensile Strength, Electrode diameter is the most significant parameter with percentage contribution of 18.25. This is further established in main effects plot for Tensile Strength where highest electrode diameter results in high tensile strength. Welding current and weld speed showing mixed behaviour towards tensile strength in main effect plot and their percentage contribution is 5.56 and 2.63 respectively.

For Hardness, most contributing factor as revealed in ANOVA is welding current with percentage contribution as high as 62.02. This is further endorsed in main effect plots where it is clearly visible that higher the current higher will be hardness. Welding speed's percentage contribution is 6.57 and it shows first increasing then decreasing behaviour towards hardness. Percentage contribution of electrode diameter is 0.54 which is negligible and in main effects plot it is clearly visible that Electrode diameter has little to no effect on hardness.

C. *Taguchi Mono Optimization*

Initially, the conventional Taguchi S/N approach was used to assess the experimental results. Lower S/N ration is used for calculation of hardness and higher for tensile strength. S/N ratio values for the best response variable parameter setting are shown in Table 5.

Taguchi analysis shows that the best optimal parameters to acquire high tensile strength are A2B1C3 while for hardness, best parameter combination and their corresponding levels are A1B3C2. Hence it is clear that multi response optimization cannot be done by employing Taguchi alone. In order to determine the best welding parameter setting that simultaneously satisfies two response factors, Taguchi based GRA is employed.

D. *GRA based Multi Optimization*

S/N ratios were determined for each response variable independently using equation (1) and (2), using the greater is better criterion for tensile strength and smaller is better criterion for hardness.

Data pre-processing or data normalization, is required for Taguchi-based GRA and is carried out using equations (3) and (4).

In GRA, the GRC's calculation has "distinguishing coefficient" which is typically taken to be 0.5 when all factors have given equal importance [20]. Equation (5) is used to calculate GRC's. The GRG can be determined by using equation (6). S/N ratio, normalized data, GRC's and GRG are all shown in Table 6.

In Table 6, highest GRG is obtained at sample no. 5. Table 7 leads to the conclusion that the ideal set of characteristics for use with GRA is A3B2C3.

Furthermore, GRA reveals that the most important factor influencing hardness and tensile strength is welding current, followed by electrode diameter. Welding speed is the least effective parameter.

Table 6. Calculated S/N ratio, Normalized, GRC and GRG

Exp No.	**S/N Ratio**		**Normalization**		**GRC**		**GRG**	**Rank**
	TS	**H**	**TS**	**H**	**TS**	**H**		
1	54.87	-42.61	0.52	0.00	0.51	0.33	0.42	8
2	54.74	-43.41	0.25	0.56	0.40	0.53	0.47	7
3	54.79	-42.98	0.35	0.27	0.44	0.41	0.42	9
4	55.04	-42.92	0.90	0.22	0.83	0.39	0.61	5
5	55.09	-43.52	1.00	0.64	1.00	0.58	0.79	1
6	54.92	-43.52	0.63	0.64	0.57	0.58	0.58	6
7	54.99	-43.81	0.80	0.84	0.71	0.76	0.74	2
8	54.63	-44.03	0.00	1.00	0.33	1.00	0.67	4
9	55.03	-43.69	0.87	0.76	0.79	0.68	0.73	3

Table 7. Average of Parameter GRG

Parameters	**Average of GRG**				
	Levels			**Delta**	**Rank**
	1	**2**	**3**		
WC	0.436	0.661	**0.713**	0.276	1
WS	0.590	**0.642**	0.577	0.064	3
ED	0.556	0.604	**0.650**	0.094	2

Table 8. Initial Condition and Final Experiment Comparative Study

	Initial Condition A2B2C2	**GRG base final experiment results**	**Improvement (%)**
Tensile Strength (Mpa)	540	586	9
Hardness (HB)	156	150	3.2
Optimal Condition		A3B2C3	
GRG	0.58	0.80	

E. *Confirmatory Experiment*

Final experiment was done on optimal levels identified in GRA. Predicted value of GRG at optimal levels is 0.80. Initial condition's value of GRG is 0.58 which authenticate the performance of optimal setting.

Table 8 shows confirmation results, comparison with initial value. The initial value is obtained from local industry's performance qualification record.

The confirmatory findings indicate a 9% rise in Tensile Strength and a 3.2% increase in Hardness.

F. Conclusion

This experimental investigation aims to resolve multi quality characteristics optimization of SMAW for high strength low alloy steel. Evaluations obtained from this study are

1. Best combination parameters received from GRA based multi response optimization is A3B2C3.
2. Optimal parameters with their levels are welding current at 125 A, welding speed at 4 mm/s and electrode diameter at 4 mm.
3. Individual response optimization through Taguchi analysis shows that the best optimal parameters to acquire high tensile strength is A2B1C3 while for hardness, best parameter combination is A1B1C2
4. The mean value of Grey Relational Grade (GRG) indicated that welding current holds the highest significance, followed by electrode diameter and welding speed.
5. Lastly, experiment based on GRG based optimal parameters showed an improvement in Tensile Strength of 9% and 3.2% in hardness.

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