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Influence of Welding Parameters on the Strength of Metal Inert Gas-Welded Mild Steel Joints

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Abstract

Metal Inert Gas (MIG) welding is a type of arc welding that uses a continuous solid wire electrode and a shielding gas to join two metals by heating them with an electric arc. We studied process parameters including current, voltage, preheat temperature, and post-weld heat treatment. We optimize process parameters of experiments done in previous work using a Taguchi Orthogonal Array (L27) design. A grey-based Taguchi method is used to optimize the process parameters. The Analysis of Variance (ANOVA) is applied to assess the significance of the input parameters on the response parameters. A mathematical model is developed using Multiple Linear Regression (MLR) equations. The results of this research show that it is possible to achieve higher strengths in weld joints using Taguchi design. We also find that increasing current (I) and Post-Weld heat Treatment (PWT) temperature increases the strength of the studied welded joints, and vice versa. Future research should validate the findings of the current study through experimental investigations.

Keywords: Weld parameters, Optimization, Taguchi relational analysis, Metal inert gas welding.

1 | Introduction

Welding is a fast and economical way of permanently joining two materials. It enables flexible designs and easy construction of large structures. It is essential in metal fabrication and the steel industries. Most of the metal products in modern times are welded. Products such as pipelines, jet engines, road vehicles, building construction, and airplanes are produced through welding processes [1]. Mild steel is widely used in industries and construction projects because it is inexpensive and possesses suitable properties for various applications, including bridges, buildings, boiler components, steam engines, and road vehicles [2]. It is the most widely used type of steel, characterized by excellent weldability [3]. Its large-scale application in various structures makes its manufacturing costs and efficiency crucial for further development [4]. To achieve greater adaptability and higher efficiency, conventional welding processes need to be more flexible and smart [5]. This is essential for industries to compete globally in the modern, dynamic world [5], [6].

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One of the common arc welding processes used for mild steel is Metal Inert Gas (MIG) welding. This process has several advantages over other welding methods, including simplicity, low cost, ease of handling, and high productivity [3]. However, MIG welding is also a complex process that involves numerous parameters influencing weld strength, such as current, voltage, gas flow rate, wire diameter, plate thickness, torch angle, and others [3]. The major challenge associated with the MIG process is the difficulty in obtaining optimal parameters that lead to excellent weld quality without welding defects. Therefore, it is essential to determine the optimal parameter settings that yield the desired weld quality [7]. The optimization of the welding process involves selecting a parameter combination that achieves the best results compared to a certain standard [8]. The optimized parameters should yield welds that are free of defects and exhibit improved mechanical and metallurgical properties [3].

Although extensive research has been conducted to model and optimize the process parameters of MIG welding mathematically, little empirical study has been conducted on the effect of varying preheat and post-weld temperatures on the strength and microstructure of weldments. According to recent studies, hybrid techniques that combine different optimization methods have become increasingly popular since 2000 for optimizing input parameters, whereas single optimization methods were dominant prior to that date [3], [9–11]. One of these studies, by [11], investigated the effects of preheating on the tensile strength of welded joints of 5083 Al alloy using NG-GMA welding and reported that proper preheating could achieve approximately 90% of the base metal strength. They explained that preheating increased the Ultimate Tensile Strength (UTS) by reducing the cooling rate in the Heat Affected Zone (HAZ), but it also slightly reduced the hardness [12], [13]. Pradhan et al. [14] used Artificial Neural Networks (ANN) and Multiple Linear Regression (MLR) models to model the weld bead shape parameters for MIG-welded T-joints and found that the ANN had higher accuracy than the MLR model. Using Taguchi optimization, Arunkumar et al. [12] investigated the impact of various MIG technique parameters on the strength of API-X42 steel. They found that welding current had the most significant influence, followed by welding voltage. They also used Backpropagation Neural Networks (BPNN) to model the MIG weld bead geometry and HAZ [15] and the Particle Swarm Optimization (PSO) algorithm to optimize the weld parameters [16]. Other researchers have applied an L-9 orthogonal array based on the Taguchi method to improve the quality response parameters of pulsed MIG welding on AISI 1008 mild steel and reported that the grey relational grading system achieved high-quality welds [17]–[19].

Different methods of experimental design have been used in various studies, such as orthogonal arrays based on Taguchi [3], [12], [20], [21], factorial design [22], central composite design [22]–[24], response surface methodology [23], [25], [26] and D-optimal design [27]. One of the drawbacks of a complete factorial design is that it requires a large number of trials, which can be both costly and time-consuming [3]. Therefore, researchers often use fractional factorial designs, which can strike a balance between cost and accuracy.

We have not found any previous study that examined the combined effect of preheat and post-weld temperatures on weld quality, taking into account other factors such as welding speed, welding current, and gap width. We address this research gap by exploring these effects and finding the best values for the factors to achieve high-quality welds using MIG welding. We use an orthogonal array based on the Taguchi method to design the experimental matrix, as it provides a coherent combination of parameters with a minimum number of experimental trials. To achieve good joint properties, the researchers needed to ensure the welds were free from defects. We build upon the work of [3] and [28] by using a grey-based Taguchi Orthogonal Array (L27) method to optimize parameters, including preheat temperatures, welding current, gap distance, weld speed, and post-weld temperatures, for improved weld quality. This is because L27 performs 27 experiments to determine the optimal parameters and has greater accuracy compared to L9.

2 | Literature Review

Using MIG welding on 6063-T5 aluminum alloy, Meseguer-Valdenebro et al. [29] investigated how weld quality was affected by welding speed, power, and separation between edges. They measured the geometric properties of the bead, including height, root width, penetration, over-thickness, perimeter, and area of the filler material. They concluded that bead shape was vital because it influenced other factors that could cause fatigue failures. However, they did not test the mechanical properties of the joint to relate them to the bead characteristics.

Later, Kumar and Singh [3] applied the grey-based Taguchi Orthogonal Array (L9) method to optimize preheat temperatures, welding current, and voltage in MIG welding of V-butt joints of AISI 1018 mild steel samples. They evaluated weld quality based on tensile properties of weldments. They used Analysis of Variance (ANOVA) to verify the effect of input parameters on response parameters. They found that preheat temperature was the most influential input parameter, followed by welding current and voltage. They validated their results through experimentation. However, they did not consider the impact of post-weld heat treatment.

Using mathematical modeling and experimental investigation, Mallick et al. [30] examined how current (I) and other MIG welding parameters, such as surface roughness, width of bed thickness, and hardness, affect weld quality in 304 stainless steel plates. They found that the best weld current was 120A with a voltage of 26V. The study was limited to stainless steel and did not consider preheat and post-weld heat treatment.

Zhao et al. [31] applied the desirability function approach (DFA) to analyze how voltage, wire feed speed, and welding speed influence the mechanical properties of the welding bead based on a Box-Behnken experimental Design (BBD). They processed the mechanical parameters using an order of preference based on similarity to ideal solutions, as well as the Shannon entropy technique. They discovered that mechanical properties are affected by voltage, welding speed, wire feed rate, and the interaction effects among the studied variables. The results were utilized in a multi-objective optimization study, which demonstrated that optimal mechanical properties are achieved with a medium wire feed speed, a high voltage value, and a high welding speed. The study strongly recommended a high welding speed. However, the effects of preheat temperatures and post-weld heat treatment on weld quality were not investigated.

Arunkumar et al. [12] employed Grey Relational Analysis (GRA) based on a Taguchi Orthogonal Array (L9) to investigate the influence of welding voltage, current, and weld bevel angle on impact strength in MIG welding of dissimilar materials. They used A387 steel alloy and SS316 stainless steel grade. Their results indicated that the optimal combination of parameters, with a current of 140 A and a welding voltage of 20 V, and an angle of bevel of 50°, gave the highest impact strength. ANOVA results showed that current had a significant effect on the impact strength of the weld joint, followed by voltage. This study also did not include the influence of preheat temperature and post-weld treatment. It also focused on dissimilar materials and did not show the effects on mild steel.

Using a Taguchi L25 orthogonal array and Desirability Function Analysis (DFA), Assefa et al. [28] investigated the effects of welding current, gas flow rate, gap distance, and filler materials on the mechanical and microstructural properties of dissimilar welds of SS 316 and AISI 1020 low-carbon steels using Tungsten Inert Gas (TIG) welding. The properties studied included tensile strength, hardness, flexural strength, and the bead width of the welds. The results showed that welding current and gas flow rate had the most significant influence on the tensile strength of the welds. The hardness and flexural strength of the weld metals were higher than those of the stainless steel and carbon steel base metals, and also higher in the Fusion Zone (FZ) and HAZ than in the base metal. No crack was observed in the weld metal after a U-shape flexural bending test. The bead width of the welded workpieces was primarily affected by the welding current and gap distance. The validation test confirmed that the predicted optimization matched well with the

3 | Statement of the Problem

The major problem associated with the MIG process is the difficulty in obtaining optimal parameters that lead to excellent weld quality without welding defects.

Weld defects can, at worst, cause serious accidents and structural damage.

The combined effects of preheat and post-weld temperatures on weld quality, as well as welding speed, welding current, and gap width, have not been adequately studied.

3.1 | Justification

Limited research on combined preheat and post-weld heat treatment effects; Existing studies focus on isolated effects of preheat or post-weld heat treatment, without exploring their combined impact on weld quality.

Investigating both parameters together can offer a more comprehensive understanding of optimization strategies for improved weld strength and durability.

Challenges in online weld quality: Assessment of traditional quality assessment methods, such as destructive testing, introduces significant delays in production processes, leading to material waste and inefficiencies.

A simulation-based approach can streamline weld quality evaluation, minimizing the need for excessive weld points while ensuring high reliability and cost-effectiveness.

3.2 | Significance

Significance to industry

- *Enhanced weld integrity and cost efficiency: the study will help manufacturers optimize welding parameters, reducing unnecessary weld points while maintaining structural integrity. Improved weld quality will minimize failure risks, resulting in lower costs and increased productivity in fabrication and manufacturing industries.*
- *Strengthening national manufacturing competitiveness*
- *Reduction in expulsion and material waste: by refining heat treatment strategies, the study can help mitigate weld expulsion, reducing material losses and improving overall efficiency. These improvements will enhance sustainability efforts within manufacturing sectors that rely on MIG welding.*

Significance to policy makers

- *Informing industry standards and guidelines: policymakers can integrate these insights into regulatory frameworks that promote high-quality, cost-effective welding practices.*

3.3 | Scope

The study focused on mathematical modeling and simulation of MIG welding parameters, including preheat and post-weld temperatures, welding speed, current, and gap distance.

Welding trials were conducted on mild steel workpieces, comparing the mechanical properties and microstructures of welded and unwelded samples.

3.4 | Limitations

The research was restricted to simulations performed in MATLAB R2022b and did not explore alternative modeling software

4 | Methodology

Objective 1. To develop a mathematical model relating to welding

Parameters for weld quality

UTS was chosen as the appropriate quality for mathematical modelling.

A log-linear model was used to relate weld UTS to the parameters

$$\text{Log WS} = \beta 0 + \beta 1\text{Log TPH} + \beta 2\text{Log S} + \beta 3\text{Log I} + \beta 4\text{LogG} + \beta 5\text{Log PWT} + \varepsilon,$$

where:

$\beta 0$: regression constant.

$\beta 1, \ldots, \beta 5$: beta coefficients of regression.

WS: weld UTS in MPa.

TPH: preheat temperature in ^{o}C.

S: speed of welding in mm/min.

I: current in A.

G: welding gap in m.

PWT: Post-Weld Temperature in ^{o}C.

ε: is the error term.

Objective 2. To simulate the influence of preheat and post-weld temperatures on weld quality

Data for the simulation were collected from previous research.

Data was of preheat temperature (TPH), weld speed (S), current (I), weld gap width (G), post-weld treatment (PWT), and Weld Strength (WS).

The data was then optimized using Taguchi Grey Relational Analysis (TGRA) with 27 experiments (L27) in Matlab R 2024b software.

Objective 3. To validate the findings of the MIG welding parameters of welded joints

Sample preparation

A sample measuring 60 mm by 40 mm with a thickness of 3 mm was prepared as shown in *Fig.1*.

Fig. 1. Pieces of mild steel plate.

Preheating

Preheating and post-weld heat treatment were performed in a furnace at the temperatures determined by the simulation results, for 30 minutes.

The preheat temperature was 205°C.

Welding

Welding speed was set at 80 mm/min.

Current was set at 120 A.

Gap width was set at 0.50 mm.

Post-weld temperature was set at 150°C.

Other parameters not varied were set at a constant value. These parameters included wire feed rate and gas flow rate, among others.

ER70S-6 filler wire with a diameter of 1.2mm was used. Welding was carried out using a MIG welding machine, and the resulting samples were machined at the machine workshop of Multimedia University of Kenya.

Fig. 2. Welded pieces.

Tensile test

Mechanical properties tested were yield, Young's Modulus, UTS, and total strain.

A tensile test was conducted using an Enkay Universal Testing Machine (UTM).

Fig. 3. Tensile test setup.

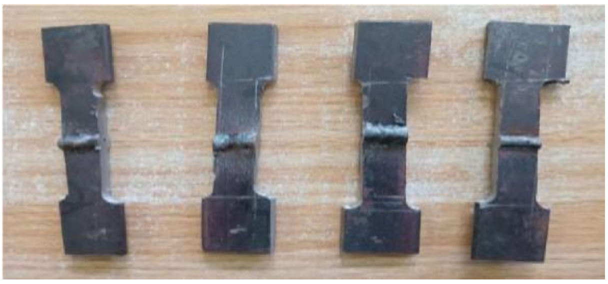

Fig. 4. ASTM E8 tensile test-pieces.

4.1 | Scanning Electron Microscope/Energy Dispersive Spectrometry Analysis

Microstructural properties were studied in Scanning Electron Microscopy (SEM) at Dedan Kimathi University of Technology.

SEM was employed as an analytical tool to characterize the morphological properties of the sample.

Numerous images were captured using the Secondary Electron (SE) detector to show the microstructure of the sample.

Some Backscattered Electron (BSE) detector images were also captured to reveal elemental phases and enhance chemical contrast during EDS analysis.

Energy-dispersive spectrometry (EDS) was employed for the qualitative analysis of the sample. Qualitative analysis involves the detection or identification of constituent elements and their relative distribution within the sample.

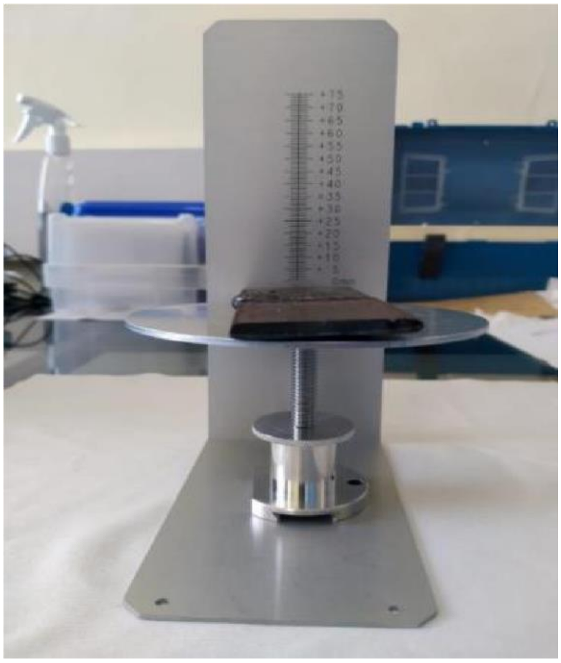

Fig. 5. Setting sample for scanning electron microscope/energy dispersive spectrometry.

4.2 | Results

Results of Objective 1. To develop a mathematical model relating welding parameters to weld quality

A log-linear regression model was found, as shown in *Table 1*.

PWT and G were found to have a significant positive relationship with weld strength.

TPH, S, and I were found to have a significant negative relationship with Weld Strength (WS).

$$\mathrm{WS} = 159.5568 \times \frac{\mathrm{PWT}^{0.9483} \times \mathrm{G}^{0.0206}}{\mathrm{PHT}^{0.5160}\mathrm{S}^{0.2929}\mathrm{I}^{0.0698}}.$$

Results of Objective 2. To simulate the influence of preheat and post-weld temperatures on weld quality

Results of simulation using L27 Taguchi grey relational analysis

Optimal values were found as:

Preheat temperature (TPH): 205 °C.

Weld speed (S): 80 mm/min.

Gap (G): 0.5 mm.

Current (I): 120 A.

Post-weld Temperature (PWT): 150 °C.

Weld Strength (WS): 380.62 MPa.

The values obtained in this research indicate that there is potential for achieving high-strength weld joints.

The strength is significantly higher than that reported by others, who achieved the highest ultimate strength of 264.14 MPa at a weld speed of 210 mm/min, a current of 130A, and a welding gap of 0.15mm, without preheat and post-weld heat treatment.

Table 1. Experimental data of welding parameters (TPH, S, I, G, PWT) and corresponding weld strength (WS) values.

TPH (°C)	S (mm/min)	I (A)	G (mm)	PWT (°C)	WS (UTS, MPa)
120	40	90	0.50	150	610.84
120	60	120	2.75	325	1007.70
120	80	150	5.00	500	1343.3
162.5	40	120	5.00	150	446.51
162.5	60	150	0.50	325	975.91
162.5	80	90	2.75	500	1185
205	40	150	2.75	325	864.62
205	60	90	5.00	500	1096.8
205	80	120	0.50	150	379.66
120	40	90	0.50	150	610.12
120	60	120	2.75	325	1007.60
120	80	150	5.00	500	1342.60
162.5	40	120	5.00	150	448.20
162.5	60	150	0.500	325	975.23
162.5	80	90	2.75	500	1185.10
205	40	150	2.75	325	864.70
205	60	90	5.00	500	1095.70
205	80	120	0.50	150	380.03
120	40	90	0.50	150	609.80
120	60	120	2.75	325	1008.00
120	80	150	5.00	500	1341.80
162.5	40	120	5.00	150	446.96
162.5	60	150	0.50	325	975.29
162.5	80	90	2.75	500	1185.1
205	40	150	2.75	325	864.44
205	60	90	5.00	500	1096.9
205	80	120	0.50	150	380.62

Results of Objective 3. To validate the findings of the simulation testing of MIG-welded joints

Table 2. Mechanical properties of metal inert gas welded joints obtained from tensile testing (yield strength, ultimate tensile strength, elongation, and Young's modulus).

Mechanical Property	Test 332	Test 335	Test 336
Yield strength (MPa)	180.40	187.60	181.59
UTS (MPa)	379.63	379.01	382.44
% Elongation	8.22%	8.00%	8.40%
Young's modulus (GPa)	209.98	201.50	208.60

Ultimate tensile strength

The predicted UTS was 380.6 MPa.

The test results showed UTS values of 379.63 MPa, 379.01 MPa, and 382.44 MPa, which were very close to the predicted value.

Young's modulus (E)

The theoretical Young's modulus was 210 GPa.

The test results showed values of 209.98 GPa, 201.50 GPa, and 208.60 GPa. While the result of Test 335 was slightly lower, the other two tests had results very close to the theoretical value.

Percentage elongation

Test results showed values of 8.22%, 8.00%, and 8.40%.

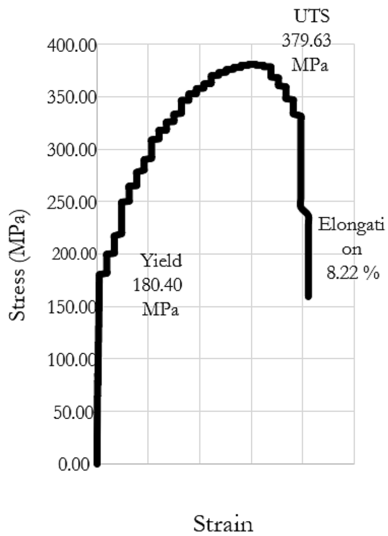

Fig. 6. Test 332 stress-strain graph.

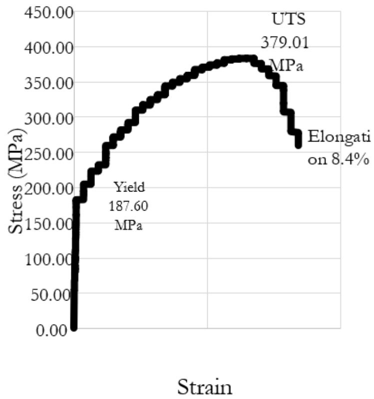

Fig. 7. Test 336 stress-strain graph.

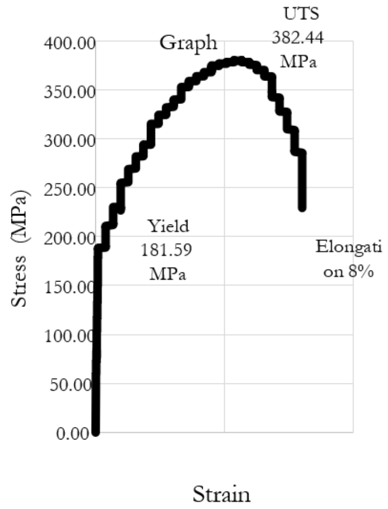

Fig. 8. Test 335 stress-strain graph.

The results of the tensile test validate the simulation results.

The test results of UTS differed from the simulation result by between 0.42% and 0.48%, which is a reasonable margin of error.

4.3 | Scanning Electron Microscope/Energy Dispersive Spectrometry Results

Welded area vs. base metal

The welded region showed a distinct fusion boundary, indicating proper metallurgical bonding.

The base metal retained its grain structure, contrasting with the refined zones within the weld.

Boundary characteristics and weld strength

The fusion line appeared smooth with a gradual grain transition, suggesting optimal heat input and metallurgical consistency.

Phase distribution in mild steel

A balanced phase of ferrite and pearlite composition enhances strength and toughness, reducing brittleness.

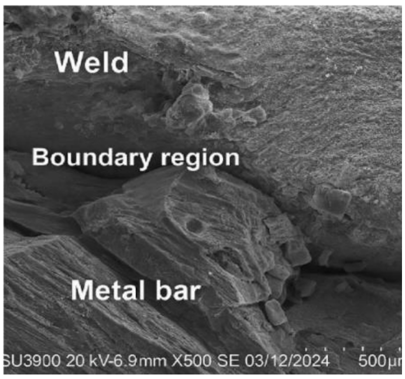

Fig. 9. Scanning electron microscopy showing the boundary of the metal base and weld at 500 µm.

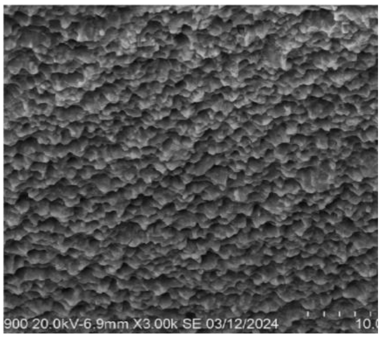

Fig. 10. Scanning electron microscopy image showing the top of the welded area at 10 µm.

The results of twenty-seven experiments done using Taguchi Grey Analysis L27 are shown in *Table 3*. The results show that the optimal values were: preheat temperature of 205 °C, welding speed of 80 mm/min, current of 120A, welding gap of 0.50 mm, and post-weld temperature of 150°C, which would result in a UTS of the welded joint of 380.62 MPa. The values obtained in this research indicate that there is potential for achieving high-strength weld joints. The strength is significantly higher than that found by those who reported the highest ultimate strength of 264.14 MPa at a weld speed of 210mm/min, a current of 130A, a welding gap of 0.15mm, and without preheat and post-weld heat treatment.

Table 3. Results of Taguchi grey relational analysis.

TPH (°C)	S (mm/min)	I (A)	G (mm)	PWT(°C)	WS (UTS, MPa)
120	40	90	0.50	150	610.84
120	60	120	2.75	325	1007.70
120	80	150	5.00	500	1343.3
162.5	40	120	5.00	150	446.51
162.5	60	150	0.50	325	975.91
162.5	80	90	2.75	500	1185
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205	60	90	5.00	500	1096.8
205	80	120	0.50	150	379.66
120	40	90	0.50	150	610.12
120	60	120	2.75	325	1007.60
120	80	150	5.00	500	1342.60
162.5	40	120	5.00	150	448.20
162.5	60	150	0.500	325	975.23
162.5	80	90	2.75	500	1185.10
205	40	150	2.75	325	864.70
205	60	90	5.00	500	1095.70
205	80	120	0.50	150	380.03
120	40	90	0.50	150	609.80
120	60	120	2.75	325	1008.00
120	80	150	5.00	500	1341.80
162.5	40	120	5.00	150	446.96
162.5	60	150	0.50	325	975.29
162.5	80	90	2.75	500	1185.1
205	40	150	2.75	325	864.44
205	60	90	5.00	500	1096.9
205	80	120	0.50	150	380.62

Linear regression of the data in *Table 3* shows that an increase in preheat temperature (TPH), welding speed (S), and welding gap (G) is associated with a reduction in Weld Strength (WS), and vice versa. The increase in current (I) and post-weld heat treatment temperature (PWT) is associated with an improvement in the strength of the welded joint, and vice versa. *Table 4* illustrates the results of the linear regression.

Table 4. Results of the regression of data from Taguchi grey relational analysis.

Parameter	Coefficients	Standard Error	t Stat	P-value
Intercept	503.8	19.9	25.3	0.00
TPH (°C)	-2.4	0.1	-33.5	0.00
S (mm/min)	-2.1	0.2	-11.0	0.00
I (A)	1.6	0.1	15.7	0.00
G (mm)	-23.2	1.7	-13.8	0.00
PWT(°C)	2.3	0.0	94.4	0.00

5 | Conclusion

This research reveals an opportunity for achieving high-strength MIG welds through preheating and post-weld heat treatment. The results indicate that the strength of weld joints can be close to that of AISI 1010 mild steel which is 365 MPa when parameters are set to preheat temperature of 205°C, welding speed of 80 mm/min, current of 120A, welding gap of 0.50mm, post-weld temperature of 150 °C that can result into strengths of 380.62MPa that is higher than that of parent material. We also find that the strength of the weld joint can be increased by increasing the current (I) and post-weld heat treatment temperature (PWT), and reducing the preheat temperature (TPH), welding speed (S), and welding gap (G) until optimality is attained. Future research can validate these findings through experimental investigations.

Author Contribution

All the authors contributed equally to this research paper.

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Data Availability

The data mentioned is present in the paper (*Table 1*) and sources indicated herein. The MATLAB code for this paper will be provided upon request.

Conflicts of Interest

The authors have no competing interests to declare that are relevant to the content of this article.

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