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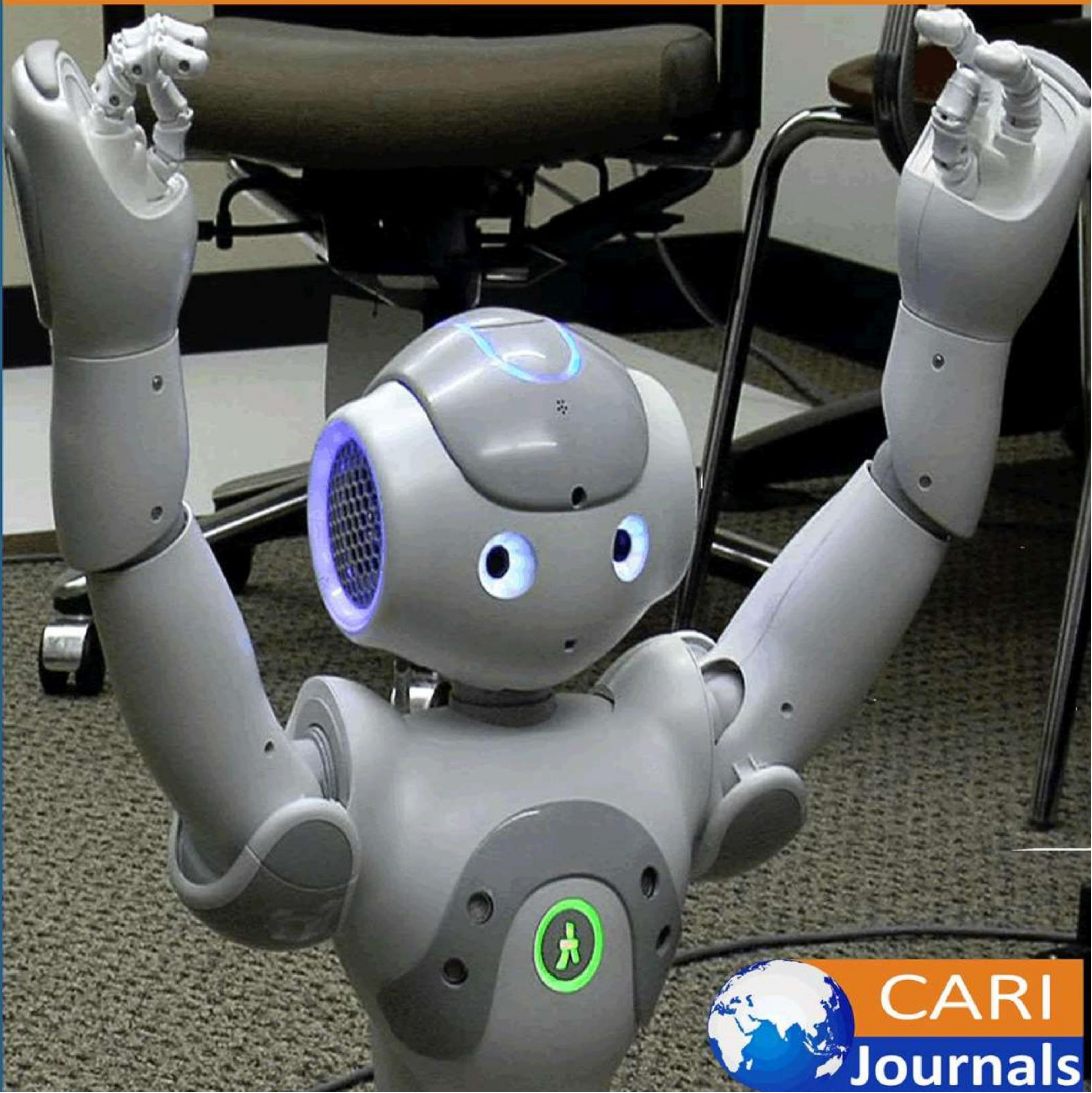

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Influence of Welding Parameters on Strength of Metal Inert Gas Welded Mild Steel Joints

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Abstract

Purpose: 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. Process parameters including current, voltage, preheat temperature and post-weld heat treatment were studied. Then, optimize process parameters of experiments done in previous work using a Taguchi Orthogonal Array (L27) design.

Methodology: 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 equations.

Findings: Results of this research show that it is possible to get higher strengths of weld joints using Taguchi design. Increasing current (I) and post-weld heat treatment temperature (PWT) increases strength of the studied welded joints, and vice versa.

Unique contribution to theory, policy and practice: Future research should validate the findings of the current research through experimental investigations.

Keywords: *Weld Parameters, Optimization, Taguchi Relational Analysis, MIG Welding*

I. 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 steel industries. Most of the metal products in modern times are welded. Products such as pipelines, jet engines, road vehicles, building construction and aero planes are produced through welding processes [1]. Mild steel is widely used in industries and construction works because it is cheap and has suitable properties for many applications in bridges, buildings, parts of boilers, steam engines and road vehicles [2]. It is the most widely used type of steel, with excellent weldability combined [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].

One of the common arc welding processes used for mild steel is metal inert gas (MIG) welding. This process has many advantages over other welding methods, such as simplicity, low cost, easy handling and high productivity [3]. However, MIG welding is also a complex process that involves many parameters that influence the weld strength, such as current, voltage, gas flow rate, wire diameter, plate thickness, torch angle and others [3]. The major challenge associated with MIG process is the difficulty in obtaining optimal parameters that lead to excellent weld quality devoid of welding defects. Therefore, it is essential to find the optimal parameter settings that can produce the desired weld quality [7]. The optimization of the welding process involves selecting the parameter combination that can achieve the best results compared to a certain standard [8]. The optimized parameters should result in welds that are free of defects and have better mechanical and metallurgical properties [3].

Though extensive research has been done to mathematically model and optimize process parameters of MIG welding, little empirical studies have been conducted on effect of variation of preheat and post-weld temperatures on strength and microstructure of weldments. According to recent studies, hybrid techniques that combine different optimization methods have become more popular since 2000 for optimizing input parameters, while single optimization methods were dominant before 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 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]. [14] Used artificial neural networks (ANN) and multiple linear regression model (MLR) to model the weld bead shape parameters for MIG welded T-joints and found that ANN had higher accuracy than MLR. Using Taguchi optimization, [12] studied the effect of various parameters of MIG technique on the strength of API-X42 steel and found that welding current had the most influence, followed by welding voltage. They also used backpropagation neural networks (BPNN) to model the MIG weld bead geometry and HAZ [15] and particle swarm optimization (PSO) algorithm to optimize the weld parameters [16]. Other researchers have applied L-9 orthogonal array based on Taguchi method to improve the quality response parameters of pulsed MIG welding process on AISI 1008 mild steel and reported that grey relational grading system achieved high quality welds [17]–[19].

Different methods of experimental design have been used in various studies, such as orthogonal array 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 full factorial design is that it requires a large number of trials, which can be costly and time consuming [3]. Therefore, researchers often use fractional factorial designs, which can balance the trade-off between cost and accuracy.

We have not found any single previous study that examined how preheat and post-weld temperatures together affect the quality of welds when other factors such as welding speed, welding current and gap width change. 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 orthogonal array based on Taguchi method to design the experimental matrix since it provides coherent combination of parameters with minimum experimental trials. In order to have good joint properties, it was important that the researchers ensure that the welds were free from defects. We build upon the work of [3], [28]by using grey-based Taguchi Orthogonal Array (L27) method to optimize parameters including preheat temperatures, welding current, gap distance, weld speed and post-weld temperatures for better weld quality. This is because L27 performs 27 experiments to determine the optimal parameters and has greater accuracy compared to L9.

II. LITERATURE REVIEW

Using MIG welding on 6063-T5 aluminum alloy, [29] investigated how weld quality was affected by welding speed, power, and separation between edges. They measured geometric properties of the bead such as height, root width, penetration, over-thickness, perimeter, and area of filler material. They concluded that bead shape was important 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, [3] applied 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 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, [30] examined how current (I) and other MIG welding parameters of 304 stainless steel plate affect weld quality based on surface roughness, width of bed thickness and hardness. They found that the best weld current was 120A with voltage of 26V. The study was limited to stainless steel and did not consider preheat and post-weld heat treatment.

[31] applied desirability function approach (DFA) to analyze how voltage, wire feed speed, and welding speed influence the mechanical properties of welding bead based on Box-Behnken experimental design (BBD). They processed the mechanical parameters using order of preference by similarity in relation to ideal solutions as well as 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 used in multi-objective optimization and showed that good mechanical properties are achieved by medium wire feed speed, a high value of voltage, and high welding speed. The study strongly recommended high welding speed is. However, the effects of preheat temperatures and post-weld heat treatment on weld quality was not investigated.

[12] Used grey relational analysis based on Taguchi Orthogonal Array (L9) to study the impact of welding voltage, currents and weld bevel angle on impact strength for MIG welding of dissimilar materials. They used A387 steel alloy and SS316 grade stainless steel. Their results indicated that optimal combination of parameters of current of 140 A and 20 V welding voltage with an angle of bevel of 50° gave highest impact strength. ANOVA results showed that current had significant effect the impact strength of 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), [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 were tensile, hardness, and flexural strength, as well as 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 heat-affected zone (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 work pieces was mainly affected by welding current and gap distance. The validation test confirmed that the predicted optimization matched well with the experimental results.

III. RESEARCH METHODOLOGY

I use mathematical model based on Taguchi grey relational analysis (GRA) to transfer multi-response problems into single-response problems to achieve optimal MIG welding process parameters. The method is known to give ultrafine metal grain structures leading to enhanced mechanical properties [32]. Taguchi Grey Relational Analysis is used to evaluate inputs, outputs and process parameters. It is selected because of its ability to reduce the number of required experiments to achieve desired characteristics. Welding parameters are set as illustrated in Table 1.

Table 1 Welding parameter levels and source literature

MIG welding parameters	Minimum	Maximum	Notation	Source
Preheat temperatures (°C)	120	205	TPH	[33]
Welding speed (mm/min)	40	80	S	[34]
Welding current (A)	90	150	I	[34]
Gap distance (mm)	0.5	5	G	[35]
Post-weld temperatures (°C)	150	500	PWT	[36], [37]

Chemical composition of base metal and filler is as described in Table 2. The base metal is AISI 1010 mild steel and filler is ER70S-6

Table 2 Chemical composition of base and filler metal

Chemicals	Symbol	Base material (AISI 1010)	Filler material (ER70S-6)
Iron	Fe	99.18-99.62 %	96.99-98.04%
Manganese	Mn	0.30-0.60 %	1.40 – 1.85%
Sulfur	S	≤0.050 %	≤0.035%
Phosphorous	P	≤0.040 %	≤0.025%
Carbon	C	0.08-0.13%	0.06 – 0.15
Nickel	Ni	-	≤0.15%
Molybdenum	Mo	-	≤0.15%
Chromium	Cr	-	≤0.15%
Copper	Cu	-	0.5%

The requirements for degrees of freedom in Taguchi’s L27 array are satisfied by the parameters that form five columns. Signal to noise ratio in Grey Rational Analysis is defined as shown in Equation 1. The higher the ratio, the better the factor

$$\mu = -10 \log 10 \frac{1}{m}\sum_{i}^{m}\frac{1}{x_{ij}^{2}} \quad , i = 1,2,\cdots m, j = 1,2,\cdots k \qquad (1)$$

Where,

m= Number of experiments;

x_{ij}=Response under consideration;

Pre-calculation is performed to obtain comparable sequences with original values. The values of the experiments are normalized to be between 0 and 1. Equation 2 illustrates actual back height (BH$_A$) and actual front height (FH$_A$) for normalized calculation of the better factors.

$$p_{ij} = \frac{Max(q_{ij}) - q_{ij}}{Max(q_{ij}) - Min(q_{ij})} \qquad (2)$$

Where,

p_{ij}=Level of preferance;

i= Number for observed experiment;

j= Number for the result of the observed experiment;

$Max(q_{ij})$=Maximum value of the experiment;

$Min(q_{ij})$=Minimum value of the experiment;

Performance of actual back width (BW$_A$) and actual front width (FW$_A$) for greater-the-better values are calculated based on Equation 3.

$$p_{ij} = \frac{q_{ij} - Min(q_{ij})}{Max(q_{ij}) - Min(q_{ij})} \qquad (3)$$

If the value of p_{ij}in the pre-calculation process of GRA is close or equal to 1, then i is selected as the best for the result j. The order of preference of *P0* is described as *P0j* for $j = 1,2,\cdots n$. The coefficient of GRA for the nearest p_{ij} to $P0_j$ is calculated. The larger the coefficient the nearer the p_{ij} to $P0_j$. Equation 4 illustrates the calculation of the coefficients.

$$(p_{0j}, p_{ij}) = \frac{\Delta_{min} + \xi\Delta_{max}}{\Delta_{ij} + \xi\Delta_{max}}, i = 1,2\cdots m, j = 1,2\cdots n \qquad (4)$$

Where,

(p_{0j}, p_{ij})= Grey relational coefficient between p_{0j} and p_{ij};

Δ_{ij}= $|p_{0j} - p_{ij}|$=Modulus of the coefficient,

Δ_{min}= Minimum $\{ij\}, i = 1,2\cdots m, j = 1,2\cdots n$

Δ_{max}= Maximum $\{ij\}, i = 1,2 \cdots m, j = 1,2 \cdots n$

$\xi \in (0,1)$=Measure of distinguishability, the smaller the ξ the higher the distinguishability and vice versa.

In this research, we take the value of ξ as 0.5 to ensure process stability. Grey relational grade is used to measure the quantity of the coefficients. Equation 5 illustrates the calculation of the grey relational grade, δ.

$$\delta\ (P0, Pi) = \sum_{j=1}^{n} w_j \eta\left(p_{0j}, p_{ij}\right), \qquad i = 1,2 \cdots m \quad (5)$$

Where,

$\sum_{j=1}^{n} w_j = 1$;

$P0$=Reference order;

Pi= Comparable order;

Experiment with highest grey relational grading have highest similarity and are therefore the best combination of multiple performance parameters for greatest weld quality. The analysis allots grade 1 to maximum value of grey relational coefficient. Means of the grey relational grades are evaluated in Matlab R2022b to obtain the influence of the best combination of parameters on weld quality. Experimental data that is used is drawn from Table 2 and objective function takes the form of log-linear model.

$$Log\ WS = \beta_0 + \beta_1 Log\ TPH + \beta_2 Log\ S + \beta_3 Log\ I + \beta_4 Log G + \beta_5 Log\ PWT + \varepsilon \qquad (5)$$

Where, β_0 is regression constant, $\beta_1, \cdots, \beta_5$ are beta coefficients of regression. Data for regression is drawn from [34]. WS is the weld ultimate tensile strength in MPa, TPH is the preheat temperature in ^{o}C, S is the speed of welding in mm/min, I is the current in A, G is the welding gap in m, PWT is the post-weld temperature in ^{o}C and ε is the error term. Table 3 below presents the data for log-linear regression analysis. Note that the research did not carry out post-weld heat treatment as well as pre-heating, temperatures are taken as room temperature.

Table 3 Weld parameters for Taguchi GRA (Source: [34].)

TPH (ºC)	S (mm/min)	I (A)	G (mm)	PWT(ºC)	WS (UTS, MPa)
25	210	80	0.05	25	169.92
25	210	100	0.05	25	182.41
25	210	130	0.05	25	221.63
25	210	80	0.1	25	173.27
25	210	100	0.1	25	206.72
25	210	130	0.1	25	234.96
25	210	80	0.2	25	114.36
25	210	100	0.2	25	153
25	210	130	0.2	25	218
25	90	80	0.15	25	137.86
25	90	100	0.15	25	188.62
25	90	130	0.15	25	210.5
25	150	80	0.15	25	227.44
25	150	100	0.15	25	251.04
25	150	130	0.15	25	255.1
25	210	80	0.15	25	116.2
25	210	100	0.15	25	229.7
25	210	130	0.15	25	264.14

IV. RESULTS AND DISCUSSIONS

Results of twenty-seven experiments done using Taguchi Grey Analysis L27 are as shown in Table 4. The results show that the optimal values were: preheat temperature is 205ºC, welding speed of 80 mm/min, current of 120A, welding gap of 0.50mm, post-weld temperature of 150 ºC that would result in ultimate tensile strength of the welded joint of 380.62 MPa. The values obtained in this research show that there is potential of having high strength weld joints. The strength is much higher than those found by who found highest ultimate strength of 264.14MPa at weld speed of 210mm/min, current of 130A, and welding gap of 0.15mm and without preheat and post-weld heat treatment.

Table 4 Results of Taguchi GRA

TPH (ºC)	**S (mm/min)**	**I (A)**	**G (mm)**	**PWT(ºC)**	**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

Linear regression of data in Table 4 shows that increase of preheat temperature (TPH), welding speed (S) and welding gap (G) is associated with reduction in weld strength (WS), and vice versa. Increase of current (I) and post-weld heat treatment temperature (PWT) is associated with improvement of strength of welded joint, and vice versa. Table 5 illustrates results of the linear regression.

Table 5 Results of regression of data from Taguchi GRA

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

CONCLUSION

We find in this research that there is an opportunity for high strength MIG welds with 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 strength of weld joint can be increase by increasing current (I) and post-weld heat treatment temperature (PWT) and reducing preheat temperature (TPH), welding speed (S) and welding gap (G) until optimality is attained. Future research can validate these findings through experimental investigations.

RECOMMANDATIONS

Welding parameters should be refined to avoid any form of incomplete fusion which might occur during welding.

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