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Development of a Predictive Model to Improve the Hardness of Mild Steel Welded Joint

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Abstract

Structural integrity of weldment is greatly influenced by its process parameters and usually, it is expected for a welded joint to be stronger than its parent metal, but in actual fact, most failures occur at the welded joints and it is mostly due to poor combination of process parameters or inexperience of the welder. This poor combination leads to poor hardness exhibited at the welded joint. The aim of this study is to predict and improve the hardness of mild steel welded zone using the tungsten inert gas (TIG) welding process. Response Surface Methodology (RSM) was employed to analyze the welded response. 200 pieces of mild steel coupons measuring 27.5 × 10 × 10 mm were prepared and used for the experiment, the experiment was performed 20 times, using 5 specimens for each run, after which the hardness was measured and results analyzed respectively. The study produced eighteen (18) optimum results with the best selected to produce a material hardness of 299.269 N/mm^2 with desirability of 95.6%, resulting from current of 120 amp, voltages of 20 and gas flow rate of 12 L/min.

Keywords

RSM, TIG, Mild Steel, Contour Plot

1. Introduction

The tendencies of any materials to resists penetration, abrasion, scratching or cutting are regarded as hardness. It is the property by which material resists permanent deformation [1]. The automobile and shipbuilding industries employ a substantial amount of mild steel in making parts, some of these parts involve bending and forming. The relative malleability and softness of mild steel materials give room to an outstanding ductility and toughness of the material [2] and

[3]. This also increases its machinability and weldability of the material. Welding is the most extensively used method of metal joining, in various industries like oil and gas, rig design and marine transportation, construction, automobile industries etc. [4]. Due to the quick joining process that creates a permanent waterproof bond and provides better cost saving, its applications are numerous. Welding operations have an overall weight reduction as compared to other joining methods. The structural integrity of the weldment is greatly influenced by its process parameters and usually, it is expected for a welded joint to be stronger than its parent metal, but in actual fact, most failures occur at the welded joints and it is mostly due to poor combination of poor process parameters or inexperience of the welder [5] and [6]. Poor weld reduces the hardness and scratch resistance of weldment, it also encourages high corrosion activities [7].

It has been proven by several researchers that the choice of welding input process parameters can alter the quality of the weldment, therefore, optimizing these process parameters to obtain the best weld quality and multi-response properties cannot be over emphasized [8] and [9]. This research aims at predicting and optimizing the Hardness of mild steel weld using tungsten inert gas (TIG) welding process and design expert 11.

2. Materials and Methods

2.1. Materials

The key parameters considered in this work are welding current, welding voltage and gas flow rate [10]. The range of the process parameters is shown in **Table 1**. The TIG welding and test were conducted at the Department of Welding and fabrication technology, Petroleum Training Institute (PTI), Warri, Delta State, Nigeria.

The selected input parameters have the upper (+) and lower limits (−). The limits of the four welding variables are shown in **Table 1**.

2.2. Methods

200 pieces of mild steel coupons measuring 27.5 × 10 × 10 mm were used for the experiments, the experiment was performed 20 times, using 5 specimens for each run for hardness test specimen presented in **Figure 1**. The hardness of the welded specimens was measured by means of Brinell hardness tester. The procedure adopted is as follows:

Table 1. Welding process parameters limits.

Process parameters	Unit	Symbol	Low (−)	High (+)
Welding Current	Amp	I	120	170
Welding Voltage	Volts	V	20	25
Gas Flow Rate	Lit/mill	F	12	14

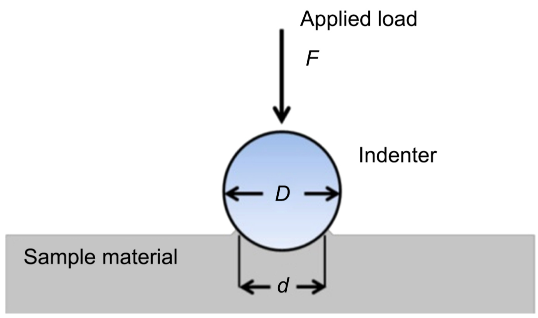

Figure 1. Working principle of Brinell hardness test.

1) The indenter is pressed into the sample by an accurately controlled test force.

2) The force is maintained for a specific dwell time, normally 10 - 15 seconds.

3) After the dwell time is complete, the indenter is removed leaving a round indent in the sample.

4) The size of the indent is determined optically by measuring two diagonals of the round indent using a portable microscope.

5) The Brinell hardness number is a function of the test force divided by the curved surface area of the indent. The indentation is considered to be spherical with a radius equal to half the diameter of the ball. The average of the two diagonals is used in the following formula to calculate the Brinell hardness.

3. Results and Discussion

3.1. Results

In this study, twenty (20) experimental runs were carried out, each experimental run, comprising the current, voltage and gas flow rate used to join two pieces of mild steel plates measuring 55 mm × 10 mm × 10 mm. The hardness test was measured and results were presented in Table 2.

Table 3 presents the model summary statistics for the hardness test, the quadratic model, was selected as the best model since it has the highest Adjusted and Predicted R^2 among listed sources whereas, the cubic source was aliased.

Table 4 shows the ANOVA for quadratic model used to analyze the hardness test with coded factors of A, B and C representing current, voltage and gas flow rate which was used to develop the quadratic model that mimics the behavior of the weldment as presented in Equation (1). The Sum of squares from the ANOVA table has a Type III Partial with the Model F-value of 6.87 which indicates a significant model. This means that there is only a 0.29% chance that an F-value this large could result from noise.

The fit statistics for the hardness test are presented in Table 5 with R^2, Adjusted R^2, Predicted R^2 and the Adequate Precision. Signal to noise ratio (S/N) is measured using the Adequate precision, according to literature, it is generally recommended to have an adequate precition value greater than four (4) to have a desirable model.

Table 2. Experimental result for the hardness test.

Run	A: Welding Current	B: Welding Voltage	C: Gas Flow Rate	Hardness Test
	Amp	Volts	Lit/mill	N/mm^2
1	145	22.5	13	255.493
2	145	22.5	13	246.792
3	187	22.5	13	281.596
4	145	22.5	11	280.014
5	170	20	12	254.702
6	145	18	13	249.956
7	170	25	14	288.478
8	120	20	14	256.284
9	170	25	12	264.194
10	120	25	12	293.461
11	120	20	12	295.834
12	102	22.5	13	302.162
13	170	20	14	238.091
14	145	22.5	14	252.329
15	145	22.5	13	250.747
16	145	22.5	13	276.059
17	145	26	13	271.313
18	145	22.5	13	259.448
19	120	25	14	283.969
20	145	22.5	13	238.091

Table 3. Model summary statistics from the hardness test.

Source	Std. Dev.	R^2	Adjusted R^2	Predicted R^2	PRESS	
Linear	17.03	0.3653	0.2463	0.008	7254.96	
2FI	16.32	0.5267	0.3083	0.0845	6695.01	
Quadratic	**10.09**	**0.8607**	**0.7354**	**0.6403**	**2630.83**	**Suggested**
Cubic	11.89	0.8841	0.633	0.3961	4416.61	Aliased

Table 4. ANOVA for quadratic model of the hardness test.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	6294.74	9	699.42	6.87	0.0029	significant
A-Welding Current	1031.19	1	1031.19	10.12	0.0098	
B-Welding Voltage	1073.99	1	1073.99	10.54	0.0088	
C-Gas Flow Rate	566.14	1	566.14	5.56	0.0401	

Prediction of Hardness test can be done using the Equation (1), the plot of the predicted versus the experimental is presented in Figure 2.

$$\begin{aligned} HT = {} & 254.51 - 8.69A + 8.87B - 6.44C + 4.32AB + 7.09AC + 8.87BC \\ & + 12.79A^2 + 1.74B^2 + 3.70C^2 \end{aligned} \tag{1}$$

From the plot presented in Figure 2, the predicted and actaul, have the same minimum value of 220 N/mm^2 and maximum of 320 N/mm^2. The positive slope with minimal scattering along the slope shows a good agreement between our model and the experimental response.

The 3D surface plot presented in Figure 3, shows the effect of current and voltage on hardness of the mild steel specimen. To design above the predicted value, one should target the point dotted in wine. The 3D surface plot gives an overall view of the design space for informed decision. The blue region indicates the region with the weakest hardness strength. From the plot, the toughest area lies in the green region of the plot.

To optimize the Hardness of the material, deign expert 11 interphase for optimization was fixed to maximize in Figure 4 under hardness test.

Table 5. Fit statistics for the hardness test.

Std. Dev.	10.09	**R^2**	0.8607
Mean	266.95	**Adjusted R^2**	0.7354
C.V. %	3.78	**Predicted R^2**	0.6403
		Adeq Precision	8.7792

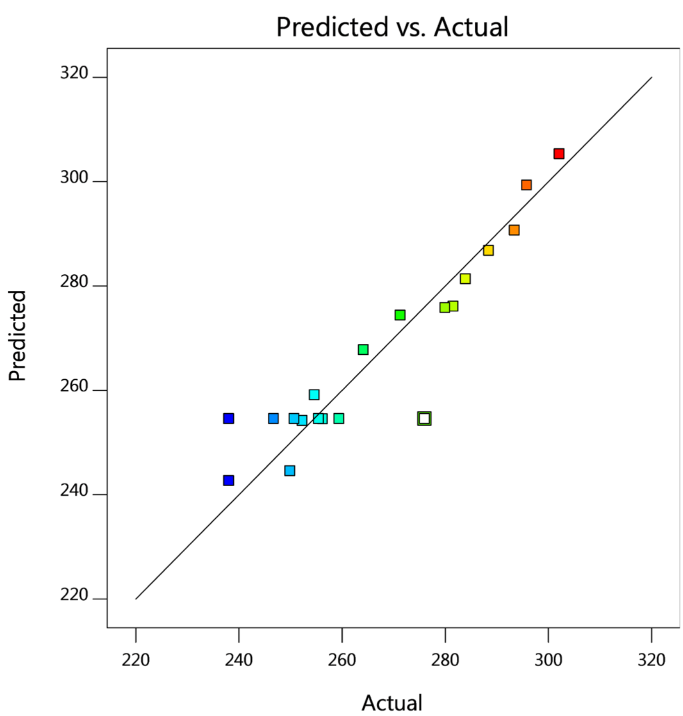

Figure 2. Plot of predicted versus actual hardness test.

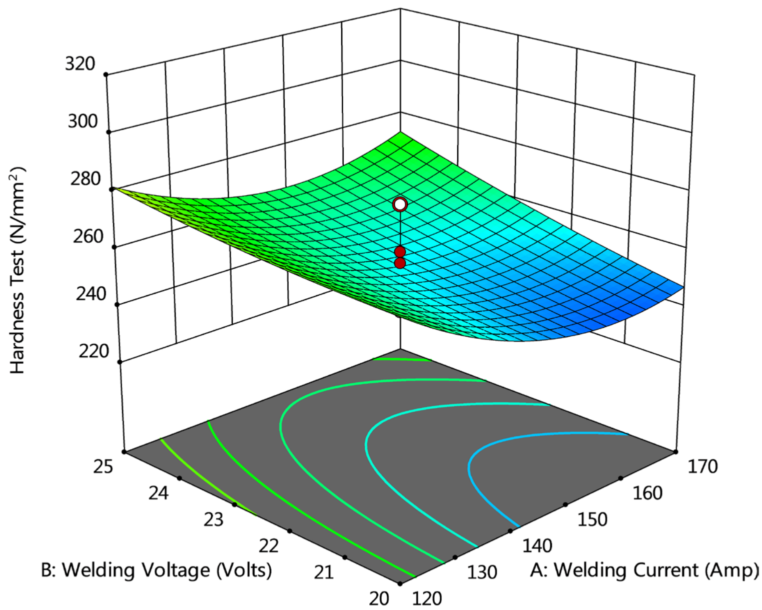

Figure 3. Surface plot for effect of current and voltage on the hardness test.

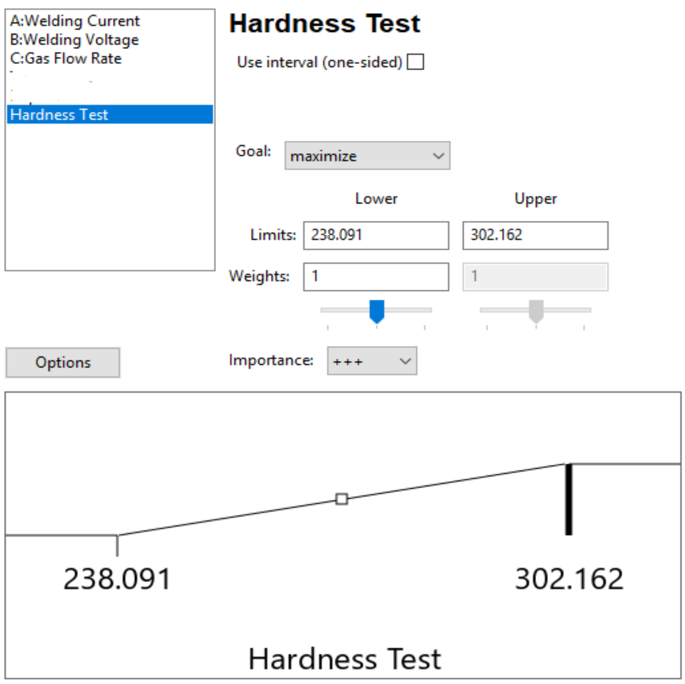

Figure 4. Interphase of numerical optimization model for Hardness test.

The interface of numerical optimization is used to define the objective function (minimize or maximize), which is used to defines the lower and upper limit of the response with the level of importance indicated. In other to maximize the material hardness, the weight leans towards the higher limit of 302.162 as seen in Figure 4.

The numerical optimization from Figure 4 was employed in producing eighteen (18) optimal solutions presented in Table 6.

From the results in Table 6, it was observed that current of 120 Amp, voltage of 20.00 volt and gas flow rate of 12.00 L/min produced a weld material with good hardness of 299.269 N/mm^2. This solution obtained was selected by design expert as the optimal solution with a desirability value of 97.30%.

The contour plots showing the hardness response variable of the material against the optimized value of the input variable are presented in Figure 5. To maximize the hardness of the material, the red region on the plot in Figure 5 should be targeted. This region of optimal responses for increased hardness can be achieved by the use of the optimal process parameters of Table 6.

3.2. Discussion

The ANOVA in Table 4 shows a P-values of 0.0029 which is less than 0.0500, this indicates a significant model. It was still observed in that same table that the coded variables of A, B, C, BC and A^2 were significant model terms, this is because their respective p-values were less than 0.05. In other to develop a robust mathematical model for the material hardness, most of the input variables (coded variables) in Equation (1) need to have a p-value less than 0.05 for the model to be significant. The Fit statistics in Table 5 show an R^2 of 0.8607, Predicted and Adjusted R^2 of 0.6403 and 0.7354. according to literature, the difference between the Predicted and Adjusted R^2 must be less than 0.2 for good agreement to be established. In our case, 0.0951 value was obtained, showing a reasonable agreement. The Adequate Precision of 8.779 was obtained, this shows a good adequate signal. With a pass mark, obtained from the ANOVA and the Fit statistics tables, a mathematical expression for the material hardness was developed in Equation (1) which was used to navigate the design space.

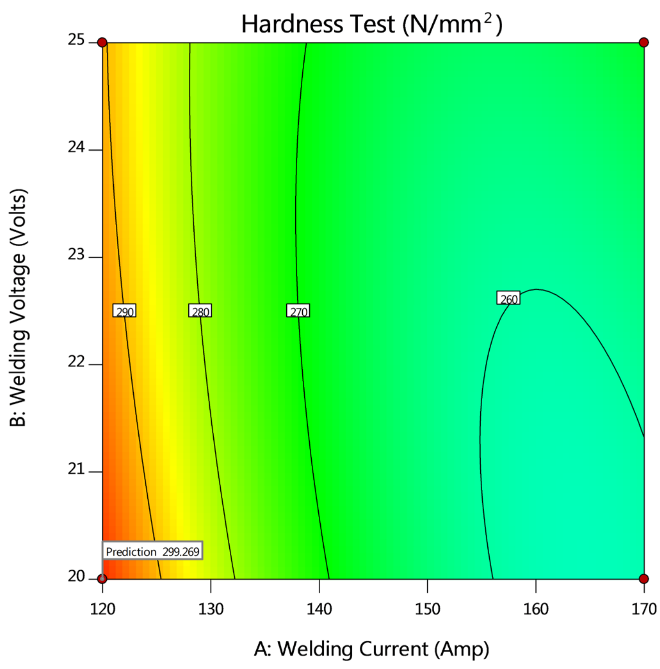

Figure 5. Contour plot for predicting the hardness of the material.

Table 6. 18 optimum solutions found.

Number	Welding Current	Welding Voltage	Gas Flow Rate	Hardness Test	Desirability	
1	**120**	**20**	**12**	**299.269**	**0.956**	**Selected**
2	120	20.036	12	299.157	0.954	
3	120.01	20	12.007	299.039	0.952	
4	120.177	20	12	298.946	0.951	
5	120	20.119	12	298.9	0.949	
6	120	20	12.015	298.838	0.949	
7	120	20.162	12	298.771	0.947	
8	120.462	20	12	298.429	0.943	
9	120	20	12.029	298.407	0.942	
10	120.715	20	12	297.972	0.936	
11	121.046	20	12	297.382	0.926	
12	120	20.718	12	297.171	0.918	
13	122.705	20	12	294.477	0.88	
14	120	21.773	12	294.612	0.874	
15	120	21.838	12	294.474	0.872	
16	120	22.318	12	293.532	0.856	
17	120	22.599	12	293.039	0.848	
18	120	22.627	12	292.994	0.848	

To maximum the material hardness, the upper limit of 302.162 N/mm^2 in **Figure 4** was targeted. This target produced eighteen (18) optimum results in **Table 6**.

The contour plots in **Figure 5** show the effect of voltage and current on the material hardness. It can be deduced from the plot that to maximize the material hardness, effort should be made toward the red region of **Figure 5**. The eighteen (18) optimum results in **Table 6** are all concentrated around the red region on the contour plot. In same table, the optimum result for the material hardness was obtained as current of 120 amp, voltages of 20 and gas flow rate of 12 to produce a material hardness of 299.269 N/mm^2 with desirability of 0.956 or 95.6%. This shows that RSM was robust enough for predicting.

4. Conclusions

In this study, mathematical model for material hardness is presented in Equation (1), using the Tungsten Inert Gas (TIG) welding process with three (3) process parameters, namely: current, voltage and gas flow rate have been developed. The outcomes obtained indicate that current of 120 Amp, voltage of 20 volt and gas flow rate of 12 L/min will produce a weld with material hardness of 299.269 N/mm^2. This optimum solution was selected at a desirability of 95.60%.

Weld current is found to have a greater influence on the material hardness as compared to voltage and gas flow rate at a moderate level.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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