



# **Optimization of Mild Steel Welding Process Parameters Using Multivariate Linear Regression**

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## **Authors' contributions**

*This work was carried out in collaboration among all authors. Author WEO designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors DA and IPO managed the analyses of the study. All authors read and approved the final manuscript.*

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## **ABSTRACT**

Local welders in Nigeria are prone to poor quality weldment because of their lack of welding technical skills. When these local welders carry out their welding operation, the welded joints are considered to be good enough because the metal materials welded together are seen to be good and satisfactory. In most case, when these welded joints have not fully served their service life, these materials fail due to the poor quality of the weldment. Material quality can easily be assessed by inspecting the microstructure of the weldment. In this work, mild steel welding process parameters were optimized using multivariate linear regression (MLR). The study involves the determination of the suitable set of conditions for the welding process parameters that would give the optimum weld of mild steel (low carbon steel) using Gas Metal Arc welding (GMAW) technique and obtain a relationship between the three welding process parameters and the ultimate tensile strength and Brinell hardness number. For this reason, an experimental study was carried out using nine samples of the specimen of mild steel. The experimental and predicted results show that arc voltage and gas flow rate affect the ultimate tensile strength and the Brinell hardness number of mild steel. The maximum ultimate tensile strength and Brinell hardness number were

obtained at 180A, 15V and 20l/min. It was also observed that the ultimate tensile strength decreases with increases in arc voltage and gas flow rate. But these two parameters tend to have a positive effect on the Brinell hardness number.

*Keywords: Welding; mild steel; optimization; multivariate linear regression.*

## 1. INTRODUCTION

The focus of this research is to address the challenges of a multinational industrial firm, specializing in pipeline installation and maintenance in the upstream and downstream sectors of the Nigerian oil industry. The weldability of steel and its alloys is of great importance to manufacturing and construction, and many modern everyday products and structures are made from steel. The success or failure of such industrial products depends a great deal on the welding process parameters chosen by industrial firms incorporated as part of their signature protocols [1]. There is an ever-increasing demand for better and more reliable welds, with greater quality control. However, most industrial firms have stuck to the same welding protocols and parameters for an inordinate number of years without much thought or investment in reassessment and improvement. Their managers seem to be content with the level of weld quality they have always produced, and even though they do have an earnest quest to improve overall weld quality, they are for the most part not as susceptible to change because they erroneously believe that they have limited options, and continue to count their losses.

Welding is a process of permanently joining two metals by localized coalescence resulting from a suitable combination of temperature, pressure and metallurgical conditions [2]. It is the most dependable, efficient and economical means of joining metals. Many products around our immediate environment are made of metals, which are joined together in one way or the other to give a particular shape or form. Virtually every area of manufacturing has been largely shaped by welding technology. Building construction, automobiles, pipelines, ships and aircraft are examples of manufacturing industries that depend majorly on welding. The quality and durability of the products of these industries are tied to the quality of the welding done. The quality of welding depends on several factors such as the skill of the welder(s), weld process parameters, dimensional accuracy, work environment, correct processes and procedures.

Metals, being the primary components in welding, are stronger than most other materials, and this quality is important in the fabrication of good quality products that will withstand different service conditions and environmental effect. It is of utmost importance that a welder produces welds of good quality strength in any fabrication design work. However, many welded joints fail in various manners because of the use of welding process parameters settings that do not give optimum weld result. Mild steel alloys are susceptible to distortion due to their high coefficient of thermal expansion. In some cases, certain steel alloys are quite prone to cracking and reduced corrosion resistance Kishore et al. [3]. These limitations are even more glaring when these steel alloys are subjected to the welding process. Considering these limitations and the stark relevance of the application of mild steel products to our everyday lives, it becomes imperative to optimize the welding process protocols and parameters. Optimization as defined by Dieter [4], is the process of maximizing the desired quantity or minimizing an undesired one. Thus, the welding process parameters should be controlled to obtain the optimum parameters that would reduce the limitations associated with mild steel and further improve their weldability and performance.

The gas-metal arc welding (GMAW) process is a commonly used welding process in industrial applications due to ease of operations and its versatility. In the GMAW process, an electric arc is formed between the consumable wire electrode and the workpiece metal. The arc formation causes the consumable wire and workpiece to melt and join. The area where the joining occurs is called a weld. To prevent contamination of the weld by the surrounding air during the welding process, an inert gas is fed along with the wire electrode to form a protective layer across the weld area during the welding process. Conventionally, testing of the weld quality is performed off-line, with either destructive testing techniques (used on as few samples as possible) and non-destructive testing (NDT) techniques. The most common NDT is a visual inspection of the GMAW runs, which involves obtaining the penetration depth and the

aspect ratio of the welds. All these testing techniques can only be used at the end of the welding runs and are mostly done on randomly selected samples. Univariate statistical analysis methods Adolfsson et al. [5]; Siewert et al. [6] have been previously used to monitor weld runs in various welding applications. Artificial neural network models have been developed to monitor the plasma radiation García-Allende et al. [7] in arc welds. These methods are univariate, whilst the welding operations are multivariable. It is a fact that univariate data analysis methods cannot accurately capture the effect of process variations in a multivariable process. This implies that multivariate techniques of modelling and analysis need to be used to ensure effective monitoring of the welding processes. Regression analysis is a statistical technique for estimating the relationship among variables which have reason and result relation. Regression models with one dependent and independent variable are called univariate regressions while models with one dependent variable and two or more independent variables are called multivariate or multiple linear regressions (MLR) [8]. In multivariate regression analysis, an attempt is made to account for the variation of the independent variables in the dependent variable at a specific point in time Uyanik and Guler [9].

Prediction of mechanical properties to optimize material production performance has been attempted by many researchers. Lee and Rhee [10] predicted welding process parameters for gas metal arc welding using multiple regression analysis to obtain the desired geometry of the back-bead in butt welding. Kim et al. [11] developed mathematical models for optimizing bead width for multi-pass welding using the multivariate regression method. Mostafa and Khajavi [12] successfully developed a model for predicting the value of weld penetration using regression analysis. Sen et al. [13] developed a mathematical model using multiple regression analysis in MINITAB 13.1 to predict the weld bead geometry and the model adequacy checked using analysis of variance (ANOVA). Joseph Achebo [14] developed a robust predictive model for determining mechanical properties of AA 6061 using multiple regression analysis. The study involved using MLR to predict the ultimate tensile strength (UTS), the yield strength (YS) and percentage elongation (% Elongation) of AA 6061. Janani and Santhi [15] used multiple regression models in Statistical Package for Social Sciences (SPSS) to study the mechanical properties and impact resistance of

concrete with fly ash and hooked-end steel fibres to predict their strength and energy at 28 and 56 days.

In this study, a mathematical model was developed using multivariate linear regression in XLSTAT PRO 7.5.2. to predict and optimize mild steel welding process parameters. The model was able to predict the optimum process parameters of mild steel.

## **2. MATERIALS AND METHODS**

### **2.1 Materials**

A 50 mm long, 8 mm square mild steel specimen was subjected to gas metal arc welding (GMAW) operation. The input parameters for this particular experiment are the welding current, arc voltage and shielding gas flow rate. The operation was carried out with a semi-automatic welding machine, a 1.6 mm consumable wire electrode of AWS classification ER70S-3, shielding gas consisting of 80% argon and 20% carbon dioxide. The Brinell hardness tester was used in this study to determine the weld or test specimen's hardness number. The higher the Brinell hardness number (BHN), the harder the specimen becomes. The Brinell test method as defined by ASTM E10 was employed to test the hardness of the mild steel weld. A very high test load (about 3000 kgf) and a 10 mm wide indenter were used so that the resulting indentation averages out the most surface and sub-surface inconsistencies.

The ultimate tensile stress of the specimens was measured using the universal tester. It is commonly expressed in Mega Pascal (MPa). The ultimate tensile strength is a material's maximum resistance to fracture. It is found by performing a tensile test on the specimen and plotting the stress-strain curve. The highest point of the stress-strain curve is the ultimate tensile strength (UTS).

### **2.2 Methods**

The basic method employed in this study is the multiple linear regression method. The modelling was done using a statistical and data analysis software package called XLSTAT PRO 7.5.2. The following steps were utilized in predicting and optimizing the welding process parameters:

1. The Gas Metal Arc Welding was used to make weld deposits for each welding

- operation. In one welding operation, six weldments were made.
- The ultimate tensile strength was obtained for each weldment using the universal tester. The average value of the test results was recorded.
  - The above steps were repeated for nine different specimens in each case varying one or more of the predictor variables.

For the Brinell hardness number:

- A predetermined test load,  $P = 3000$  kg was applied to carbide ball indenter of diameter  $D = 10$  mm.
- The load on the indenter was held for some time and then removed.
- The resulting impression was measured across two diameters orthogonal to each other and the average diameter,  $d$ , is computed using the values of  $P, D$ . With  $d$  obtained, the Brinell hardness number, BHN was computed from the relation in equation (1). The unit of BHN is  $kg/mm^2$ .

$$BHN = \frac{2P}{\pi D(D - \sqrt{D^2 - d^2})} \quad (1)$$

Where:

$P$  = applied force (kgf)  
 $D$  = diameter of indenter (mm)  
 $d$  = diameter of indentation (mm)

- Steps 1 to 3 were repeated for nine different specimens again varying one or more input parameters.
- The results are as shown in Table 1.
- Multiple linear regression was thereafter employed to model the relationship between the input and output variables.

The general form of multiple linear regression models is shown in equation (2)

$$y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \dots + \beta_n X_n \quad (2)$$

Where

$y$  = dependent variable  
 $X_1, X_2, X_3, \dots, X_n$  = independent variables  
 $\beta_0, \beta_1, \beta_2, \beta_3, \dots, \beta_n$  = parameters

### 3. RESULTS AND DISCUSSION

#### 3.1 Results

In Table 1, the three process parameters and the levels that were used for this study is shown.

Where the notations  $X_1, X_2$  and  $X_3$  represent the current, voltage and gas flow rate respectively. From Table 1, it can be seen that the minimum and maximum levels of current, voltage and gas flow rate are 160-210 A, 15-20 V and 16-25 l/min respectively. This range of values was used for welding of the specimens. Table 2 shows the results obtained for the Brinell hardness number (BHN) and ultimate tensile strength (UTS) from the experimental tests carried out on nine samples of the specimens, with varying input parameters. It can be seen from Table 2 that optimal values were obtained for Brinell hardness number (BHN) and the ultimate tensile stress (UTS) when the current, voltage and gas flow rate were at levels of 180A, 15V and 20l/min respectively. Table 3 shows the relationship between the three process parameters and the Brinell hardness number (BHN). The process parameters were used to carry out the welding process. The Brinell Hardness number was determined for the run and the result recorded. The recorded result becomes the dependent variable while the process parameter is the independent variables.

The data in the Tables 1 and 2 were modelled using the multiple linear regression in the XLSTAT 7.5.2 software package.

$$y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 \quad (3)$$

where  $X_1, X_2$  and  $X_3$  represent the independent variables; current, voltage and gas flow rate respectively. While  $\beta_1, \beta_2$  and  $\beta_3$  represent their coefficients in the modelled relation. Table 3 shows the relationship between the three independent variables and the dependent variable, Brinell hardness number (BHN).

The process parameters were used to carry out the welding process. The Brinell Hardness number was determined for the run and the result recorded. The recorded result becomes the dependent variable while the process parameter is the independent variables. Using the XLSTAT 7.5.2 package, the (fitted) model was obtained as shown in equation (4).

$$y = 260.0 - 2.23X_1 + 1.22X_2 + 0.21X_3 \quad (4)$$

Table 4 shows the relationship between the three independent variables and the dependent variable, which is the ultimate tensile strength (UTS). Once again, the process parameters were used to make weldment. The weldments were machined into tensile specimen using the

**Table 1. Process parameters and their levels**

Process parameters	Unit	Notations	Levels	
			High	Low
Current	A	X <sub>1</sub>	210	160
Voltage	V	X <sub>2</sub>	15	20
Gas flow rate	l/min	X <sub>3</sub>	16	25

**Table 2. Experimental results of BHN and UTS**

Run	Current (A)	Voltage (V)	Gas flow rate (l/min)	BHN	UTS (MPa)
1	160	15	16	240	520
2	160	17	20	280	490
3	160	20	25	260	480
4	180	15	20	340*	550*
5	180	17	25	220	530
6	180	20	16	310	499
7	210	15	25	275	510
8	210	17	16	256	515
9	210	20	20	290	500

**Table 3. Experimental and predicted Brinell Hardness Number (BHN)**

Current (A) (X <sub>1</sub> )	Voltage (V) (X <sub>2</sub> )	Gas flow rate (l/min) (X <sub>3</sub> )	BHN (Y)	Predicted BHN
160	15	16	240	276.5
160	17	20	280	270
160	20	25	260	262.2
180	15	20	340	335.8
180	17	25	220	273
180	20	16	310	306.8
210	15	25	275	266.8
210	17	16	256	289.4
210	20	20	290	284.1

**Table 4. Experimental and predicted Ultimate Tensile Strength (UTS)**

Current (A) (X <sub>1</sub> )	Voltage (V) (X <sub>2</sub> )	Gas flow rate (l/min)(X <sub>3</sub> )	Exp. UTS (MPa) (Y)	Predicted UTS (MPa)
160	15	16	520	524.5
160	17	20	490	489
160	20	25	480	486.1
180	15	20	550	549.7
180	17	25	530	509.5
180	20	16	499	494.4
210	15	25	510	520
210	17	16	515	519.5
210	20	20	500	497.2

universal tensometer and the ultimate tensile strength of each of the weldment were determined and recorded. The XLSTAT 7.5.2 package was used to obtain the predictive (fitted) model as expressed in equation (5).

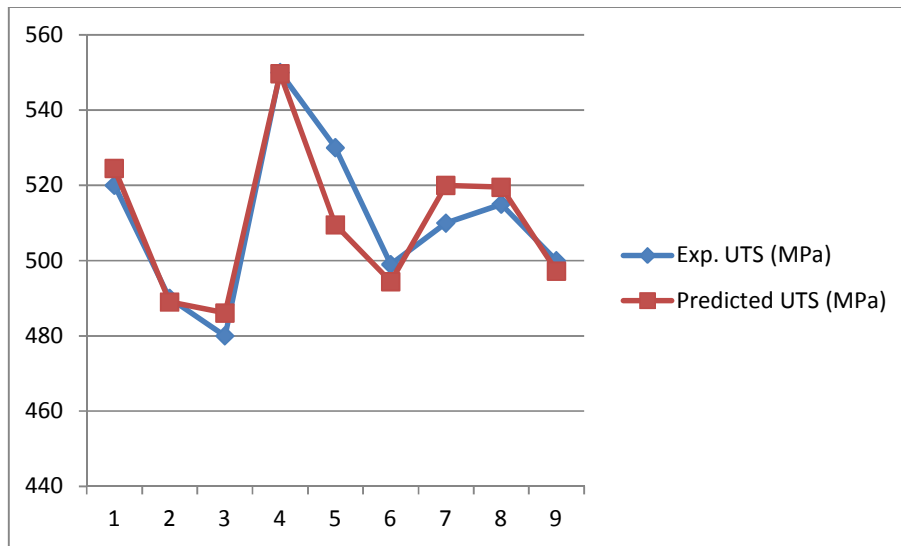
The fitted model is  $y = 606.96 + 0.17X_1 - 6.70X_2 + 0.55X_3$  (5)

Where X<sub>1</sub>, X<sub>2</sub>, and X<sub>3</sub> represent the current, voltage and gas flow rates respectively, as shown in Table 3. While y represents the ultimate tensile strength.

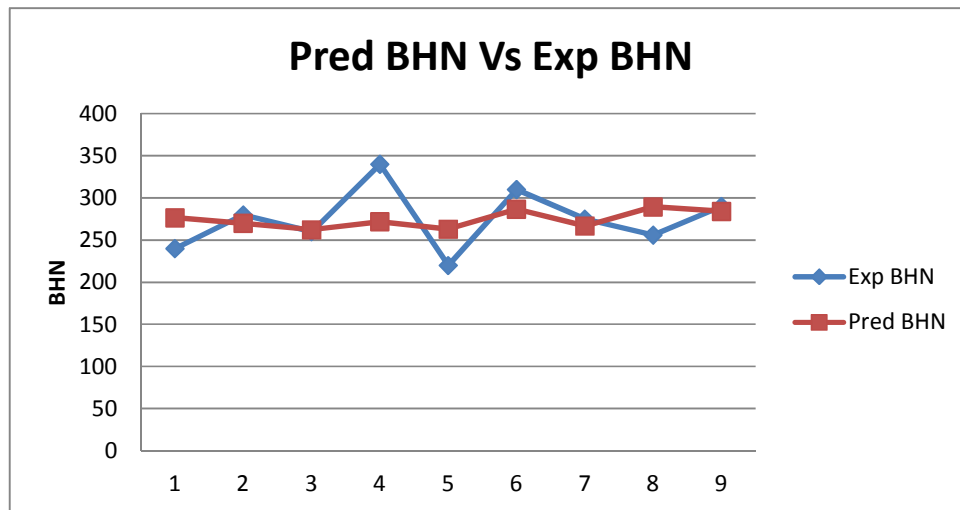
Table 5 shows the regression model coefficients obtained by substituting process parameters in Tables 3 and 4 into equations (4) and (5).

**Table 5. Regression model coefficients**

Regression coefficients	UTS (MPa)	BHN
$b_0$	606.96	260
$b_1$	0.17	0.21
$b_2$	-6.70	1.22
$b_3$	0.55	-2.23



**Fig. 1. Predicted UTS vs experimental UTS**



**Fig. 2. Predicted BHN vs experimental BHN**

The developed predictive models shown in Table 4 are expressed in equations(6) and (7).

$$UTS = 606.96 + 0.17x_1 - 6.7x_2 + 0.55x_3 \quad (6)$$

$$BHN = 260 + 0.21x_1 + 1.22x_2 - 2.23x_3 \quad (7)$$

### 3.2 Discussion

Tables 3, 4 and 5 show the result obtained for the Brinell hardness number (BHN) and ultimate tensile strength (UTS) from the experimental tests carried out on nine samples of the

specimens with varying input parameters. From Table 1, it can be seen that maximum values of ultimate tensile strength and Brinell hardness number were obtained when the process parameters; welding current, arc voltage and shielding gas flow rate were 180A, 15V and 20l/min respectively. It was also noted that increases in the welding current and arc voltage resulted in increased hardness and decrease in ultimate tensile strength. It was also observed that increases in shielding gas flow rate increased the ultimate tensile strength of mild steel.

Fig. 1 shows the correlation between the predicted Ultimate Tensile Strength (UTS) and the experimental Ultimate Tensile Strength (UTS). From the graph representation, it can be seen that there is some correlation between the predicted UTS and the experimental UTS, but with some obvious variation. Fig. 2 shows the correlation between the predicted BHN and the experimental BHN. From the graph, it is obvious that there is no correlation between the predicted Brinell Hardness Number (BHN) and the experimental Brinell Hardness Number (BHN). Therefore, the predictive model is considered not potent enough to effectively predict the Brinell Hardness Number of the material under consideration in this study. The experimental and predicted results show that arc voltage and gas flow rate affect the ultimate tensile strength and the Brinell hardness number of mild steel. It was also observed that the ultimate tensile strength decreases with increases in arc voltage and gas flow rate. But these two parameters tend to have a positive effect on the Brinell hardness number.

## 4. CONCLUSION AND RECOMMENDATION

### 4.1 Conclusion

The optimization of mild steel welding process parameters using multivariate linear regression (MLR) has been studied. The study includes the determination of the suitable set of conditions for the welding process parameters that would give the optimum weld of mild steel (low carbon steel) using gas metal arc welding (GMAW) technique and obtain a relationship between the three welding process parameters and the ultimate tensile strength and Brinell hardness number. For this reason, an experimental study was carried out using nine samples of the specimen of mild steel. Modelling and analysis of the ultimate tensile strength and the Brinell hardness

number in gas metal arc welding by using multivariate (multiple) linear regression analysis were also done. The experimental and predicted results show that arc voltage and gas flow rate affect the ultimate tensile strength and the Brinell hardness number of mild steel. The maximum ultimate tensile strength and Brinell hardness number were obtained at 180A, 15V and 20l/min. It was also observed that the ultimate tensile strength decreases with increases in arc voltage and gas flow rate. But these two parameters tend to have a positive effect on the Brinell hardness number.

### 4.2 Recommendation

From the study, the following recommendations are made:

That other method of optimization such as Taguchi method, Artificial Neural Networks etc should be employed and the results compared with this study.

The microstructure analysis should be done on the weldment to ascertain the quality of the welded joints and welding process.

### COMPETING INTERESTS

Authors have declared that no competing interests exist.

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