Development of a predictive model for determining mechanical properties of AA 6061 using regression analysis

Joseph Achebo*

Department of Production Engineering, University of Benin, Benin City, Nigeria

(Received 25 November 2013; accepted 1 March 2015)

Aluminum alloys (AA) such as AA 6061 are difficult to weld, and their application to high-strength demands tends to be limited because of their inherently low-strength threshold levels when compared to other alloys. To effectively use this alloy to its full potential, its tensile strength, is investigated. In actual manufacturing settings, it has proven beneficial to attempt a prediction of the tensile properties of potential weld joints. To achieve this, a model was developed using the multiple linear regression analysis to predict these tensile properties such as the ultimate tensile strength, the yield strength (YS), and percentage elongation (% Elong). It was found from the scattered diagrams that the measured and predicted values were almost a perfect fit with a coefficient of determination of between 0.99 and 1.0. The analysis of variance further validated the adequacy of the model. The analysis showed that the claims observed in the study match with those of other investigators. The predictive model obtained is expected to help the welding community to pre-determine the tensile properties of AA 6061 weldment using selected values for each of the process parameters applied in this study.

Keywords: aluminum alloy 6061; mechanical properties; process parameters; regression analysis

1. Introduction

Materials can either be regarded as being ductile or brittle depending on their ability to undergo plastic deformation under the application of load without fracturing. Ductile materials are often used for engineering projects because they usually exhibit homogeneous load distribution. Brittleness is regarded as the opposite of ductility. In a brittle material, at critical conditions, fractures may likely occur suddenly when loads are applied because the YS equals the ultimate tensile strength (UTS). Therefore, because it is expected that most structural materials are bound to be subjected to repeat loading stretching over a long period, and at the same time, are expected to absorb impact energies without fracturing, the elastic property of these materials is of great importance in engineering applications, and ductility is therefore a highly prized quality.

Ductility could be measured by determining the % Elong and reduction in area of the structural material. Percent elongation as considered in this study shows the extent to which a material can endure the application of stress before a fracture can occur. The ability of an engineering material to withstand stresses cannot be overemphasized, in terms of equipment maintainability, coupled with the fact that replacement and

*Email: josephachebo@yahoo.co.uk

© 2015 The Author(s). Published by Taylor & Francis.
This is an Open Access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.
breakdown maintenance due to material failure could be very costly. Such unwarranted failures invariably lead to the resultant increase in idle time or downtime. Thus, in today’s engineering landscape, structural materials are designed to carry even heavier loads, so that their service lives could exceed expectations with optimum efficiency. For instance, in bridge construction, structural materials are designed to serve for a very long period, as it would be quite uneconomical to sustain continued major routine overhauling processes.

Since ductility is a major factor to consider in selecting materials for structural engineering purposes, it has become imperative to develop a model to predict the tensile properties that define ductility. In this study, the ductile material considered is the AA 6061 aluminum alloy. Kumar, Kolhe, Morey, and Datta (2011) wrote that aluminum alloy 6061 (Al-Mg-Si) is widely used for the fabrication of food processing equipment, chemical containers, passenger cars, road tankers, and railway transport systems due to its high specific strength, excellent weldability, and resistance to corrosion. These aluminum alloy 6061 plates were welded with the gas metal arc welding (GMAW) equipment used to make weld deposits. Singla, Singh, and Deepak (2010) defined the GMAW as a process in which the heat source produces an arc between the consumable electrode and the workpiece.

Prediction of mechanical properties to optimize material production performance has been attempted by many investigators, such as Chiteka (2014). They aimed at using artificial neural networks in predicting UTS of a weldment, given rotational speed as well as the welding speed in a friction stir welding environment. Kim, Son, and Jeung (2001) applied novel algorithms to develop mathematical models for optimizing bead width for multi-pass welding using neural network as well as multiple regression methods. Xue et al. (2005) used the fuzzy regression method for predicting and controlling bead width in a robotic arc welding process. Mostafa and Khajavi (2006) developed a model for predicting the value of weld penetration using regression analysis. Karthikeyan and Mahadevan (2014) wrote on the modeling of the friction stir welded Al 6351 plates reinforced with SiC particles in the butt-joint region. Taguchi’s experimental design was used to design the experiment matrix and a mathematical model was developed to predict the mechanical properties of the welded Al 6351 plates. The predicted results were compared with the actual experimental results Khorram, Ghoreishi, Yazdi, and Moradi (2011) employed the response surface methodology to model and predict weld bead geometry parameters. Palanivel, Mathews, and Murugan (2011) used mathematical model to predict the mechanical properties of AA 6351 aluminum alloy. Cavaliere, Campanile, Panella, and Squillace (2006) studied the effect of welding parameters on mechanical and microstructural properties of AA 6056 joints produced by friction stir welding. Sreeraj, Kannan, and Maji (2013) used a five-level five-factor full factorial design matrix based on central composite rotatable design technique for the mathematical development of the model used for predicting clad bead geometry of austenitic stainless steel deposited by GMAW. They also used a simulated annealing algorithm tool available in MATLAB 7 software which was efficiently employed for predicting this same clad bead geometry. Heidarzadeh, Mahmoudi, Khodaverdizadeh, and Nazari (2012) worked on tensile behavior of friction stir welded AA 6061-T4 aluminum alloy joints. Elangovan, Balasubramanian, and Babu (2009) predicted the tensile strength of friction stir welded AA 6061 aluminum alloy joints using mathematical model. Sen, Mukherjee, and Pal (2014) developed a mathematical model using a multiple linear regression analysis in MINITAB 13.1 to predict the weld bead geometry.
and the authors also checked for the adequacy of the model by conducting analysis of variance (ANOVA). It was found from their study that the predicted optimum bead geometry correlates very well with the confirmation test result.

In this study, a model was developed to predict tensile properties and to optimize the extent of ductile content in an aluminum alloy 6061 using the multiple linear regression analysis. Dhas and Satheesh (2012) acknowledged the claim made by other investigators that weld parameter optimization through experimental methods and mathematical models has grown substantially over time to achieve a common goal of improving higher weld efficiency. The model which was developed in this study, successfully predicted the tensile properties of AA 6061. The results obtained were almost perfect match with the corresponding experimental results obtained from the weldments produced using GMAW.

2. Materials and methods

2.1. Materials

Five tensile specimens each were prepared for 16 different clusters or combinations of process parameters, giving a total of 80 weld joints. These joints were prepared according to ASTM E8M-04 procedures (see Figure 1) using a CNC Lathe machine as shown in Figure 2. Tensile tests were carried out in a 100 kN computer-controlled Universal Testing Machine (see Figure 3) as used by Prasad, Rao, and Rao (2011). The specimens were loaded at a rate of 1.5 kN/min as per ASTM specifications, so that these tensile specimens could undergo the deformation process. From the stress strain curve, UTS, YS, and % Elong of the weld joints were evaluated and the average of the five test results is presented in Table 3.

2.2. Methods

The following steps were conducted:

1. The 16 sets of welding process parameters (see Table 3) were applied, using a GMAW operation, to make weld deposits at five joints each on 60 mm × 140 mm × 10 mm AA 6061 aluminum plates (see Figure 4).

2. Following the above GMAW welding operations, each of the 80 weld deposits was sawn off to form individual weldment.

3. Each weldment was machined using the CNC Lathe machine resulting in individual tensile specimens according to ASTM E8M-04 procedures.

Figure 1. Tensile specimen.
(4) These machined tensile specimens were loaded into a 100 kN computer-controlled Universal Testing Machine.
(5) Each of the 80 loaded tensile specimens was measured for their UTS, YS, and % Elong.
(6) The results of these tensile tests were displayed in a digital screen.
(7) The average of the five tests conducted within each set for the 16 clusters of process parameters made was recorded.
A statistical model was developed to predict the tensile properties of AA 6061 aluminum weldments.

The effect of each of the 16 process parameters on the tensile properties of the aluminum weldments was examined.

3. Results and discussions

3.1. Results

Table 1 shows the design matrix containing both the process parameters (i.e. A, B, C, and D) and their interactions.

Table 2 shows the process parameters and their levels that were used for this study.

In Table 1, only the main parameters were considered, which comprises A, B, C, and D because linear multiple regression analysis would be used here to predict the tensile properties of aluminum plates treated in this study. The process parameters and their levels in Table 2 were substituted into the main parameters of the matrix design and used for welding the aluminum plates at their joints. Each weldment was tested for its UTS, YS, and % Elong and the measured values are recorded in Table 3.

Table 1. Design matrix.

| A | B | C | D | –AB | –BC | –CD | ABD | –AC | –BD | ABC | BCD | –ABCD | ACD | –AD |
|---|---|---|---|-----|-----|-----|------|-----|-----|-----|-----|------|-----|-----|
| 0 | 1 | 2 | 3 | 4  | 5   | 6   | 7    | 8   | 9    | 10  | 11  | 12   | 13  | 14  |
| + | + | – | – | +  | –   | +   | –    | +   | –    | +   | +   | +    | +   | +   |
| + | + | + | – | –  | +   | –   | –    | +   | –    | +   | +   | +    | +   | +   |
| + | + | + | + | +  | +   | –   | +    | –   | +    | –   | +   | +    | +   | +   |
| + | + | + | + | –  | +   | –   | –    | +   | –    | +   | +   | +    | +   | +   |
| + | + | + | + | –  | +   | –   | –    | +   | –    | +   | +   | +    | +   | +   |
| + | + | + | + | +  | +   | +   | +    | +   | +    | +   | +   | +    | +   | +   |
| + | + | + | + | –  | +   | –   | –    | +   | –    | +   | +   | +    | +   | +   |
| + | + | + | + | –  | +   | –   | –    | +   | –    | +   | +   | +    | +   | +   |
| + | + | + | + | +  | +   | +   | +    | +   | +    | +   | +   | +    | +   | +   |
| + | + | + | + | –  | +   | –   | –    | +   | –    | +   | +   | +    | +   | +   |
| + | + | + | + | +  | +   | +   | +    | +   | +    | +   | +   | +    | +   | +   |
| + | + | + | + | –  | +   | –   | –    | +   | –    | +   | +   | +    | +   | +   |
| + | + | + | + | +  | +   | +   | +    | +   | +    | +   | +   | +    | +   | +   |
| + | + | + | + | –  | +   | –   | –    | +   | –    | +   | +   | +    | +   | +   |
| + | + | + | + | +  | +   | +   | +    | +   | +    | +   | +   | +    | +   | +   |
| + | + | + | + | –  | +   | –   | –    | +   | –    | +   | +   | +    | +   | +   |
| + | + | + | + | +  | +   | +   | +    | +   | +    | +   | +   | +    | +   | +   |
| + | + | + | + | –  | +   | –   | –    | +   | –    | +   | +   | +    | +   | +   |
| + | + | + | + | +  | +   | +   | +    | +   | +    | +   | +   | +    | +   | +   |
3.1.1. Developing the regression analysis model

The regression analysis model as proposed by Achebo (2008) is expressed as follows:

$$
SSE = \sum_{i=1}^{n} (y_i - \bar{y})^2 = \sum_{i=1}^{n} (y_i - b_0 - b_1x_1 - b_2x_2 - b_3x_3 - b_4x_4) = 0 = \text{minimum} \quad (1)
$$

where SSE is the sum of square error

$$
\text{but } y_i = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 \quad (2)
$$

therefore,

$$
b_0 = y - b_1x_1 - b_2x_2 - b_3x_3 - b_4x_4 \quad (3)
$$

Differentiating (1) with respect to $b_0$

$$
\frac{\partial SSE}{\partial b_0} = -2\sum_{i=1}^{n} (y - b_0 - b_1x_1 - b_2x_2 - b_3x_3 - b_4x_4) = 0 \quad (4)
$$

Table 2. The process parameters and their levels.

| Process parameters | Unit | Notations | Low | High |
|--------------------|------|-----------|-----|------|
| Current | A | $A(x_1)$ | 320 | 390 |
| Voltage | V | $B(x_2)$ | 18 | 20 |
| Electrode diameter | mm | $C(x_3)$ | 1.6 | 3.2 |
| Welding speed | mm/s | $D(x_4)$ | 80 | 120 |

Table 3. Process parameters with the corresponding measured and predicted (calculated) tensile properties.

| $x_1$ | $x_2$ | $x_3$ | $x_4$ | Measured UTS (MPa) | Predicted UTS (MPa) | Measured YS (MPa) | Predicted YS (MPa) | Measured Elong (%) | Predicted Elong (%) |
|-------|-------|-------|-------|---------------------|---------------------|-------------------|-------------------|---------------------|---------------------|
| 390   | 18    | 1.6   | 80    | 298                 | 318.96              | 265               | 301.23            | 4.74                | 5.10                |
| 390   | 20    | 1.6   | 80    | 342                 | 311.61              | 316               | 288.38            | 5.8                 | 5.27                |
| 390   | 20    | 3.2   | 80    | 260                 | 270.77              | 238               | 246.56            | 3.7                 | 4.75                |
| 390   | 20    | 3.2   | 120   | 160                 | 261.14              | 143               | 238.77            | 5.2                 | 4.83                |
| 320   | 20    | 3.2   | 120   | 216                 | 181.24              | 198               | 153.51            | 4.7                 | 4.12                |
| 320   | 18    | 3.2   | 120   | 155                 | 268.49              | 136               | 251.61            | 4.9                 | 4.66                |
| 320   | 20    | 1.6   | 120   | 248                 | 222.07              | 226               | 195.35            | 5.2                 | 4.64                |
| 320   | 18    | 3.2   | 80    | 320                 | 278.12              | 308               | 259.39            | 3.8                 | 4.66                |
| 320   | 20    | 1.6   | 120   | 175                 | 301.98              | 168               | 280.60            | 3.2                 | 5.35                |
| 320   | 20    | 3.2   | 80    | 158                 | 190.87              | 132               | 161.30            | 4.6                 | 4.03                |
| 320   | 18    | 3.2   | 120   | 324                 | 188.58              | 297               | 166.37            | 3.6                 | 3.95                |
| 390   | 18    | 1.6   | 120   | 150                 | 309.33              | 279               | 293.44            | 4.7                 | 5.18                |
| 320   | 20    | 1.6   | 80    | 269                 | 231.71              | 240               | 203.13            | 4.8                 | 4.55                |
| 320   | 18    | 3.2   | 80    | 210                 | 198.21              | 188               | 174.14            | 4.3                 | 3.87                |
| 320   | 18    | 1.6   | 120   | 336                 | 229.42              | 314               | 208.19            | 5.8                 | 4.47                |
| 320   | 18    | 1.6   | 80    | 220                 | 239.05              | 202               | 215.97            | 5.1                 | 4.39                |
From (4), it is deducted that
\[
\sum_{i=1}^{n} y - b_0 - b_1 \sum_{i=1}^{n} x_1 - b_2 \sum_{i=1}^{n} x_2 - b_3 \sum_{i=1}^{n} x_3 - b_4 \sum_{i=1}^{n} x_4 = 0 \tag{5}
\]
Making \(b_0\) the subject of the equation
\[
b_0 = \sum_{i=1}^{n} y - b_1 \sum_{i=1}^{n} x_1 - b_2 \sum_{i=1}^{n} x_2 - b_3 \sum_{i=1}^{n} x_3 - b_4 \sum_{i=1}^{n} x_4 \tag{6}
\]
Differentiating (6) with respect to \(b_1\)
\[
\frac{\partial \text{SSE}}{\partial b_1} = -2x_1 \sum_{i=1}^{n} (y - b_0 - b_1 x_1 - b_2 x_2 - b_3 x_3 - b_4 x_4) = 0 \tag{7}
\]
Rearranging (7), we have:
\[
\sum_{i=1}^{n} (yx_1 - b_0 x_1 - b_1 x_1^2 - b_2 x_1 x_2 - b_3 x_1 x_3 - b_4 x_1 x_4) = 0 \tag{8}
\]
Rearranging (8), we have
\[
\sum_{i=1}^{n} (yx_1) - b_0 \sum_{i=1}^{n} x_1 - b_1 \sum_{i=1}^{n} x_1^2 - b_2 \sum_{i=1}^{n} x_1 x_2 - b_3 \sum_{i=1}^{n} x_1 x_3 - b_4 \sum_{i=1}^{n} x_1 x_4 = 0 \tag{9}
\]
Differentiating (1) with respect to \(b_2\)
\[
\frac{\partial \text{SSE}}{\partial b_2} = -2x_2 \sum_{i=1}^{n} (y - b_0 - b_1 x_1 - b_2 x_2 - b_3 x_3 - b_4 x_4) = 0 \tag{10}
\]
Rearranging (10), we have:
\[
\sum_{i=1}^{n} (yx_2) - b_0 \sum_{i=1}^{n} x_2 - b_1 \sum_{i=1}^{n} x_1 x_2 - b_2 \sum_{i=1}^{n} x_2^2 - b_3 \sum_{i=1}^{n} x_2 x_3 - b_4 \sum_{i=1}^{n} x_2 x_4 = 0 \tag{11}
\]
Differentiating (1) with respect to \(b_3\)
\[
\frac{\partial \text{SSE}}{\partial b_3} = -2x_3 \sum_{i=1}^{n} (y - b_0 - b_1 x_1 - b_2 x_2 - b_3 x_3 - b_4 x_4) = 0 \tag{12}
\]
Rearranging (12), we have:
\[
\sum_{i=1}^{n} (yx_3) - b_0 \sum_{i=1}^{n} x_3 - b_1 \sum_{i=1}^{n} x_1 x_3 - b_2 \sum_{i=1}^{n} x_2 x_3 - b_3 \sum_{i=1}^{n} x_3^2 - b_4 \sum_{i=1}^{n} x_3 x_4 = 0 \tag{13}
\]
Differentiating (1) with respect to \(b_4\)
\[
\frac{\partial \text{SSE}}{\partial b_4} = -2x_4 \sum_{i=1}^{n} (y - b_0 - b_1 x_1 - b_2 x_2 - b_3 x_3 - b_4 x_4) = 0 \tag{14}
\]
Rearranging (14), we have:
\[
\sum_{i=1}^{n} (yx_4) - b_0 \sum_{i=1}^{n} x_4 - b_1 \sum_{i=1}^{n} x_1 x_4 - b_2 \sum_{i=1}^{n} x_2 x_4 - b_3 \sum_{i=1}^{n} x_3 x_4 - b_4 \sum_{i=1}^{n} x_4^2 = 0 \tag{15}
\]
From (9), we have that
\[ b_1 = \frac{\sum_{i=1}^{n} (yx_1^i) - b_0 \sum_{i=1}^{n} x_1^i - b_2 \sum_{i=1}^{n} x_1^i x_2^i - b_3 \sum_{i=1}^{n} x_1^i x_3^i - b_4 \sum_{i=1}^{n} x_1^i x_4^i}{\sum_{i=1}^{n} x_1^2} \] (16)

From (11), we have that
\[ b_2 = \frac{\sum_{i=1}^{n} (yx_2^i) - b_0 \sum_{i=1}^{n} x_2^i - b_1 \sum_{i=1}^{n} x_1^i x_2^i - b_3 \sum_{i=1}^{n} x_2^i x_3^i - b_4 \sum_{i=1}^{n} x_2^i x_4^i}{\sum_{i=1}^{n} x_2^2} \] (17)

From (13), we have that
\[ b_3 = \frac{\sum_{i=1}^{n} (yx_3^i) - b_0 \sum_{i=1}^{n} x_3^i - b_1 \sum_{i=1}^{n} x_1^i x_3^i - b_2 \sum_{i=1}^{n} x_2^i x_3^i - b_4 \sum_{i=1}^{n} x_3^i x_4^i}{\sum_{i=1}^{n} x_3^2} \] (18)

From (15), we have that
\[ b_4 = \frac{\sum_{i=1}^{n} (yx_4^i) - b_0 \sum_{i=1}^{n} x_4^i - b_1 \sum_{i=1}^{n} x_1^i x_4^i - b_2 \sum_{i=1}^{n} x_2^i x_4^i - b_3 \sum_{i=1}^{n} x_3^i x_4^i}{\sum_{i=1}^{n} x_4^2} \] (19)

Process parameters values in Table 3 were substituted into Equations (6), (16)–(19) and the model coefficients in Table 4 were obtained.

The developed predictive models as contained in Table 4 are expressed below:

1. UTS, is
   \[ \text{UTS (MPa)} = -0.0099 + 1.1415x_1 - 3.6731x_2 - 25.5238x_3 - 0.2408x_4 \]

2. YS, is
   \[ \text{YS (MPa)} = -0.7846 + 1.2179x_1 - 6.4208x_2 - 26.1426x_3 - 0.1946x_4 \]

3. % Elongation, is
   \[ \% \text{Elong} = -0.0089 + 0.0101x_1 + 0.0844x_2 - 0.3251x_3 + 0.0021x_4 \]

The above predictive models were used to predict the various ductile properties in Table 3.

3.1.2. Confirmation tests

Confirmation tests were done to ascertain the adequacy of the developed model. Five weldments were tested for their tensile properties using the computerized tensile test machine. For each weldment, five tensile test results were obtained. The average of the five results was recorded for each of the tensile properties and this process was repeated for the five weldments. The developed model was used to predict the values of these tensile properties to confirm the adequacy of the model by comparing its values with those of the corresponding measured ones, as presented in Table 5.

Table 4. Regression model coefficients.

| Regression coefficients | UTS (MPa) | YS (MPa) | Elong (%) |
|------------------------|----------|----------|-----------|
| \( b_0 \)              | -0.0099  | -0.7846  | -0.0089   |
| \( b_1 \)              | 1.1415   | 1.2179   | 0.0101    |
| \( b_2 \)              | -3.6731  | -6.4208  | 0.0844    |
| \( b_3 \)              | -25.5238 | -26.1426 | -0.3251   |
| \( b_4 \)              | -0.2408  | -0.1946  | 0.0021    |
3.1.3. Effect of process parameters on tensile properties

The effects of the process parameters on the tensile properties of aluminum alloy plates were studied as shown in Figures 5–8.

Figure 5 depicts the observed effects of welding current on tensile properties of each specimen. It can be seen from the graph that the curves representing UTS, YS, and % Elong increase following graduated increments of the current applied. This indicates that a small increase in current can alter the tensile property of the aluminum alloy. The atoms that make up this aluminum alloy were still within their elastic limits until the current reached 350 A. At this current, the atoms become more agitated and the atomic collision increases. When this molten aluminum alloy cools under controlled conditions, the material experiences some strain hardening effects. This means that as it cools down, the atoms experience less agitation and dislocation. This resistance to dislocation formation makes the aluminum alloy more plastic, thereby establishing the strength properties of the tensile specimen.

As the current is increased from 360 to 380 A, the parameters reduced. This is because as more current is applied the molten aluminum drops in a process known as necking down. This process negatively affects UTS, YS, and % Elong properties of the aluminum alloy leading to a reduction in these properties. Achebo (2012) was of the opinion that welds at certain high temperatures tend to absorb moisture rapidly. Moisture lowers the cooling rate. At low cooling rate, more time is available for the molten aluminum alloy to mix with moisture. This action leads to the coarsening of the weld grains by making the grains angular in shape. This angular shape of the grains creates voids. The presence of voids in welds lowers the quality of such welds. Prasad et al. (2011) observed that the formation of coarser grains in the fusion zone is responsible for lower UTS of the welded joints.

As the current reaches 380 A, the strain hardening effect of the aluminum alloy becomes plastic. This is because at this current, the temperature also increases, further altering the atomic nature of the molten aluminum alloy, making it less susceptible to moisture interference while cooling. As a result of the reduction in the effect of moisture, the grain formation of the aluminum alloy weldment becomes less coarse or finer, thereby increasing its plastic nature. This plastic nature increases the ability of the alloy to absorb energy and this eventually increases the alloy’s UTS and YS. The increase in percentage elongation indicates that the material is still ductile and at the same time slightly malleable but has almost exceeded its proportionality limits. This observation compares well with the claim made by Prasad et al. (2011), who emphasized that rapid cooling due to the decrease in current leading to decrease in heat input could lead to the formation of finer grains which eventually increases the UTS.

Table 5. Measured and predicted results of mechanical properties.

|  x₁  | x₂  | x₃  | x₄  | Measured UTS (MPa) | Predicted UTS (MPa) | Measured YS (MPa) | Predicted YS (MPa) | Measured Elong (%) | Predicted Elong (%) |
|------|-----|-----|-----|-------------------|-------------------|------------------|------------------|-------------------|-------------------|
| 340  | 19  | 1.6 | 110 | 251               | 250.99            | 227              | 228.07           | 4.74              | 4.72              |
| 360  | 18  | 1.6 | 80  | 286               | 284.71            | 266              | 264.69           | 4.79              | 4.81              |
| 330  | 20  | 3.2 | 100 | 201               | 197.47            | 168              | 169.59           | 4.18              | 4.23              |
| 380  | 18  | 3.2 | 90  | 265               | 264.30            | 242              | 245.27           | 4.50              | 4.54              |
| 390  | 18  | 1.6 | 85  | 319               | 317.75            | 301              | 300.25           | 5.11              | 5.09              |
Figure 6 shows the relationship between tensile properties and the welding voltage. It is observed that at a constant welding voltage of 18 V, UTS, YS, and % Elong increased steeply. However, as the voltage increases from 18 V, the UTS, YS, and % Elong reduced drastically. This indicates that at 18 V, the aluminum weld was still at its solid–plastic transition state where the grains are assumed to have disintegrated repeatedly and eventually become finer and denser, but as the voltage increases, the weld transits from plastic to liquid. The hot liquid weld metal absorbs moisture and becomes coarser. This action reduces the quality of the weld which negatively affects the weld’s UTS, YS, and eventually its % Elong. Its reduction in percentage elongation indicates that the weldment is not as ductile. Bahman and Alialhosseini (2010) showed that as the arc voltage increases, hardness, UTS, and YS decrease. Yang, Chandel, and Bibby (1992) said that at high voltage, bead widths are large and large bead widths are associated with a poor-quality welding process, which invariably negatively affects the UTS, YS, and % Elong.

Figure 7 shows the relationship between tensile properties and the electrode diameter. It is observed that when 1.6-mm electrode diameter was used for the welding process, UTS, YS, and % Elong increased steeply and as the electrode diameter increases, the UTS, YS, and % Elong decrease. This indicates that the 1.6-mm electrode diameter gave a more localized welding process where spatter was eliminated. This theoretically shows that at this electrode diameter, the weld dilution and deposition rate would have been high with adequate and controlled weld penetration, which is assumed to have occurred due to the Marangoni flow process. However, as the diameter of the electrode exceeds 1.6 mm, the increase in the size of the electrode produces beads with large widths forming spatter, which oxidizes rapidly and forms coarse grains, eventually reducing the UTS, YS and % Elong of the aluminum weld. Too much of an oxidization process of the spatter causes the weld to contract.
Figure 6. Effect of voltage on UTS, YS, and % elongation.

Figure 7. Effect of electrode diameter on UTS, YS, and % elongation.

Figure 8 shows the relationship between tensile properties and the welding speed. It is observed that as the welding speed increases from 80 to 85 mm/s, the UTS, YS, and % Elong also increase. However, when the welding speed increased above 85 mm/s, the UTS, YS, and % Elong decreased. These tensile properties also increased when the
welding speed increased from 100 to 110 mm/s. The tensile behavior of the weld indicates that the increase in welding speed, reduces the time spent in welding, this leads to a smaller heat affected zone (HAZ) and a small bead width, and as a result, less heat is utilized for the welding process. This process is used to achieve increased UTS and YS of weldment. These observations confirm the claim made by Bahman and Alialhosseini (2010) that increasing the welding speed, increase hardness, YS, and UTS of weld metal and the situation occurs when a low heat input is achieved. Conversely, prolonged heating at incremental welding speeds produces welds with a large HAZ, this eventually reduces the tensile properties of the weld.

3.1.4. Validation of the developed model
The adequacy of the developed model tested by making a scattered diagram of the results in Table 5, to show the correlation between the measured and the predicted (calculated) UTS of the aluminum alloy studied, as shown in Figure 9.

The adequacy of the developed model tested by making a scattered diagram of the results in Table 5, to show the correlation between the measured and the predicted (calculated) YS of the aluminum alloy studied, as shown in Figure 10.

The adequacy of the developed model tested by making a scattered diagram of the results in Table 5, to show the correlation between the measured and the predicted (calculated) % Elong of the aluminum alloy studied, as shown in Figure 11.

3.1.5. Analysis of variance
Table 6 presents the ANOVA at 95% confidence level. In addition, the coefficient of determination was also determined for each of the measured and predicted (calculated) tensile property.

Figure 8. Effect of welding speed on UTS, YS, and % elongation.
3.2. Discussion

A predictive model is developed for determining the tensile properties of AA 6061. These tensile properties include UTS, YS, and % Elong. Process parameters as shown in Table 2, and explicitly distributed in Table 3, were used to conduct 16 welding experiments. Each welding experiment was used to produce five weld samples, the five weld samples were subjected to tensile tests and the average of the responses from the tensile test results obtained such as UTS, YS, and % Elong were recorded for the 16 welding experiments conducted.

These test results were used to develop a model for predicting the tensile properties that define ductility. These mechanical properties are UTS, YS, and % Elong. In this study, the measured UTS is in the range of 155–342 MPa, the predicted value UTS is within the range of 180.24–317.96 MPa. The measured YS is in the range of 132–316 MPa, the predicted YS is found to be in the range of 153.51–301.23 MPa whereas, the measured % Elong is in the range of 3.2–5.8%, the predicted % Elong is within the range of 3.87–5.35%. Lakshminarayanan and Balasubramanian (2009) in their study measured AA 7039 weld joint whose tensile strength was obtained to be within the range of 170–317 MPa using friction stir welding process. Venkateswarlu, Mandal, Mahapatra, and Harsh (2013) determined UTS and % Elong of AA 7039 alloy, the measured UTS is in the range of 125.67–267.05 MPa, the predicted UTS is 116.49–261.97 MPa. Also these researchers determined the measured % Elong of AA 7039 to

![Figure 9](image-url) Scattered diagram of the UTS.

![Figure 10](image-url) Scattered diagram of the yield strength.
be between 1.84 and 5.9%, whereas the predicted value of the % Elong is within the range of 1.72–6.32%. Kumar et al. (2011) applied the modified Taguchi method to optimize process parameters. In their research work, they determined UTS and % Elong of AA 6061, the experimental results obtained for UTS are within the range of 256.40–386.07 MPa, with a corresponding predicted UTS of 389.31 MPa. The measured % Elong results are within the range of 7.84–12.94%, whereas the predicted % Elong is 12.98%. Hsieh and Chen (2008) determined the tensile strength of AA 6061 T-6 alloy to be within the range of 225.4–247.9 MPa and the % Elong of 5.5–6.8%. Palanivel et al. (2011) used regression model to predict UTS, YS, and % Elong of AA 6351 aluminum alloy. They obtained for measured UTS, a range of 193–219 MPa, YS within the range of 166–190 MPa and % Elong of between 3.61 and 5.24%, whereas the predicted values for UTS are within the range of 199.70–216.54 MPa, predicted YS is within the range of 172.92–187.29 MPa, and predicted % Elong is within the range of 3.52–5.08%. The mechanical properties obtained in this study falls within the range of values obtained in other reported literature. From the correlation analysis, it is shown that the measured and predicted (calculated) values are nearly a perfect fit with coefficient of determination of between 0.99 and 1.0. The effects of the process parameters used for the welding process on the tensile properties of the AA 6061 were examined. It was proposed that a prolonged increase in current could have a negative effect on the tensile properties of the weld. The increased current also increases in the HAZ profile of the weld. It was found that the increase in voltage could lead to a tremendous reduction in the UTS, YS, and % Elong. The 1.6-mm electrode diameter appears to produce welds with better mechanical properties than the 3.2 mm ones. In Figure 4, it is shown that the increase in welding speed also increases tensile properties.

Table 6. ANOVA and coefficient of determination.

| Mechanical properties | SSE     | $F_{\text{test}}$ | $F_{\text{table}}$ | $r^2$ |
|-----------------------|---------|-------------------|---------------------|-------|
| UTS (MPa)             | Predicted | 0.000049          | $1.1767 \times 10^{10}$ | 1     |
|                       | Measured | 16.198869         | 35594.88209         | 0.99  |
| YS (MPa)              | Predicted | 0.000016          | $3.039 \times 10^{10}$ | 230   |
|                       | Measured | 16.664116         | 29183.65826         | 0.99  |
| Elong (%)             | Predicted | 0.000046          | 3940066.116         | 0.99  |
|                       | Measured | 0.005146          | 35220.17903         | 0.99  |

Figure 11. Scattered diagram of the % elongation.
An ANOVA was done to determine the significance of the level of tensile properties to the quality of the weld at 95% confidence. In each case, the Fisher test was conducted for both measured and predicted (calculated) weld properties. The predicted (calculated) and measured Fishers test values were in each case greater than the table value. This shows that the predictive model has great potential when compared with the measured values.

4. Conclusion
A predictive model using linear regression analysis was painstakingly developed along with a detailed methodology, showing a step-by-step approach. The developed model has proved to be very potent and quite beneficial. It has been used to predict the mechanical properties of AA 6061 with a focus on its UTS, YS, and Fisher Test. These tensile properties are known to be major determinant factors regarding the ductility level of the said alloy considered in this study. The proposed predictive models for determining these tensile properties are expected to ensure that engineers are equipped with a reliable means of pre-determining these tensile properties to ensure that weld operations are properly planned and concomitantly efficient. The correlation analysis and ANOVA conducted confirmed the adequacy of the model. The confirmation tests showed that the variances between the measured and calculated tensile properties were not significant. Also the measured and predicted values of these tensile properties were compared with those obtained in related literature. It was found that values obtained in this study compare well with those from other investigators. This also further confirms the potency of the derived predictive models.

Disclosure statement
No potential conflict of interest was reported by the author.

References
Achebo J. I. (2008). Development of aluminium welding flux from local raw materials (PhD Thesis). Department of Production Engineering, University of Benin, Nigeria.
Achebo J. I. (2012, July 4–6). Optimization of fluence energy in relation to weld properties based on vogel approximation method. World Congress on Engineering: International Conference on Mechanical Engineering, 3. London.
Bahman, A. R., & Alialhosseini, E. (2010). Change in hardness, yield strength and ultimate tensile strength of welded joints produced in st 37 grade steel. Indian Journal of Science and Technology, 3, 1162–1164.
Cavaliere, P., Campanile, G., Panella, G., & Squillace, E. (2006). Effect of welding parameters on mechanical and microstructural properties of AA6056 joints produced by friction stir welding. Journal of Materials Processing Technology, 180, 263–270. doi:10.1016/j.jmatprotec.2006.06.015
Chiteka, K. (2014). Artificial neural networks in tensile strength and input parameter prediction in friction stir welding. International Journal of Mechanical Engineering and Robotics Research, 3, 145–150.
Dhas, R. E. J., & Satheesh, M. (2012). Multiple objective optimization of submerged arc welding process parameters using grey based fuzzy logic. Advances in Production Engineering & Management, 7, 5–16.
Elangovan, K., Balasubramanian, V., & Babu, S. (2009). Predicting tensile strength of friction stir welded AA6061 aluminium alloy joints by a mathematical model. Materials & Design, 30, 188–193. doi:10.1016/j.matdes.2008.04.037
Heidarzadeh, A., Mahmoudi, A., Khodaverdizadeh, H., & Nazari, E. (2012). Tensile behavior of friction stir welded AA 6061-T4 aluminum alloy joints. *Materials & Design, 37*, 166–173. doi:10.1016/j.matdes.2011.12.022

Hsieh, H., & Chen, J. L. (2008). Influence of welding parameters on mechanical properties of friction stir welded 6061-T6 launch box. *Materials Transactions, 49*, 2179–2184.

Karthikeyan, P., & Mahadevan P. K. (2014, August 17). A study of modeling on the mechanical properties of friction stir welded Al 6351 plates added with six particles in the butt-joint region. Proceedings of Eleventh IRF International Conference, 62–65, Chennai. ISBN: 978-93-84209-47-6

Khorram, A., Ghoreishi, M., Yazdi, M. R. S., & Moradi, M. (2011). Optimization of bead geometry in CO2 laser welding of Ti 6Al 4 V using response surface methodology. *Engineering, 3*, 708–712. doi:10.4236/eng.2011.37084

Kim, I., Son, S., & Jeung, Y. (2001). Control and optimization of bead width for multipass welding in robotic arc welding process. *Australian Welding Journal, 46*, 43–47.

Kumar, P., Kolhe, K. P., Morey, S. J., & Datta, C. K. (2011). Process parameters optimization of an aluminum alloy with pulsed gas tungsten arc welding (GTAW) using gas mixtures. *Materials Sciences and Applications, 2*, 251–257. doi:10.4236/msa.2011.24032

Lakshminarayanan, A. K., & Balasubramanian, V. (2009). Comparison of RSM with ANN in predicting tensile strength of friction stir welded AA7039 aluminium alloy joints. *Transactions of the Nonferrous Metals Society of China, 19*, 9–18. doi:10.1016/S1003-6326(08)60221-6

Mostafa, N. B., & Khajavi, M. N. (2006). Optimization of welding parameters for weld penetration in FCAW. *Journal of Achievements in Materials and Manufacturing Engineering, 16*, 132–138.

Palanivel, R., Mathews, K. P., & Murugan, N. (2011). Development of mathematical model to predict the mechanical properties of friction stir welded AA6351 aluminium alloy. *Journal of Engineering Science and Technology Review, 4*, 25–31.

Prasad K. S., Rao C. S., & Rao D. N. (2011). Optimizing pulsed current micro plasma arc welding parameters to maximize ultimate tensile strength of inconel 625 nickel alloy using response surface method. *International Journal of Engineering Science and Technology, 3*, 226–436. doi: http://dx.doi.org/10.4314/ijest.v3i6.18

Sen M., Mukherjee, M., & Pal, T. K. (2014, December 12–14). Prediction of weld bead geometry for double pulse gas metal arc welding process by regression analysis. 5th International & 26th All India Manufacturing Technology, Design and Research Conference, 814-6, IIT Guwahati, Guwahati.

Singla, M., Singh, D., & Deepak, D. (2010). Parametric optimization of gas metal arc welding processes by using factorial design approach. *Journal of Minerals & Materials Characterization & Engineering, 9*, 353–363.

Sreeraj, P., Kannan, T., & Maji, S. (2013). Prediction and control of weld bead geometry in gas metal arc welding process using simulated annealing algorithm. *International Journal of Computational Engineering Research, 3*, 213–222.

Venkateswarlu, D., Mandal, N. R., Mahapatra, M. M., & Harsh, S. P. (2013). Tool design effects for FSW of AA7039. *Welding Journal, 92*, 41s–47s.

Xue, Y., Kim, I. S., Son, J. S., Park, C. E., Kim, H. H., Sung, B. S., ... Kang, B. Y. (2005). Fuzzy regression method for prediction and control the bead width in the robotic arc-welding process. *Journal of Materials Processing Technology, 164–165*, 1134–1139. doi:10.1016/j.jmatprotec.2005.02.174

Yang, L. J., Chandel, R. S., & Bibby, M. J. (1992). The effects of process variables on the bead width of submerged-arc weld deposits. *Journal of Materials Processing Technology, 29*, 133–144. doi:10.1016/0924-0136(92)90430-Z