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DEVELOPMENT OF A SUITABLE MATHEMATICAL MODEL FOR PREDICTION OF PERCENT ELONGATION OF STAINLESS STEEL WELD JOINTS

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ABSTRACT

A mathematical model for predicting the percent elongation of GTAW welded austenitict stainless steel joint was developed. Deviational and statistical analyses as well as scatter diagrams were used to test and confirm its validity and accuracy. The maximum deviation between the model-predicted and actual experimental values was less than 5%, in absolute terms, and the R^2 values were above 80%. Also the scatter diagram showed that the predicted and experimental values were close to the 45^o line.

Keywords: Percent elongation, welding current, mathematical model, analysis

INTRODUCTION

Austenitic stainless steel is the most common and abundantly used stainless steel in the process industry (Nansaarng and chaisang, 2007) including high and low temperature applications. This steel known as the 300 series make up over 70% of total stainless steel production (Wikipedia, 2011) and its using ratio is increasing constantly because of its superior corrosion resistance and mechanical properties (Lin and Chen, 1997 and Kou, 2003). Ideally this steel exhibits a single phase, the face centred cubic (FCC), structure which is maintained over a wide range of temperatures. However, because of the physical properties of this class of stainless steel, the welding behavior is different from that of other stainless steels. It has higher thermal coefficient of expansion and electrical resistance but lower thermal conductivity than for most other steels (Cary, 1998). Therefore high speed welding or welding at reduced heat gradient is recommended to achieve the same level of penetration, reduced carbide precipitation and minimize distortion. This steel can be welded by various welding processes such as shielded metal arc welding (SMAW), submerged arc welding (SAW), gas metal arc welding (GMAW), gas tungsten arc welding (GTAW), resistance welding, (RW), friction welding (FW) and plasma arc welding (PAW). However the GTAW process is preferred for welding stainless because of its reliability, especially for thin gauges.

The quality of any weld joint can be determined on the basis of its mechanical properties since they demonstrate the ability of the joint to resist failure and determine its behavior under the action of external forces (Khurmi and Sedha (2004). These properties are expected to be at least equal to those of the parent metals being joined. One of the critical mechanical properties is the percent elongation.

Percent elongation is a mechanical property of a metal that indicates the degree to which a metal may be bent, stretched or compressed before it ruptures and so quantifies the ability of a metal to stretch up to its breaking point. It is a measure of ductility, which provides the confidence that a metal can be formed without cracking or fracturing. It is also a measure of toughness of a metal. Therefore percent elongation, especially at fracture, is of engineering importance not only as a measure of ductility but also as an index of the quality of the metal. It is one of the essential mechanical properties for weld joints (frepd.com, 2010) and can be affected by welding parameters as reported by Bang et al (2008) and Tewari, Gupta and Prakash (2010). It is usually determined by carrying out tensile tests and expressed as

$$\%\text{Elongation} = \frac{\text{increase in length}}{\text{original length}} \text{x}100$$

Some scholars, Zou et al (2004), Quan et al (2008), Kahraman et al (2010) and Nnuka et al, while working on different materials and processes established that increase in welding current results in decrease in percent elongation. Studies have shown that welding current is the most influential parameter since the amount of welding heat developed depends on it, for any giving size of filler metal and electrode, thus it controls the depth of fusion, the electrode feed rate and depth of penetration (Jah and Jah, 2014 and Okonji, Nnuka and Odo, 2015). It is therefore crucial for welders to apply the correct amount of current during welding to ensure good quality and minimize the problem of distortion on the welded material.

This work is aimed at developing a suitable mathematical model for predicting the percent elongation for AISI 304L austenitic stainless steel grade weld joint.

DEVELOPMENT OF MATHEMATICAL MODEL

The data for the formulation of this model was obtained from the work of Nnuka et al (2015) and shown in Table 1.

Table 1: Percent Elongation

Current (A)	Filler Metal Type	%Elongation
91	308L	27.388
	309L	23.048
	316L	25.224
92	308L	27.684
	309L	26 532
	316L	25.439
93	308L	28.729
	309L	28.261
	316L	25.654
94	308L	29.084
	309L	28.697
	316L	25.798
95	308L	30.436
	309L	29.133
	316L	26.085
control	-	30.436

Source: Nnuka, Okonji and Odo (2015)

Model Formulation

The development of this model for the prediction of percent elongation (PEl) as a function of welding current (I) a procedure based on regression was employed and expressed as

$Y = f(I)$, where Y = PEl

Applying a first order response yields the following relationship

$$Y = a + bI$$

The coefficients a *and* b represent the free term and the linear term, respectfully, of the regression. The values of coefficients a and b were calculated by regression analysis using the following equations:

$$Y = f(I), \tag{1}$$

$$Y = a + bI \tag{2}$$

Taking the actual response to be σ and the predicted Y, the standard deviation of prediction, ϵ will be given by

$$\epsilon^2 = \frac{\Sigma(Y-\sigma)^2}{n} \tag{3}$$

$$n\epsilon^2 = K = \Sigma(Y-\sigma)^2 = \Sigma(Y-a-bI)^2 \tag{4}$$

Differentiating with respect to a, we have

$$\frac{\delta K}{\delta a} = -2\Sigma(Y - a - bI) = 0 \text{ or } \Sigma Y - na - b\Sigma I = 0 \tag{5}$$

$$\therefore \Sigma Y = na + b\Sigma I \tag{6}$$

$$\therefore a = \frac{\Sigma Y}{n} - \frac{b\Sigma I}{n} = \tilde{Y} - b\tilde{I} \tag{7}$$

Differentiating with respect to b, we have

$$\frac{\delta K}{\delta b} = 2I\Sigma(Y - a - bI) = 0 \text{ or } \Sigma Y - a\Sigma I - b\Sigma I^2 = 0$$

$$\therefore \Sigma YI = a\Sigma I + b\Sigma I^2 \tag{8}$$

Multiplying (6) by ΣI gives

$$\Sigma Y\Sigma I = na\Sigma I + b(\Sigma I)^2 \tag{9}$$

Multiplying (8) by n gives

$$n\Sigma YI = na\Sigma I + nb\Sigma I^2 \tag{10}$$

(8) − (9) yields

$$\Sigma Y\Sigma I - n\Sigma YI = b[(\Sigma I)^2 - n\Sigma I^2$$

$$\therefore b = \frac{\Sigma Y\Sigma I - n\Sigma YI}{(\Sigma I)^2 - n\Sigma I^2} \tag{11}$$

n = number of welding currents

The values of the coefficients were calculated using Texas Instrument, TI-84 Plus using the data from Table 1, resulting in:

$a = -106.181$

$b = -1.433$

Inserting the values of the coefficients into equation (1) yields the following:

$$Y = 1.433I\ 106.181 \qquad (12)$$

Boundary and Initial Conditions

The welding process, including the cooling, was carried out under the atmospheric conditions and the values of welding current and percent elongation used are as shown in Table 1. The materials used were AISI 304L grade of stainless steel, ER309L filler metal(2mm diameter), 2% thoriated non-consumable electrode (2mm diameter) and high purity (99.99%) argon as shielding. The weld metal was cooled with natural air, no pressure and no force (tension or compression) were applied to the heat affected zone (HAZ) during or after the welding process. Also the sides and shapes of the coupons were symmetries.

Model Validation

The developed model was validated using deviation and statistical analyses as well as scatter diagrams.

Deviational analysis

This involves the direct analysis and comparison of the model-predicted (MP) values and those of the actual experimental (AE) values for equality or near equality. The deviation or error percent (Dv) was determined using the following equation:

$$Dv = \frac{AE-MP}{MP} X\ 100$$

The results are contained in Table 2.

Statistical Analysis

This was carried out to determine the correlations between process variables by calculating the coefficients of determination (R^2). Results are in Figures 1-3.

Scatter Diagrams

The formulated model was further validated using scatter diagrams, Figures 4.

RESULTS and DICUSSIONS

Table 2. Comparison of model-predicted and experimental values

Welding current (A)	%Elongation		%Error
	Actual Estimate	Model-Predicted	
91	23.048	24.222	-4.847
92	26.523	25.655	3.383
93	28.261	27.088	4.33
94	28.697	28.521	0.617
95	29.133	29.954	-2.741

From Table 2 above it can be observed that the deviations between the model-predicted values and those of the actual experimental values are very low and quite within acceptable range. Thus, indicating the validity of the model.

Statistical Analysis and Graphical Presentation

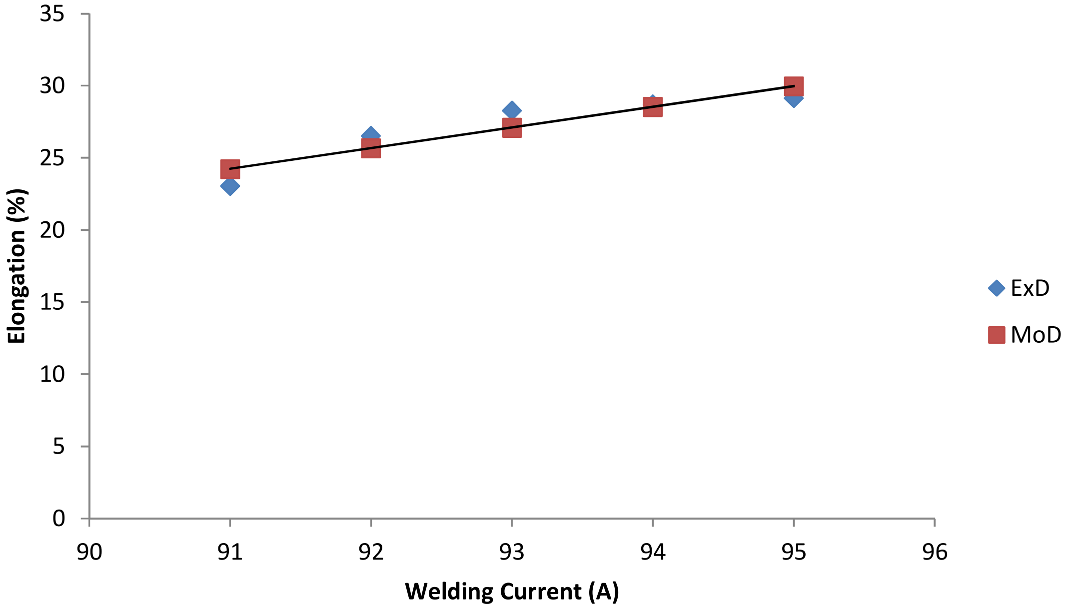

Figure 1. Interaction between %elongation and welding current

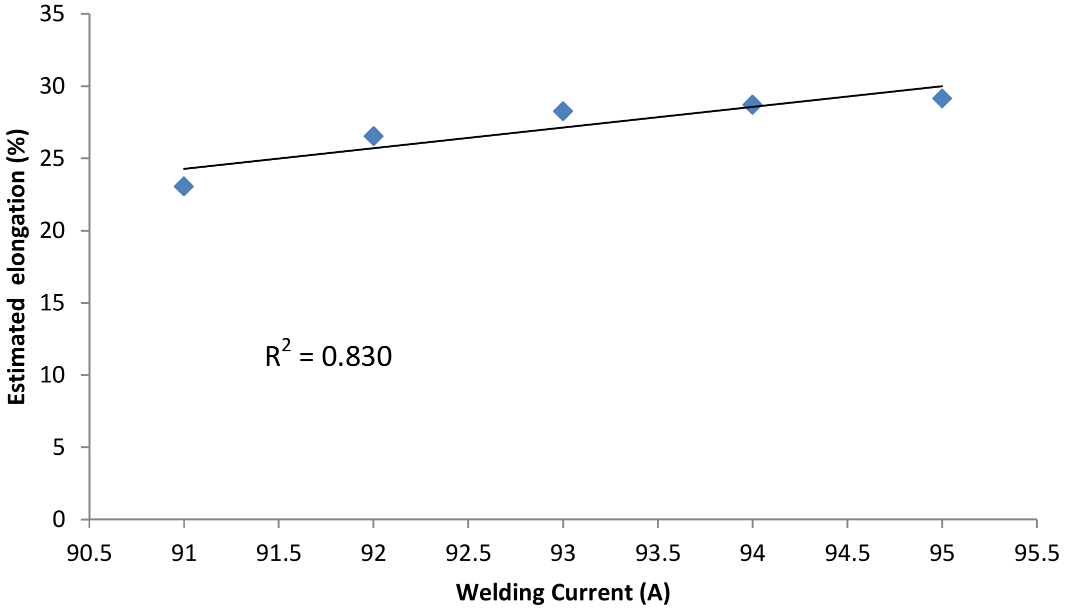

Figure 2. Interaction between estimated %elongation and welding current

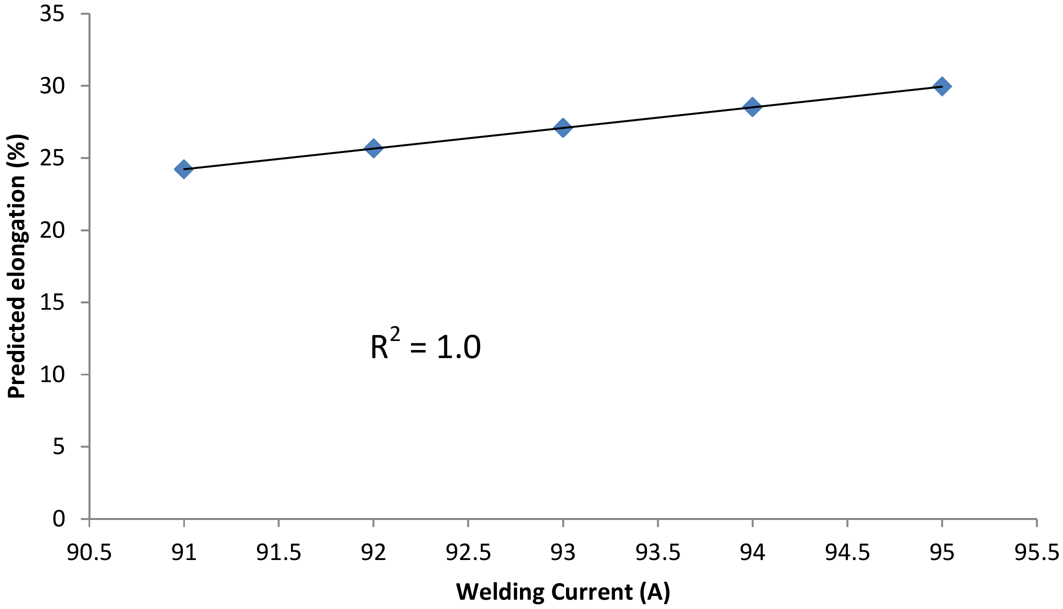

Figure 3. Interaction between predicted %elongation and welding current

The determined R^2 values of the developed model (Figures 1 and 2) were generally above 80% indicating that the regression model was quite adequate, hence the validity. It can also be observed that the R^2 (and indeed the R) value for the model-predicted percent elongation is better (1.00) is better than that for the actual experiment. This suggests that the model predicts more accurately and reliably than the actual experiment. This further strengthens the model validity.

Scatter Diagrams

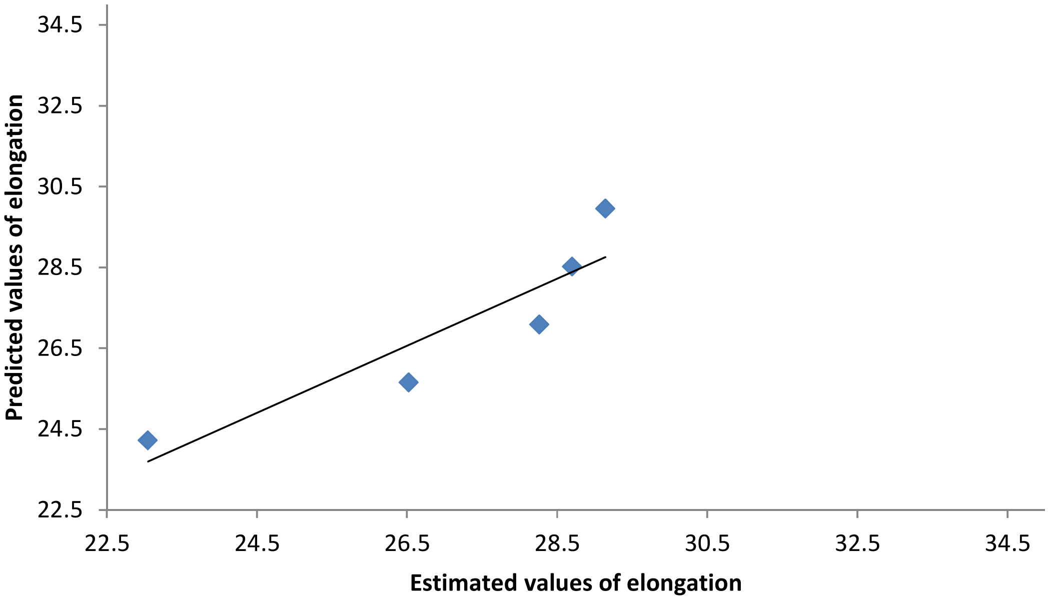

Figure 4. Scatter diagram of the %elongation

From Figure 4 above it can be observed that the experimentally estimated and the model-predicted values are scattered close to the 45^{o} line, demonstrating an almost perfect fit of the developed model. This further establishes the adequacy of the derived models.

CONCLUSION

The results of the validity and accuracy tests of the model have demonstrated that the developed model is accurate to a very reasonable degree. The model-predict values were in proximate agreement with the values obtained from actual experiment. Therefore the developed model can be successfully used to predict the percent elongation of GTAW welded austenitic stainless steel joints.

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