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DEVELOPMENT OF SUITABLE MATHEMATICAL MODEL FOR THE PREDICTION OF THE EFFECT OF WELDING CURRENT ON THE HARDNESS OF AUSTENITIC STAINLESS WELD JOINT

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ABSTRACT:
A mathematical model for predicting the effect of welding current and 309L filler metal on the hardness of GTAW welded austenitic stainless steel joint was developed. The developed model was tested using deviational and statistical analyses as well as scatter diagrams to confirm its validity and accuracy. The maximum deviation between the model-predicted and actual experimental values was.02%, in absolute terms, and the coefficient of determination $(R)^2$ values were above 95%. Also the scatter diagram showed that the predicted and experimental values were close to the 45^o line.
Keywords: Welding current, Mathematical model, Hardness

Introduction

Hardness is the property of a material that enables it to resist plastic deformation, penetration, indentation, and scratching and it is one of the most basic mechanical properties of engineering materials (Khurmi and Sedha (2004). Hardness test is practical and provides a quick assessment and the result can be used as a good indicator for material selection and also employed for quality assurance in parts which require high wear resistance. Therefore, hardness is important from an engineering standpoint because resistance to wear by either friction or erosion by steam, oil, and water generally increases with hardness. Thus, the value of hardness serves an important need in industry.

Effect of Welding Current on Hardness

Some researchers have demonstrated the effect of welding current on the hardness of metals. They reported that increase in welding current increased the welding heat which resulted in production of coarse grains and decrease in hardness. Fowles and Blake (2008), Calik (2009), Yilmaz and Uzun,. (2002), Kumar and shahi (2011), and Okonji, Utu and Akaluzia (2016) reported that increase in current resulted in decrease in hardness of austenitic stainless steel weld joint. In their study on the effect of TIG welding on microstructure and mechanical properties of butt-joined-unalloyed titanium, Uygur and Dogan (2005) showed that increase in welding current resulted in coarse grains and decrease in hardness. This agreed with the observation of Zou et al (2004) in their study on the microstructure and properties of the welded joint of magnesium alloy AZ31B.

Because of the importance of hardness in selection of engineering materials, there is therefore the need to be able to predict the hardness value of a welded joint prior to use. This work is aimed at developing a mathematical model for the prediction of the effect of welding current the hardness of austenitic stainless steel weld joint. In this work austenitic stainless steel sheet metal (3mm), 309L filler metal (2mm diameter) and welding current 91-95 amperes at 1 ampere interval were employed.

DEVELOPMENT OF MATHEMATICAL MODEL

The data for formulation of this model was taken from Okonji (2014) and shown in Tables 1 and 2 below.

Table1. Chemical Composition of Base Metal and Filler Rod

Material	**C**	**Si**	**Mn**	**P**	**S**	**Cr**	**Ni**	**Mo**	**Cu**	**V**	**Al**	**SN**	**N**	**Ti**
Base metal 304L	0.02	0.42	0.05	0.031	0.001	18.80	7.18	0.008	0.029	0.079	0.013	0.004	0.042	0.005
Filler Metal Type														
ER309L	0.016	0.41	1.84	0.019	0.002	23.28	13.68	0.03	0.04					

Table 2: Hardness

Current (A)	Hardness (HBR)
91	76.90
92	76.70

93	76.50
94	76.30
95	76.00
Control	76.00

Model Formulation

In the development of this model for the prediction of hardness (H), as a function of welding current (I), a procedure based on regression was employed and expressed as

Y $= f(I)$, where Y = Response 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:

$$Y = f(I) \quad (1)$$

$$Y = a + bI \quad (2)$$

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

$$\theta^2 = \frac{\Sigma(Y-\Phi)^2}{n} \quad (3)$$

$$n\theta^2 = K = \Sigma(Y-\Phi)^2 = \Sigma(Y-a-bI)^2 \quad (4)$$

Differentiating with respect to a, we have

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

Where n = number of welding currents per filler metal

$\therefore \Sigma Y = na + b\Sigma I$ (6)

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

Differentiating with respect to b, we have

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

$\therefore \Sigma YI = a\Sigma I + b\Sigma I^2$ (8)

Multiplying (6) by ΣI gives

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

Multiplying (8) by n gives

$n\Sigma YI = na\Sigma I + nb\Sigma I^2$ (10)

(9) − (10) gives

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

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

The values of the coefficients were calculated using Texas Instrument, TI-84 plus and are as follows: a = 95.08; b = -0.20

Introducing the values of the coefficients, the developed final mathematical equation is given as

Y = 95.08 + 0.20I (12)

The calculated values are shown in Table 3.

Table 3. Calculated (Predicted) hardness values

Current (A)	Predicted Hardness (HBR)
91	76.88
92	76.68
93	76.48

94	76.28
95	76.08

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, (2mm diameter) filler metal, 2% thoriated non-consumable electrode (2mm diameter) and high purity (99.99%) argon as shielding gas. The weld metal was cooled with natural air; neither pressure nor force (tension or compression) was applied to the heat affected zone (HAZ) during or after the welding process. Also the sides and shapes of the specimen were symmetries.

Model Validation

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

Deviational analysis

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

$$\mathrm{Dv} = \frac{\mathrm{AEV} - \mathrm{MPV}}{\mathrm{MPV}} \mathrm{X}\ 100$$

The result is contained in Table 4.

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, Figure 4.

Results and Discussions

Deviational Analysis

Table 4. Comparison of model- predicted and experimental hardness values

Filler Metal	Current (A)	Hardness (HBR)		%Error
		Experimental	Predicted	
309L	91	76.90	76.88	0.026
	92	76.70	76.68	0.026
	93	76.50	76.48	0.026
	94	76.30	76.28	-0.026
	95	76.00	76.08	0.11

From Table 4 above it can be seen that the deviations between actual experimental values and the predicted are very low and within acceptable range. This demonstrates the validity of the model.

Statistical Analysis and Graphical Presentation

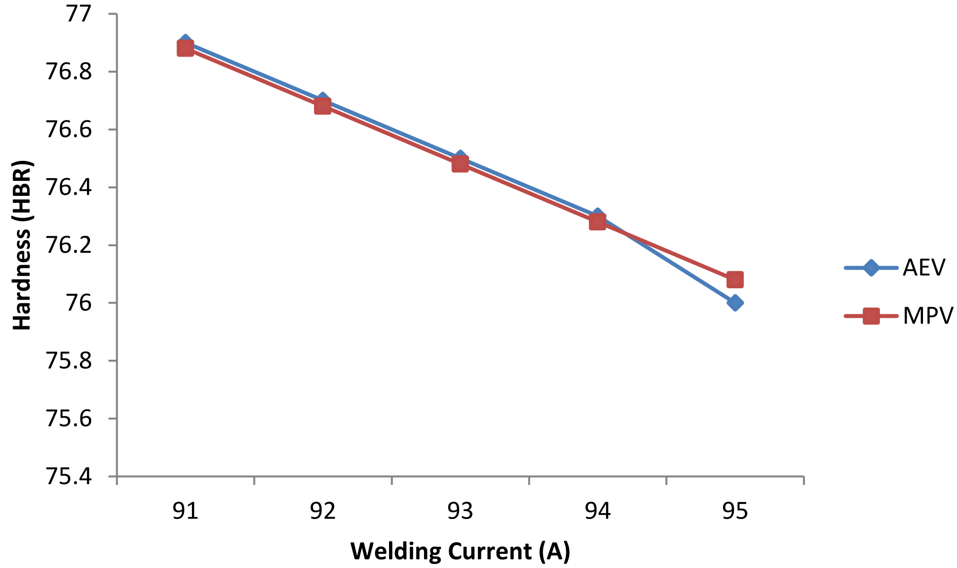

Figure 1. Interaction between hardness and welding current

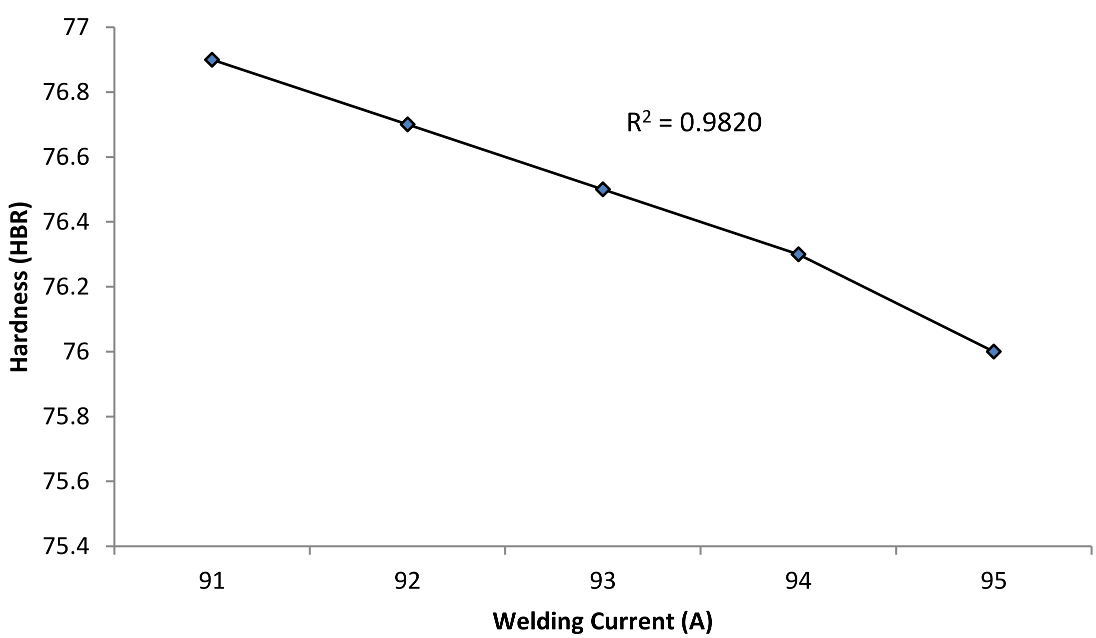

Figure 2. Interaction between actual experimental hardness values and welding current

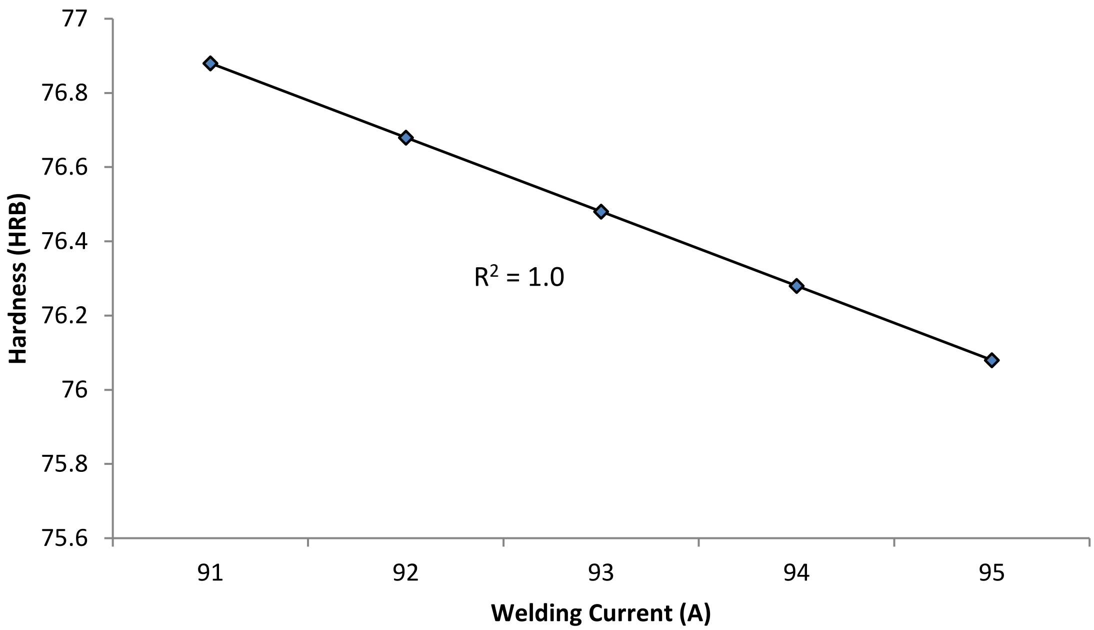

Figure 3. Interaction between model-predicted hardness values and welding current

From Figure 3 the value of the coefficient of determination (R^2) for the developed model is generally above 95% indicating that the regression model was quite adequate, hence the validity. It can also be observed that the model-predicted R^2 (and indeed the R) values (1.00) are better than the values 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 diagram

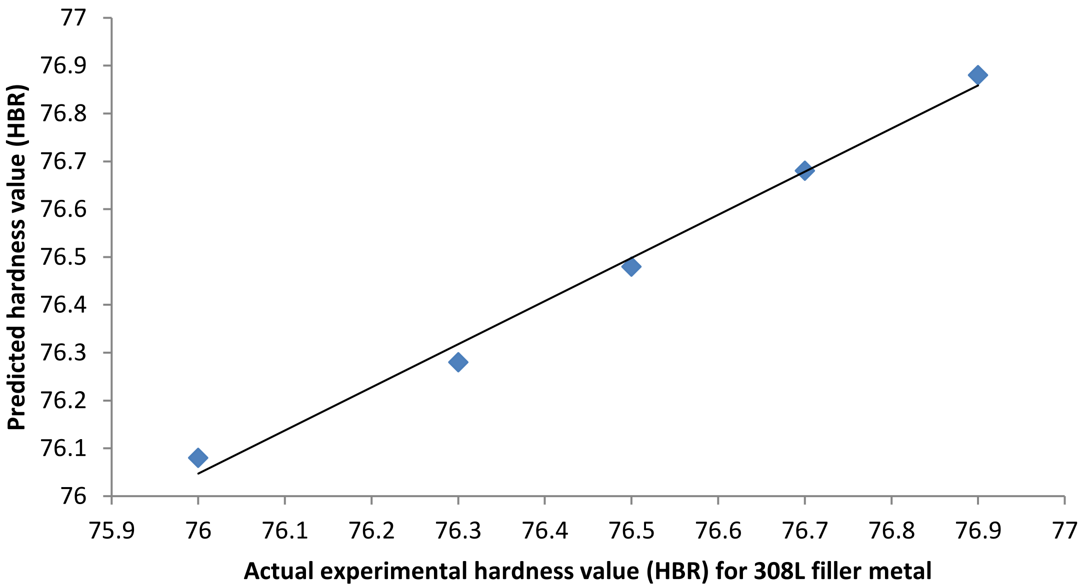

Figure 4. Scatter diagram

From Figure 4 above it can be observed that the experimentally estimated and the model-predicted hardness 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 since the model-predicted values were in proximate agreement with the values obtained from actual experiment. Therefore the developed model can be successfully used to predict the hardness of GTAW welded austenitic stainless steel joints using 309L filler metal..

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