International Journal of Manufacturing, Material and Mechanical Engineering Research
Vol.2, No.1, pp.1-6, December 2015
Published by European Centre for Research Training and Development UK (www.eajournals.org)

DEVELOPMENT OF A SUITABLE MATHEMATICAL MODEL FOR PREDICTING ULTIMATE TENSILE STRENGTH (UTS) OF STAINLESS STEEL WELD JOINTS

[1]Okonji P. O., [2]Akaluzia R. O. and [1]Utu O. G.

[1]Department of Welding and Fabrication Engineering,
Delta State Polytechnic, Ogwashi-Uku
[2]Department of Metallurgical and Materials Engineering,
Delta State Polytechnic, Ogwashi-Uku

ABSTRACT: *A mathematical model for predicting the tensile strength (UTS) of TIG welded austenitic stainless steel weld joint was developed. The validity and accuracy of the model was confirmed using deviational and statistical analyses as well as scatter diagram. The maximum deviation between the model-predicted UTS values and those obtained from actual experiment was less than 1.3% and the R^2 values were above 90%. Furthermore, the scatter diagram showed that the experimental values and the predicted values lie close to the 45^o line.*

KEYWORDS: Mathematical Model, Deviational Analysis, Statistical Analysis, Scatter Diagram.

INTRODUCTION

Stainless steels are a family of iron-based alloys having excellent resistance to corrosion and are generally classified by their microstructure (or crystalline structure) as ferritic, austenitic, martensitic or duplex (Cary, 1998 and Kou, 2003). The microstructure significantly affects the weld properties and choice of welding process to be used. The steels are subject to weld metal and heat affected zone cracking, formation of embrittling second phases and ductile to brittle fracture transition. These should be considered when selecting base metal, filler metal and welding procedures for fabricating components from these steels.

The most common and abundantly used stainless steels in the process industry are the austenitic class (Nansaarng and Chaisang, 2007) and make up over 70% of total stainless steel production (Wikipedia, 2011). They contain a maximum of 0.15% C, a minimum of 16% Cr and sufficient nickel and/or manganese to retain an austenitic structure at all temperatures, from the cryogenic region where they exhibit high toughness to high temperatures where they exhibit high oxidation resistance (Uhlig, 1985 and Kou, 2003). They also exhibit freedom from transformation to martensite (Llewellyn and Hudd, 1998). Because of their physical properties, the welding behaviour of this class of steels is different from that of other stainless steels. Their thermal coefficient of expansion and electrical resistance are higher but their thermal conductivity is lower than for most other steels (Carry, 1998). Therefore high speed welding is recommended to reduce heat input and achieve good penetration, reduce carbide precipitation and minimise distortion. The molten weld pool of austenitic stainless steel is commonly viscous or sluggish and this slows down the metal flow and wettability of welds, which may promote lack-of-fusion defects when poor welding procedures are employed.

Tungsten inert gas (TIG) welding is an arc welding process that generally uses a non-consumable tungsten electrode to produce the weld. The energy necessary for melting the metal is supplied by an electric arc struck and maintained between tungsten or a tungsten alloy electrode and the work piece, under an inert gas or slightly reducing atmosphere. Many delicate components in aircraft and nuclear reactors are TIG welded because of its reliability.

Quality of Weld Joints

In welding practice the integrity of weld joints is ascertained by the mechanical properties since they are associated with the ability of the joints to resist failure and their behaviour under the action of external forces (Khurmi and Sedha, 2004). One very essential mechanical property is the tensile strength (frepd,com, 2010) which defines the ability of the weld joint to withstand or support an external force without rupture. It plays a decisive role in designing various structures and components as well as determines service performance of weld joints.

Tensile strength is generally affected by welding parameters such as welding current, welding voltage and welding speed, which have been described as the most important factors affecting the quality, productivity and cost of weld joints (Srivastava, Tiwari and Prakash, 2010).

Effect of Welding Current on Tensile Strength

Ghazvinloo and Honarbkhsh (2010) in their study of the effect of welding current on the tensile strength of weld metal in low carbon steel using fluxed core arc welding (FCAW) process demonstrated that increase in welding current lowered the tensile strength.

Therefore this work is aimed at developing a suitable mathematical model for predicting ultimate tensile strength (UTS) of low carbon austenitic stainless steel weld joints produced by using TIG welding process given the welding current and filler metal type.

Experimental work

Austenitic stainless steel sheets of type AISI 304L measuring 400 x 50 x 3mm were welded to produce square butt weld joints with edge preparation. The chemical composition of the AISI 304L stainless steel and the filler metal are shown in Table 1. The welding process was carried out with a manually operated air-cooled welding machine (Precision TIG 225) to produce a square butt weld joint. High purity argon gas was used for shielding and purging at the rates of 12 litres per minute and 7.5 litres per minute respectively. Using a post-flow timer the post-weld shielding gas flow was 10 minutes. The welding consisted of two runs, the root and cap, in the 1G position using 308 filler metal (2.0mm) and five welding currents ranging from 91–95 amperes at one ampere interval. During the welding operation the heat input was varied by varying the welding current (other parameters were held constant) according to the equation

$$H = 60EI/1000S$$

Where

H = heat input (KJ/mm)

E = arc voltage (volts)

I = welding current (ampere)

S = welding speed (mm/min)

After the welding process the welded joints were air-cooled, examined for defects and prepared for tensile test.

Table 1. Composition of Base Metal and Filler Metals

Material	C	Si	Mn	P	S	Cr	Ni	Mo	Cu	V
	Al	SN	N	Ti						
Base metal	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	.005						
Filler Metal Type	ER308L	0.013	0.43	1.86	0.023	0.002	19.85	9.95	0.05	0.07

Tensile Test

The welded coupons were cut to size using power hacksaw and subjected to longitudinal tensile test using a tensile testing machine, model 316Q with 300KN maximum load. The test was carried out following the ASTM E8 Standard procedure for all-weld tensile test. The coupons were fitted into the jaws of the testing machine and subjected to tensile stress until they fractured. The result is shown in Table 2.

Experimental results obtained from research work (Okonji, Nnuka and Odo, 2015), as shown in Table 2, were used for the model formulation.

Table 2. ultimate Tensile Test

Current (A)	91	92	93	94	95
UTS (MPa)	995.528	979.314	963.825	955.429	945.387

DEVELOPMENT OF MATHEMATICAL MODELS

Model Formulation

A procedure based on regression was used to develop a mathematical model for predicting the ultimate tensile strength (UTS) as a function of welding current (I) and can be expressed as

$\Phi = f(I)$ Where Φ =UTS (1)

The relationship selected is a first order response expressed as

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

Where the coefficient a, is the free term of the regression and the coefficient b is a linear term. The values of the coefficients were calculated by regression analysis with the help of the following equations

Calculation of regression coefficients a and b

$$\Phi = f(I) \quad (3)$$

$$\Phi = a + bI \quad (4)$$

Let actual response be Φ and predicted be Y

Standard error of prediction, θ is given by

$$\theta^2 = \frac{\Sigma(Y-\Phi)^2}{n} \quad (5)$$

$$n\theta^2 = K = \Sigma(Y-\Phi)^2 = \Sigma(Y-a-bI)^2 \quad (6)$$

Differentiating with respect to a, we have

or

Multiplying (5) by ΣI gives

Multiplying (6) by n gives

yields

$$\frac{\Sigma Y \Sigma I - n\Sigma YI}{(\Sigma I)^2 - n\Sigma I^2} \quad (7)$$

Where n = number of welding currents per filler metal.

The values of the coefficients for different responses were calculated with Texas Instrument, TI-84 plus using the data shown in Table 2. This resulted in:

a = 1989

b = 11

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

$$Y = 1989 - 11I \quad (8)$$

Boundary and Initial Conditions

The welding process was carried out under atmospheric condition. After welding, weldments were also maintained under atmospheric condition. The values of welding current and ultimate tensile strength (UTS) considered are as shown in Table 2. The grade of low carbon austenitic stainless steel used was 304L, grade of filler metal used was ER308L (2mm diameter), Electrode type: non-consumable 2% thoriated tungsten, (2mm), shielding gas, argon (99.99% purity level). Air was used as coolant for the welded spots. No pressure was applied to the HAZ during or after the welding process. No force due to compression or tension was applied in any way to the HAZ during or after the welding process. The sides and shapes of the samples were symmetries.

Model Validation

The data for the formulation of the model was taken from Table 2 and the formulated model validated using Deviational Analysis, Statistical Analysis and Scatter Diagrams.

Deviational analysis

This involves direct analysis and comparison of model-predicted values and those obtained from experiment for equality or near equality. Deviation (or error percent) of model-predicted values from the experimental values is given by

Where

ExD = Experimental results

MoD = Model-predicted values

Statistical analysis

This involved evaluating the correlations between process variables by calculating the coefficient of determination (R^2)

Scatter Diagrams

The validity of the model was further tested by drawing scattered diagrams.

RESULTS

The results of deviational analysis, statistical analysis and scatter diagram are shown in Table 3, Figures 1-2 and Figure 3 respectively.

Table3 Comparison of model predicted and experimentally estimated values

Welding Current	91	92	93	94	95
Predicted UTS	988.00	977.00	966.00	955.00	944.00
Estimated UTS	995.528	965.314	961.825	955.429	945.387
%Error	0.762	1.196	0.432	0.045	0.147

DISCUSSION

From Table 3 the analysis and comparison between the predicted and experimental values reveal that the deviations between them were very low (less than 1.3%) and quite within acceptable range. This demonstrates the validity of the model.

From Figures 1 and 2 the calculated coefficients of determination (R^2) values are quite close and generally above 90%. These values indicate that the regression model is quite adequate. Furthermore the correlation coefficient (R) calculated from R^2 above shows a better correlation (1.00) with model-predicted UTS than that obtained by experiment. This suggests that the model predicts more accurate and reliable values than the actual experiment. This is an indication of the model validity.

From the scatter diagram presented in Figure3 it can be observed that the experimented values and the predicted values of the responses are scattered close to the 45^{o} line, indicating an almost perfect fit of the developed models (Kim, Son, Yang and Yaragada, 2003 and Palanivel, Mathews and Murugan, 2011). This further establishes the adequacy of the derived models.

CONCLUSION

The results of tests of the validity and accuracy of the model showed that the developed model is reasonably accurate. The model-predicted UTS values were in proximate agreement with the values obtained from the actual experiment. Therefore the developed model can be used to predict the UTS values of TIG welded austenitic stainless steel weld joints.

REFERENCES

Carry, H. B. (1998). "Historical Development of Welding", Modern Welding Technology, 4th Edition. Pp 6-7, 492-500. Prentice Hall Inc. New Jersey.

Ghazvinloo, H. R., Honarbakhsh-Raouf, A. (2010). Effect of gas shielded flux cored arc welding parameters on weld width and tensile properties of weld metal in low carbon steel. Journal of Applied Science, 10(8): 658-663.

Khurmi, R. S. and Sedha, R. S. (2004). "Mechanical Properties of Metals". Material Science, pp 133-194. S. Chand & Company Ltd., New Delhi – 110 055.

Kim, I. S., Son, K. J., Yang, Y. S. and Yaragada, P. K. D. V. (2003). Sensivity analysis for process parameters in GMA welding process using factorial design method. International Journal of Machine Tools and Manufacture, vol. 43, 763-776.

Kou, S. (2003). Corrosion-Resistant Materials: Stainless Steels". Welding Metallurgy, 2nd edition, pp 431-454. John Wiley & Sons, Inc., Hoboken, New Jersey.

Llewellyn, D. T. And Hudd, R. C. (1998). "Welding of stainless steels". Steels: Metallurgy and Applications, 3rd edition, pp334-336. Butterworth Heinemann, oxford OX2 8DP

Nansaarng, S. And Chaisang, C. (2007). Influence of parameters for gas metal arc welding on macrostructures and mechanical properties of austenitic stainless steels. 6th WSEAS international Conference on System Science and Simulation in Engineering. Venice, Italy, November, 21-23.

Okonji, P. O. (2014). Effect of welding current and filler metal types on structure and Mechanical properties of stainless steel weld joints. M.Sc. Thesis, Nnamdi Azikiwe University, Awka, Anambra State.

Palanivel, R., Mathews, P. K. and Murugan, N. (2011). Development of mathematical model to predict the mechanical properties of friction stir welded AA6351 aluminum alloy. Journal of Engineering Science and Technology Review, Vol4(1), 25-31.

Srivastastava, B. K., Tewari, S. P. And Prakash, J. (2010). A review of effect of arc welding parameters on mechanical behaviour of ferrous metals/alloys. International Journal of Engineering Science and Technology, vol. 2(5), 1425-1432.

Uhlig. H. H. (1985). Corrosion and Corrosion Control. Wiley, New York, NY.

Wikipedia (2010). "Stainless steel". Retrieved from http://en.wikipedia.org/wiki/stainless_steel on 1/7/2011.