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Empirical Model for Predicting Tensile Behaviour of Butt-welded Mild Steel Joints Treated to Vibration-during-welding

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ABSTRACT

The objective of this study was to establish empirical relationships between process parameters (inputs) and process responses (outputs) which correctly predict tensile behaviour of butt welded joints produced by employing vibration during welding. Using EXEL environment, the relationships were obtained in terms of input parameter F (= vibration frequency) and output parameters which included yield strength (σ_y), tensile strength (σ_{ts}), and elongation (ε). Different regression functions were fitted to available experimental data for each response parameter. The respective correlation factors (R^2) for each function were computed and compared and the function with highest R^2 value selected as best for predicting the behaviour. Assuming plane state conditions, the relationships between independent and dependent variables were modeled in general terms as $f(F) = \propto F^2 \pm \varphi F + \cup$. Model adequacy checking included test for significance of the regression model and test of significance on the model coefficients. The associated P-value for this model is lower than 0.05; i.e. α = 0.05 or 95% confidence level which illustrates that the model is statistically significant.

Keywords: Empirical, model, vibration-during- welding, tensile behaviour.

1. INTRODUCTION

Welding processes induce a state of residual stress into materials and jobs. This poses a series of problems in terms of dimensional stability, corrosion cracking, reduced fatigue life and structural integrity. Thermal cycle produced near weld line generates residual stresses and inhomogeneous plastic deformation in weldments. Vibration induced welding is a method developed, investigated and shown to have tremendous beneficial effects on the quality of welded joints (Pucko and Gliha, 2006; Dogan, 2005; Dahunsi and Audu, 2006; Qinghua et al., 2007, Tewari, 2009; Ashwe, 2010; Ashwe and Tuleun, 2010, and Verma et al., 2011). Comprehensive experimental data on tensile properties of vibrated mild steel welded joints are now available. Unfortunately, a common problem that has faced the manufacturer is the control of process input parameter (vibration frequency) to obtain a good welded joint with the required fracture properties and vice versa. Traditionally, it has been necessary to determine this weld input parameter for every new welded product to obtain a welded joint with the desired specifications (Dahunsi and Audu, 2006; Tewari, 2009; and Ashwe, 2010). To do this requires time-consuming trial and error development efforts, with the welding input parameter chosen by the skill of the engineer or machine operator followed by examination of the welds to determine whether they meet the required specifications. Finally, the optimum vibration frequency may be determined which produces a joint that closely meets the requirements. It is the belief of this author that a pre-specified vibration frequency that will result in ideal weld output characteristics can be used if it can only be determined. Similar procedures have been used in the past to obtain ideal welding parameters combination which yielded accurate prediction of welding input parameters. Marksji and Tusek (2001) modeled the current and voltage in tungsten inert gas (TIG) welding as quadratic polynomials of sheet thickness. The results were presented for algorithmic optimization in the case of T-joints with fillet weld. Kim et al (2003) compared experimental data obtained for weld bead geometry with those obtained from empirical formulae in gas metal arc welding. Kolahan and Heidari (2009) used experimental data to relate important process parameters to process output characteristics, through developing empirical regression models for various target parameters. Computational results proved the effectiveness of the proposed model and optimization procedure. In the present study, available experimental data were generated and used to relate an important process parameter to process output characteristics of vibrated welds through developing empirical models for tensile characteristics - tensile strength, yield strength and elongation of the welded joint.

2. MATERIALS

Commercially available mild steel bars were obtained from a metal scrap market at High Level Makurdi in Benue State-Nigeria. The chemical compositions of the steel material and welding electrodes were confirmed using Energy-Dispersive X-Ray Spectrometry (EDX) conducted at Federal Institute for Industrial Research Oshodi (FIIRO) and are presented in Tables 1 & 2 respectively.

3. EXPERIMENTAL PROCEDURE

The steel bars were cut into several plates measuring 90x50x14mm using a power saw. Two plates were paired together to give six pairs. Welding grooves were marked out on each paired piece and then milled to give a full butt type edge with a bevel angle of 30^{O}. The steel pieces with smooth and uniform bevels were cleaned of oxides, rust, grease and paints by sand grinding followed by degreasing using methanol. The cleaned pieces were swabbed in water and then dried in hot air. Further, the paired steel pieces with smooth and uniform bevels were tack-welded together with a root gap of 3 mm. The tack-welded pairs were marked as specimen A, B, C, D, E and F; to be welded at six different vibration conditions. Welding of the paired plates was done on a vibratory platform using a manual electric arc welding machine. Welding current of 100A and gauge 10 (SAW E6013) filler metal were selected. The vibrator was calibrated into five different frequencies using a vibration meter [*model*- VB-8201HA] along with vibration pick-up. The five frequencies

Ashwe et al.
Empirical Model for Predicting Tensile Behaviour of Butt-welded Mild Steel Joints Treated to Vibration-during-welding,
Indian journal of engineering, 2013, 4(9), 17-20,

Table 1
Chemical Composition of Steel Material

Element	C	Si	Mn	P	S	Cr	Mo	Ni
Percent (%)	0.15	0.26	0.18	0.005	0.001	0.058	0.016	0.318

Table 2
Chemical Composition of Welding Electrode

Element	C	Si	Mn	P	S	Cr	Mo	Ni
Percent (%)	0.11	0.18	0.37	0.02	0.02	0.04	0.47	0.40

Table 3
Optimization Results for the Proposed Model

Vibration Freq.(Hz)		Predicted Values		Measured Values		Error %	
	σ_y	σ_{ts}	ε	σ_y	σ_{ts}	ε	
0.00	321.2	411.10	47.24	321.04	405.95	48	0.08
1.59	328.25	414.04	45.35	333.91	421.85	43	0.38
7.96	345.8	425.50	39.88	337.38	425.03	43	0.44
14.32	346.24	436.46	37.91	339.74	427.26	38	0.31
20.69	329.57	446.95	39.29	346.59	457.79	37	1.24
27.06	295.77	456.96	44.09	288.09	453.00	46	0.31

were recorded as 1.59 Hz, 7.96 Hz, 14.32 Hz, 20.69 Hz and 27.06 Hz. Samples were vibrated or un-vibrated during welding. The pair in (A) was welded without vibration while the other remaining pairs were separately welded by applying vibration at the preset frequencies. Due to the thickness of the plates, four passes in all were deposited (Tewari, 2009). At the end of each pass, excess slag was removed from the weld metal by use of an electric grinding stone followed by cleaning with a wire brush. From each pair of the welded plates, test samples were extracted using a hacksaw. All samples were obtained in the same direction from the flat position of each welded plate such that the welded zone was in the middle of each sample. From each pair of the welded plates, test samples (15 mm thick, 20 mm wide and 120mm long) were extracted in such a manner that the welded section was in the middle of each sample. A total of twelve (12) tension test samples (three samples per pair and representing each vibration frequency) were used. The samples were machined into cylindrical shaped specimens of gauge length 30 mm and diameter 5 mm. The gauge section contained base metal, heat-affected zone and the weld metal with weld metal at the middle of the gauge length. The ends were made 10 mm to suit the gripping device of the tension testing machine. Sharp corners and all surface irregularities were removed and smoothened out to avoid stress concentration effects (Perovic, 2007; Babu et al., 2008). Tensile test was conducted on a 100 kN, electro-mechanical controlled universal testing machine (Instron UNITEK-94100) incorporated with a software that automatically plots the load-displacement curves. The machine also has the capacity to automatically compute all the tensile properties; yield strength, tensile strength, and percent elongation at the same time.

3.1. Model development

Different regression functions (Linear, Curvilinear, Power and Logarithmic) were fitted to the experimental tensile test data and adequacies of the various functions were evaluated using analysis of variance (ANOVA). The model adequacy checking included test for significance of the regression model and test for significance on the model coefficients (Montgomery et al, 2003).

3.2. Optimization Procedure

In the optimization process, the objective function was first defined in the form of an error function given by Kolahan and Heidari, (2009) in equation 1:

$$Error\ (\%) = \sum \frac{(Q_p - Q_m)^2}{Q_m} \qquad (1)$$

In the above function the quantity Q_p is individual value of output parameter estimated using the model while Q_m is the individual value of measured output parameter. The objective was to set the process parameter at such levels that these output values are achieved. In other words, it was intended to minimize the difference between the measured and the predicted output parameters by minimizing the error function given in equation 1. This way, the process parameter is calculated in such a way that the output weld characteristics approach their desired values.

4. RESULTS AND DISCUSSION

The experimental results are summarized in Figures 1-3. Based on ANOVA, the values of R^2 in the curvilinear model were over 95% for all the tensile characteristics investigated. The results therefore, recommend that the curvilinear models are the best fit in this case as they provide an excellent representation of the actual process in terms of tensile responses. The associated p-value for this model was lower than 0.05; i.e. $\alpha < 0.05$ or 95% confidence level. The relationships between vibration frequency (F) and yield strength (σ_y), tensile strength (σ_{st}) and elongation (ε) were modeled respectively as in equations 2 – 4.

$$\sigma_y = -gF^2 + hF + k; \qquad R^2 \geq 0.96 \qquad (2)$$

For this model g = 0.211, h = 4.77 and k = 321.2

$$\sigma_{ts} = -\vartheta F^2 + \mu F + \emptyset; \qquad R^2 \geq 0.95 \qquad (3)$$

The constants for this model are ϑ = 0.006, μ = 1.857 and ø = 411.1

$$\epsilon = \eta F^2 - \omega F + \phi; \qquad R^2 \geq 0.945 \qquad (4)$$

Model constants are η = 0.042, ω = 1.253 and ø = 47.24

Comparison between the predicted and measured values of process responses (Table 3) show that the output parameters deviated by at most 1% from their measured values (most of them by less than 1%). These results also show that the proposed procedure can be effectively used to determine optimal vibration frequency for any desired weld bead output characteristics in vibration welding process.

Ashwe et al.
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Indian journal of engineering, 2013, 4(9), 17-20,

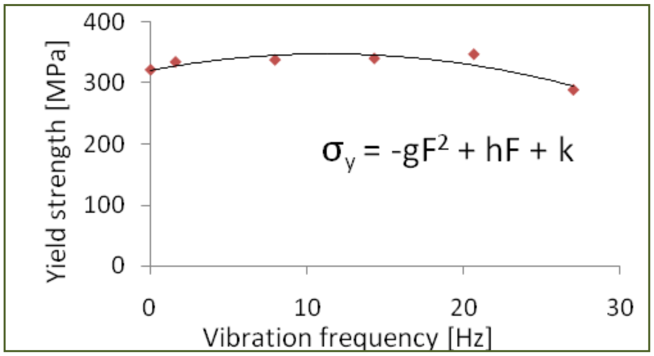

Figure 1
Variation of yield strength with vibration frequency

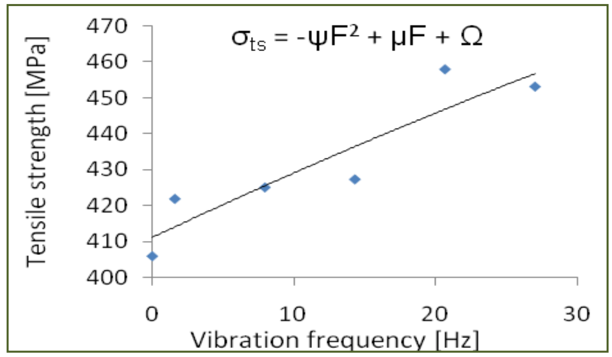

Figure 2
Variation of tensile strength with vibration frequency

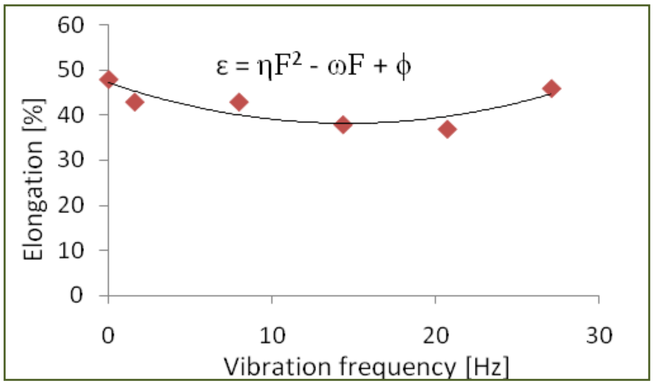

Figure 3
Variation of elongation with vibration frequency

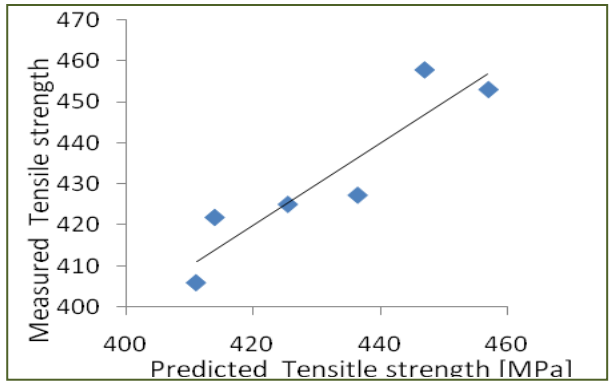

Figure 4
Measured vs predicted tensile strength

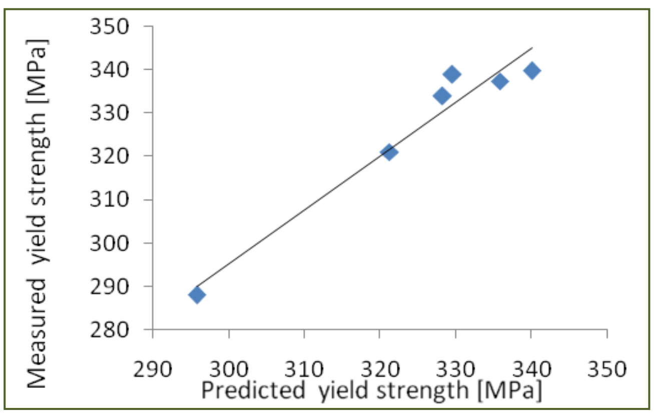

Figure 5
Measured vs predicted yield strength

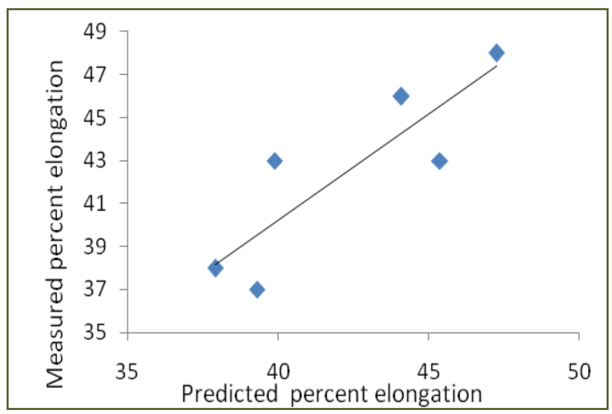

Figure 6
Measured vs predicted percent elongation

Accuracy of the prediction was also illustrated by considering scatter of predicted and measured values around regression lines as shown in Figures 4 - 6. The distributions of real data around regression lines for the models demonstrate a good conformability of the developed models to the real process (Kolahan and Haidari, 2009).

5. CONCLUSION

In this research, a procedure was proposed to model and optimize tensile behaviour of mild steel joints produced under vibratory conditions: a regression based method was employed to model the process. Mathematical models were developed to establish the relationships between welding input parameter and weld output tensile characteristics. Statistical analysis and optimization procedures showed that the models are adequate and can effectively and accurately predict tensile response of welds produced under vibratory conditions.

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Ashwe et al.
Empirical Model for Predicting Tensile Behaviour of Butt-welded Mild Steel Joints Treated to Vibration-during-welding,
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Ashwe et al.
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