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Empirical Model for Predicting Fracture 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 relationships between process parameters (inputs) and process responses (outputs) which correctly predict fracture life of butt welded joints produced by employing vibration during welding. Using statistical regression analysis, the relationships were obtained in terms of input parameter F (= vibration frequency) and output parameters which included grain size (G), and Vickers hardness (HV). Different regression functions were fitted to available experimental data for each response parameter in EXEL environment. The respective correlation factors (R^2) for each function were computed and compared and the function with highest R^2 value was selected as best for predicting the behaviour. Assuming plane state conditions, the relationships between independent and dependent variables were modeled in general terms as $f(F) = \propto F^{\varepsilon} \pm \varphi F + \cup$. The 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, Vibration, Frequency, Grain size, Hardness, Welding.

1. INTRODUCTION

Welding processes play an important role in metal fabrication industries and various welding techniques are commonly in use these days. There are also many methods for improving the quality of welded structures (Davies, 1993). Vibration induced welding is one such method developed, investigated and observed to have tremendous effects on the quality of the joints (Pucko and Gliha, 2006; Dogan, 2005; Dahunsi and Audu, 2006; Qinghua et al., 2007, and Tewari, 2009). Comprehensive experimental data on fracture properties for mechanically 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. 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 (Tewari, 2009; Dahunsi and Audu, 2006). 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 the authors that a pre-specified vibration frequency that will result in ideal weld output characteristics can be used if it can only be determined. These procedures have been used in the past to obtain ideal welding parameters combination which yielded accurate prediction of welding input parameters. Markeji 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 used to relate an important process parameter to process output characteristics of vibrated welds through developing empirical models for fracture characteristics- grain size and hardness 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

3.1. Sample preparation

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

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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 %
	G_p	Hv_p	G_m	Hv_m	
0.00	17.86	212.60	18.00	220.0	0.25
1.59	17.46	213.95	16.90	214.0	0.02
7.96	16.18	218.91	16.90	203.0	1.28
14.32	15.38	223.14	15.80	220.0	0.06
20.69	15.07	226.64	14.10	249.0	2.07
27.06	15.24	229.41	16.00	218.0	0.64

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 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.

3.2. Grain size measurement

One test sample measuring 8x8x20mm was extracted from each of the welded plates (A, B, C, D, E and F). Each extracted sample was ground using silicon carbide belt grinders of 120 grit sizes to remove the coarse surfaces. This was followed by grinders of finer silicon carbide with grit sizes of 240, 320, 400 and 600. Final grinding was carried out with 1000 grit size silicon carbide roll grinder. Each sample was then polished using magnesium oxide (MgO) powder and etched using a solution composed of 2% Nital (i.e. 2% Nitric acid and 98% ethyl alcohol). The etched surfaces were then washed thoroughly with distilled water and then left to dry in air. The samples were then singly mounted and viewed through a light optical microscope (MIL-7100) incorporated with an image analyzing software, starting from a low magnification to a final magnification of 400X. Grain size measurement was done for the parent metal, heat-affected zone and the weld metal. Field diameter of 330 microns was employed in the measurement of grain size and the approximate grain size obtained using the intercept method.

3.3. Hardness test

Hardness test was conducted in accordance with ASTM E-92 Standard (2006). Each extracted sample was prepared in the same manner as explained in the case of grain size measurement above. The etched samples were then separately mounted on the Vickers Micro-hardness testing machine ([*Model* MTH-I]). A load of 300g was applied at a holding time of five (5) seconds. In all, six different readings were taken in each zone of the joints and average values recorded. Spacing between indentations was set and maintained at 1mm in all the zones of the welded joints.

4. RESULTS AND DISCUSSION

The experimental results are summarized in Figure 1 & 2.

4.1. Model development

Different regression functions (Linear, Curvilinear, Power and Logarithmic) were fitted to the experimental grain size and hardness data and adequacies of the various functions were tested 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). Based on ANOVA, the values of R^2 in the curvilinear model were over 95% for both grain size and hardness. 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 grain size and hardness responses. The associated p-value for this model is lower than 0.05; i.e. $\alpha < 0.05$ or 95% confidence level. The proposed models for prediction of grain size and hardness values are presented respectively in equations 1 and 2:

$$G = \propto F^2 - \varphi F + \cup \qquad R^2 \leq 0.962. \qquad (1)$$

$$HV = -\propto F^2 + \varphi F + \cup \qquad R^2 \leq 0.958. \qquad (2)$$

In the above models, $\propto$ = 0.006; φ = 0.259; and $\cup$ = 17.86 are regression coefficients for the grain size model while for the hardness model the respective regression coefficients are 0.009; 0.865 and 212.60.

4.2. Optimization procedure

In our optimization process, we first defined the objective function in the form of an error function given by Kolahan and Heidari, (2009) in equation 3:

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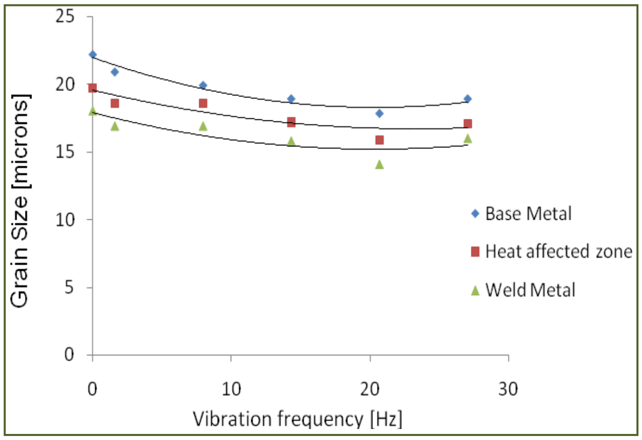

Figure 1
Variation of grain size with vibration frequency

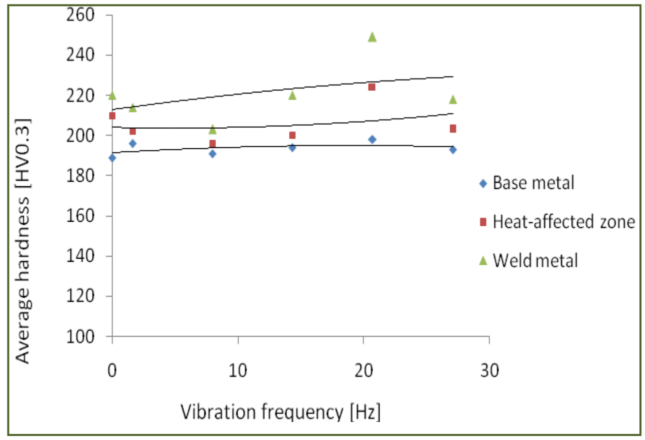

Figure 2
Variation of hardness with vibration frequency

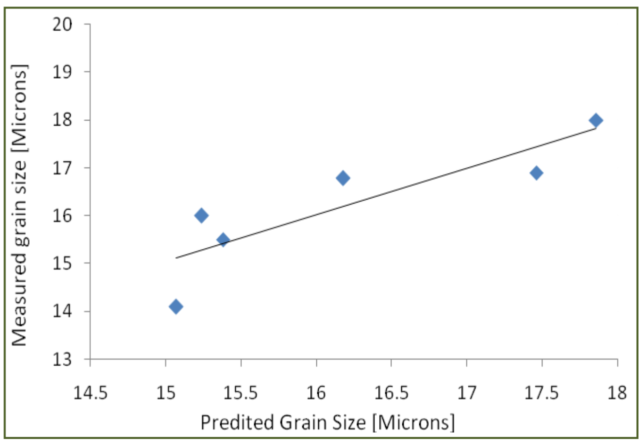

Figure 3
Predicted vs. measured values of grain size

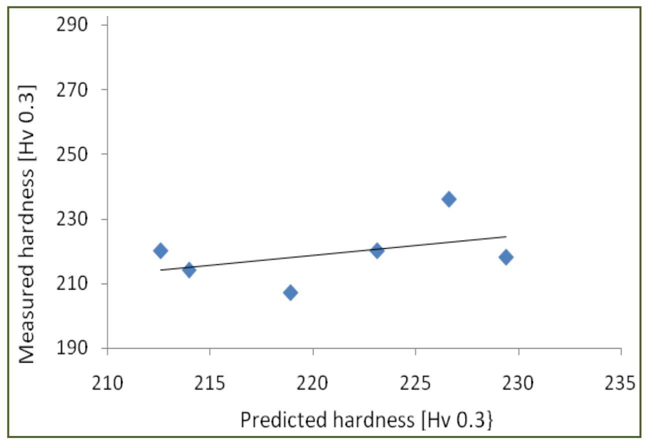

Figure 4
Predicted vs. measured hardness values

$$Error\ (\%) = \sum \frac{(Q_p - Q_m)^2}{Q_m} \qquad (3)$$

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 3. This way, the process parameter is calculated in such a way that the output weld characteristics approach their desired values. Comparison between the predicted and measured values of process responses (Table 3) show that the output parameters deviated by at most 2% 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. Accuracy of the prediction was also determined by considering scatter of predicted and measured values around regression lines as shown in Figure 3 & 4. The distributions of real data around regression lines for the models demonstrate a good conformability of the developed models to the real process.

5. CONCLUSION

In this research, a procedure was developed to model and optimize fracture characteristics 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 fracture characteristics. Statistical analysis and optimization procedures proved that the models are adequate and can effectively and accurately determine fracture behavior of welds produced under vibratory conditions.

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