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Mathematical Analysis of Heat Affected Zone Hardness (HAZH) in Mild Steel Weldment Similarly Cooled with Welded Aluminum at Regulated Temperature

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Abstract: This paper presents a mathematical analysis of heat affected zone hardness (HAZH) of mild steel weldment similarly cooled with welded aluminum in different media at regulated temperature. The metals were welded using shielded metal arc technique (SMAW) and HAZ hardness results of the respective weldments similarly cooled in palm oil, groundnut oil, air and water(maintained at 25°C) generated. An empirical model; $V \approx (\ln \vartheta)^{1.1562} + 0.0001\S)^3$ was derived and validated using graphical, statistical and deviational analysis prior to application for the analysis. The validity of the model is rooted in the core model expression $V^N = (\ln \vartheta)^e + K\S$ where both sides of the expression are approximately equal. The standard error incurred in predicting the HAZH of mild steel weldment relative to values of the actual results is 3.25%. The maximum deviation of model-predicted results from the actual was <3.9%. This invariably translates to over 96% model confidence levels and over 0.96 Reliability Dependence Coefficient (RDC) of mild steel weldment HAZH on aluminum weldment HAZH and temperature of cooling media.

Key words: Mathematical analysis -Heat affected zone hardness -Metal weldments- Temperature cooling media

INTRODUCTION

Microstructure of weldment, depth of heat affected zone and weld metal hardness have been underscored as factors on which structural considerations are based during welding. These factors are strongly influenced by welding method, cooling rate, structural integrity, strength, rusting probability of weldment, and grain structure.

Report [1] have revealed that a commendable and accurate results during welding could be achieved following a good control of process parameters such as electrode wire materials and diameter, cooling process, welding current, feed rate, arc length and voltage. The report also indicates that during MIG welding process, welding current electrode wire diameter and feed rate as well as arc length, significantly affects the hardness, depth of heat affected zone and microstructure of weldment.

Research [2] has clearly revealed that metal weldment is basically of four distinct zones; fusion zone (FZ), partially melted zone (PMZ), heat affected zone (HAZ) and the unaffected base material (UBM). Results of the research indicate that FZ is the part of the work piece where the inherent temperature does not exceed the liquidus point during welding. The PMZ is the part that is mushy and is partially liquid. It was observed that heat is conducted away from the PMZ during welding at points where it affects the material properties of the base material. The HAZ is part of the work piece where the microstructure is significantly influenced by the heat input. The temperature at this zone is below the solidus point.

Gas tungsten arc welding (GTAW) was carried out on a lean super martensitic stainless steel using heat inputs; 7.97, 8.75 and 10.9 kJ/cm. It was observed that the tensile strength of the weld joint decreased with rise in the heat input and temperature. The hardness of the weld joint produced was slightly affected by Increase in the heat input whereas the toughness of weld deposit was improved.

Scientists [4] have successfully evaluated the effect of process variables such as heat input on grain growth, grain refinement regions of the HAZ, widths of the HAZ and weld interface using mathematical models. The model aided predictive analysis go with response surface methodology and color metallography technique for the purpose of precision. Results of the work carried out by the researchers

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indicate that heat input and wire feed rate made a positive impact during the welding process, though the welding speed had a negative effect on all HAZ characteristics. It was observed that a decrease weld interface and increase in arc voltage increases the width of grain growth and grain refinement zones. The research also revealed a resultant maximum width of HAZ following minimum inputs of both wire feed rate and welding speed.

Research [5] has underscored the applicability of mathematical models for the purpose of predicting HAZ dimensions at any given process variables. The research indicates that desired weld bead HAZ characteristics and its mechanical properties are achievable by correctly selecting the process variables. The resourcefulness in the models helps to improve understanding of the effect of process parameters on bead quality and quantitative evaluation of the interactive effects of process variables on HAZ characteristics. The models have also helped to obtain a better quality welded joint with desirable properties at a relatively low cost through optimization of the size of the weld bead's HAZ.

The pattern of results from a welding process has been successfully evaluated through ANN based modeling [6]. The research revealed a distinction in the microstructure of the weldments compared with those of the base metal. It was discovered that microstructures, hardness and depth of weldment HAZ all depends on the process parameters used. The researchers concluded that experimental results of hardness and depth of weldment HAZ are in good agreement with predictions from ANN models.

Mathematical models [7-9] have been developed to give account of the metallurgical activities in the weld pool for clear understanding of the flow ability fluid material under intense heat. of the Empirical models [10-16] have also been developed evaluation, assessment and predictive analysis of the weldment HAZ hardness of selected engineering materials such as mild steel, cast iron and aluminum similarly cooled (in each case) in palm oil, air, water and groundnut oil. Deviation less than 0.5% was recorded in each case.

This work embarks on a mathematical analysis of heat affected zone hardness (HAZH) of mild steel weldment similarly cooled with welded aluminum in palm oil, groundnut oil, air and water maintained at 25°C.

MATERIALS AND METHODS

Clean samples of aluminum and mild steel obtained from First Aluminum Company Ltd. Port Harcourt were used for the welding operations. Prior to welding, two parts of each standard sample of these materials were butt welded end to end at the interface of separation. The joints were prepared by chamfering the edges to be joined to create a "double V" kind of groove. The welding operation was carried out using the Shielded Metal Arc Welding (SMAW) process. This technique was considered because of its versatility and ability to give moderately sized heat affected zone. Furthermore, the technique was employed because it offers protection to the molten metal (during welding) against atmospheric gas interference. Consumable electrodes of length 230- 240mm were used. These electrodes were coated with SiO_2. The welded samples were similarly cooled in palm oil (maintained at room temperature), and the HAZ hardness of their respective weldments determined using Vickers hardness testing machine . Ten samples from each of the two materials were welded, similarly cooled together in palm oil, groundnut oil, air and water and their respective weldment HAZ hardness tested. The average HAZ hardness for the weldments of each of the two materials investigated were evaluated.

Table 1 shows the variation of materials with the input welding current type (C/Type), welding current (W/C) and voltage (W/V). The results of HAZ hardness of aluminum and mild steel weldments similarly cooled in palm oil, groundnut oil, air and water were presented in Table 2.

Table 1: Variation of materials with their welding currents and voltages

Material	C/Type	W/ C	W/V
Aluminum	D.C	120	280
Mild Steel	A.C	180	220

Table 2: Hardness of HAZH of mild steel and aluminum weldments Similarly cooled in different media

Material	PO	GO	WR	AR
Aluminum	407	412	458	368
Mild Steel	503	513	560	471

PO - Palm oil; GO - Groundnut oil; WR - Water; AR -Air

Model Formulation: Results from the experiment were used for the model formulation. Computational analysis of results in Table 2 indicates that;

$$V^{N} = (\ln\vartheta)^{e} + K\S \quad (1)$$

Introducing the values of e, N and K into equation (1) reduces it to;

$$V^{1/3} = (\ln\vartheta)^{1.1562} + 0.0001\S \quad (2)$$

Multiplying the index of both sides of equation (2) by 3 gives;

$$V = ((\ln\vartheta)^{1.1562} + 0.0001\S)^{3} \quad (3)$$

Re-arranging equation (3)

$$\vartheta = \exp\,(V^{1/3} - 0.0001\S)^{0.8649} \quad (4)$$

where

(V) = HAZ hardness of mild steel weldment (VHN)
(ϑ) = HAZ hardness of aluminum weldment (VHN)
(ʆ) = Temperature of cooling media (°C)

e = 1.1562, N = 1/3 and K = 0.0001; equalizing constant. ђ = 3, Ä = 0.8649; empirical constants (determined using C-NIKBRAN [17]).

The derived models are equations (3) and (4).

Model Validation: Evaluation of results in Table 2 gives rise to Table 3. Prior to application for the HAZH evaluation, graphical, statistical and deviational analyses were used to ascertain the validity of the derived model . The validity of the model is rooted in the core model expression $V^N = (\ln\vartheta)^e + K$ʆ where both sides of the expression are approximately equal. Table 3 also agrees with equation (1) or (2) following the values V^N and $(\ln \vartheta)^e + K$ʆ evaluated from the experimental results in Table 2. The maximum deviation of model-predicted values of the mild steel weldment HAZH from the experimental values was evaluated by comparing HAZH of mild steel as evaluated from experiment and derived model.

Table 3: Variation of $V^{1/3}$ with $(\ln \vartheta)^{1.1562}$+0.0001ʆ

$V^{1/3}$	$(\ln \vartheta)^{1.1562}$ +0.0001ʆ
7.9528	7.9537
8.0052	7.9724
8.2426	8.1347
7.7805	7.7999

Boundary and Initial Conditions: The welding process was carried out under atmospheric condition and produced weldments maintained at same condition. Input welding current and voltage range are 120-180A and 220-280V respectively. SiO_2-coated electrodes were used to avoid oxidation of weld spots. Range of electrode length used: 230-240mm. Welded samples were cooled in 1000°Cm^3 of palm oil, groundnut oil, water which was maintained at 25°C. Some samples designated for air cooling were also maintained at 25°C.

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 are symmetries.

RESULTS

Analysis of Experimental and Model-Predicted Weldments HAZH: Figs. 1-4 indicate the comparison between HAZ hardness of mild steel and aluminum weldments similarly cooled together in palm oil, groundnut oil, water and air under the same conditions. These figures show alignment of graphs of the actual and model-predicted results in each case. These translated into significantly similar trend of data points distribution for the experiment and model-predicted values.

Statistical Analysis: The standard error incurred in predicting the HAZH of mild steel weldment relative to values of the actual results is 3.25%, indicating high precision prediction of mild steel weldment HAZH.

Deviational Analysis: Critical comparative analysis of the HAZHs in mild steel and aluminum weldments as obtained from the experiment and derived model revealed a maximum deviation < 3.9% (of model-predicted results from the experiment). This invariably translates to over 96% model confidence level and also over 0.96 Reliability Dependence Coefficients (RDC) of mild steel weldment HAZH on aluminum weldment HAZH and temperature of cooling media. Model-predicted results deviate from the experimental or actual results due to non-consideration and non-inclusion of some experimental process conditions which actually influenced the research results , during the model formulation. This necessitated the introduction of correction factor, to bring the model-predicted weldment HAZH to those of the corresponding experimental values.

Deviation (Dv) of model-predicted weldment HAZH from that of the experiment is given by;

$$Dv = \left(\frac{H_p - H_{ex}}{H_{ex}}\right) \times 100 \tag{5}$$

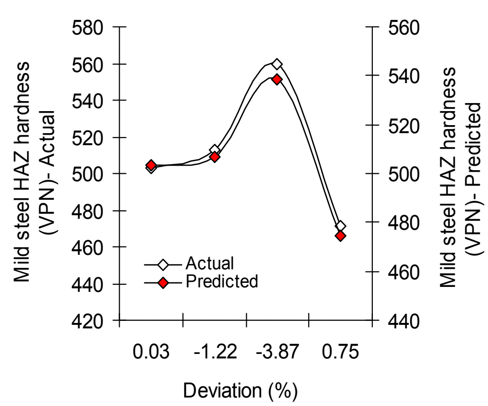

Fig. 1: Comparison of mild steel weldment HAZ hardness (relative to deviation of predicted result) as obtained from actual and model-prediction

The deviation of model predicted results from that of the experiment is basically the numerical value. The associated sign preceding the value signifies that the deviation is a deficit (negative sign) or surplus (positive sign).

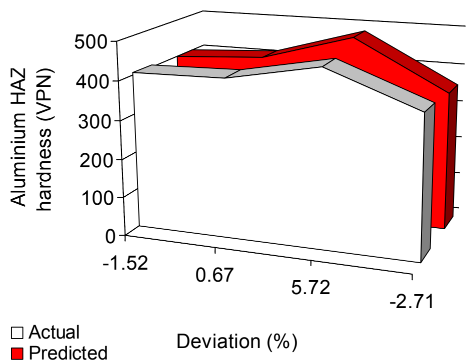

Fig. 2: Comparison of aluminium weldment HAZ hardness (relative to deviation of predicted result) as obtained from actual and model-prediction

Correction factor (Cr) is the negative of the deviation i.e,

$$Cr = -Dv \quad (6)$$

Therefore

$$Cr = -\left(\frac{H_p - H_{ex}}{H_{ex}}\right) \times 100 \quad (7)$$

where,

Dv = Deviation (%)

H_p = Model-predicted HAZ hardness of weldment (VPN)

H_{ex} = HAZ hardness of weldment from experiment (VPN)

Cr = Correction factor (%)

Substitution of the values of Cr from equation (7) into the model, gives the exact corresponding experimental based weldment HAZH.

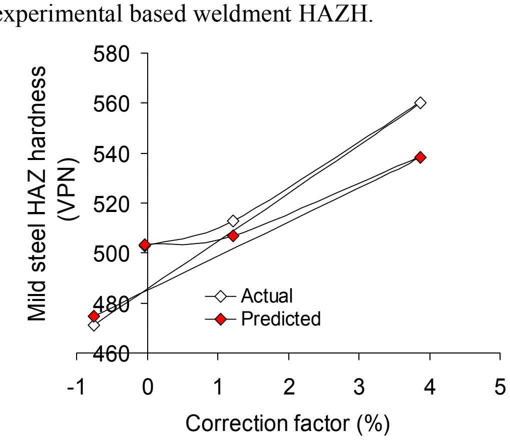

Fig. 3: Comparison of mild steel weldment HAZ hardness (relative to correction factor to predicted result) as obtained from actual and model-prediction

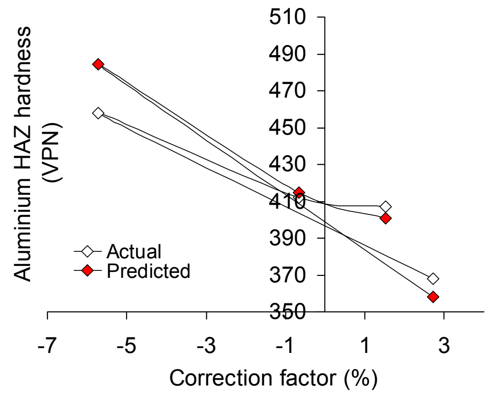

Fig. 4: Comparison of aluminium weldment HAZ hardness (relative to correction factor to predicted result) as obtained from actual and model-prediction

CONCLUSIONS

Mathematical analysis of heat affected zone hardness (HAZH) of mild steel weldment similarly cooled with welded aluminum in palm oil, groundnut oil, air and water (maintained at 25°C) were carried out. Developed empirical model; $V \approx ((\ln\vartheta)^{1.1562} + 0.0001\S)^3$ was validated using graphical, statistical and deviational analysis prior to application for the analysis. The validity of the model is rooted in the core model expression $V^N = (\ln \vartheta)^e + K\S$ where both sides of the expression are approximately equal. The standard error incurred in predicting the HAZH of mild steel weldment relative to values of the actual results is 3.25%. The maximum deviation of model-predicted results from the actual was < 3.9%. This invariably translates to over 96% model confidence levels and over 0.96 Reliability Dependence Coefficients (RDC) of mild steel weldment HAZH on aluminum weldment HAZH and temperature of cooling media.

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