American-Eurasian Journal of Scientific Research 15 (1): 34-38, 2020
ISSN 1818-6785

DOI: 10.5829/idosi.aejsr.2020.34.38

Logarithmic Analysis of Heat Affected Zone Hardness (HAZH) of Cast Iron Weldment as Equivalent of Aluminium and Mild Steel HAZH of Weldments Similarly Cooled in Different Media

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Abstract: Logarithmic analysis of heat affected zone hardness (HAZH) of cast iron weldment similarly cooled with mild steel and aluminium weldments in different media was carried out. The metals were welded using shielded metal arc technique and their respective weldments similarly cooled in palm oil, groundnut oil, air and water to obtain their corresponding hardnesses. An empirical model; $\vartheta \approx$ antilog $(\text{Log } V + \text{Log } Ђ)^{0.648}$ being derived from experimental results, predicts the HAZ hardness of cast iron as equivalent of mild steel and aluminium weldments HAZH on cooling them altogether similarly in any of the cooling medium; palm oil, groundnut oil, air and water. The derived model was validated using graphical and deviational analysis prior to application for the predictive analysis. The validity of the model is rooted in the core model expression Log ϑ= $(\text{Log } V + \text{Log } Ђ)^{0.648}$ where both sides of the expression are approximately equal. The maximum deviation of model-predicted results from the actual was <4.5%. This invariably translates to over 95% model confidence levels and over 0.95 Reliability Equivalence Coefficients (REC) of cast iron weldment HAZH relative to weldment HAZHs of mild steel and aluminium.

Key words: Logarithmic analysis - Heat affected zone hardness - Metal weldments - Cooling media

INTRODUCTION

Structural considerations during welding are based on microstructure of weldment, depth of heat affected zone and weld metal hardness. These factors are very much influenced by structural integrity, strength, welding method, rusting probability of weldment, cooling rate, and grain structure.

Scientists [1] have revealed that a good control of process parameters such as welding current, feed rate, cooling process, arc length, voltage, electrode wire materials and diameter ascribes commendable and accurate results during welding. The research also shows that arc length, electrode wire diameter and feed rate as well as welding current affects greatly the hardness, depth of heat affected zone and microstructure of weldment during MIG welding process.

It has been shown [2] that submerged arc welding of two low-carbon Q & T steels which produced hardness gradient in the heat affected zones (HAZs) show unequivocally that the gradient differs from the ones found in steel of lower carbon equivalent, in that the peak HAZ hardness is displaced from the grain coarsened heat affected zone (GCHAZ) into the grain refined heat affected zone (GRHAZ). The researchers clarified the cause of this unexpected phenomenon after carrying out thermal cycle simulation to confirm the results obtained from actual welds.

Successful study [3] was carried out following gas tungsten arc welding of a lean super martensitic stainless steel using generated heat inputs of 7.97, 8.75 and 10.9 kJ/cm. Results of the study revealed that the tensile strength of the weld joint decreased with rise in the heat input and temperature. It was also observed that increase in the heat input in significantly affected the hardness of weld joint while the toughness of weld deposit was improved. The researchers attributed this to increased ferrite content in the matrix of martensite resulting from increased heat input. The researchers concluded eventually that the resulting microstructure is made up of mixed phase of marten site, austenite and some amount of

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ferrites while more elongated bright and larger phases of banded delta ferrite in a matrix of marten site are within the HAZ near the fusion line, irrespective of change in heat input.

Research [4] has unveiled the possibility of using mathematical models in evaluating the effect of process variables and heat input on grain growth and grain refinement regions of the HAZ, widths of the HAZ and weld interface. The color metallography technique and response surface methodology were also used. Results of the work indicate that in as much as the welding speed had a negative effect on all HAZ characteristics, the heat input and wire feed rate made a positive impact. It was observed that width of grain growth and grain refinement zones increased while weld interface decreased with an increase in arc voltage. The research also submitted that minimum inputs of both wire feed rate and welding speed results to maximum width of HAZ Mathematical models have proven [5] viable for predicting HAZ dimensions for any given process variables. The research streamlines a careful selection of correct process variables for achievement of the desired weld bead HAZ characteristics and mechanical properties. These models have significantly helped to improve understanding of the effect of process parameters on bead quality and for quantitative evaluation of the interactive effects of process variables on HAZ characteristics. The models have also helped to optimize the size of the weld bead's HAZ in order to obtain a better quality welded joint with desirable properties at a relatively low cost.

ANN based modeling of the experiment has tremendously helped to realize the patterns of results obtained from the experiments [6]. The researchers reported that the microstructures obtained in these weldments are distinctly different from those of the base metal. Findings from the work also indicate that microstructures, hardness and depth of weldment HAZ depends on the process parameters used. The scientists concluded that ANN model are in very good agreement with experimental results of hardness and depth of weldment HAZ.

Models [7-13] which are empirical in nature have been derived for evaluation, assessment and predictive analysis of the weldment HAZ hardness of selected engineering materials such as mild steel, cast iron and aluminum. The materials used were welded using Shielded Metal Are Welding (SMAW) technique and similarly cooled (in each case) in palm oil, air, water and groundnut oil. Each of these models recorded maximum deviation (of model-predicted weldment HAZ hardness values from the experimental) less than 0.5%.

The present work aims at carrying out a logarithmic analysis of heat affected zone hardness (HAZH) of cast iron weldment as equivalent of aluminium and mild steel HAZH of weldments similarly cooled in palm oil, groundnut oil, air and water.

MATERIALS AND METHODS

Clean samples of aluminum, cast iron 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. Palm oil, groundnut oil, air and water were used as the cooling media. Consumable electrodes of length 230-240mm were used. These electrodes were coated with SiO_2. The welded samples were similarly cooled in Palm oil, groundnut oil, air and water (maintained at room temperature), and the HAZ hardness of their respective weldments determined using Vickers hardness testing machine. Ten samples from each of the three materials were welded, similarly cooled in the media and their respective weldment HAZ hardness tested were processed and the average HAZ hardness for the weldments of each of the three of the 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 aluminium, mild steel and cast iron 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
Aluminium	D.C	120	280
Cast Iron	A.C	180	220
Mild Steel	A.C	180	220

Table 2: Hardness of HAZH of metal weldments similarly cooled in different media

Material	PO	GO	WR	AR
Aluminium	407	412	458	368
Cast Iron	870	920	1010	820
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;

$$\text{Log } \vartheta = (\text{Log } V + \text{Log } \text{ƀ})^{N} \quad (1)$$

Introducing the value of N into equation (1)

$$\text{Log } \vartheta = (\text{Log } V + \text{Log } \text{ƀ})^{0.648} \quad (2)$$

$$\vartheta = 10^{(\text{Log } V + \text{Log } \text{ƀ})^{0.648}} \quad (3)$$

Re-arranging equation (3)

$$V = 10^{([\text{Log } \vartheta]^{1.5432} - \text{Log } \text{ƀ})} \quad (4)$$

$$\text{ƀ} = 10^{([\text{Log } \vartheta]^{1.5432} - \text{Log } V)} \quad (5)$$

where
(ϑ) = HAZ hardness of cast iron weldment (VHN)
(V) = HAZ hardness of mild steel weldment (VHN)
(ƀ) = HAZ hardness of aluminium weldment (VHN)
N = 0.648; equalizing constant.
K = 1.5432; empirical constant (determined using C-NIKBRAN [14]). The derived models are equations (3), (4) and (5)

Model Validation: Computational analysis of results in Table 2 gives rise to Table 3. The derived model was validated using graphical and deviational analysis prior to application for the predictive analysis. The validity of the model is rooted in the core model expression Log ϑ= $(\text{Log } V + \text{Log } \text{ƀ})^{0.648}$ where both sides of the expression are approximately equal. Table 3 also agrees with equation (2) following the values Log ϑ and $(\text{Log } V + \text{Log } \text{ƀ})^{0.648}$evaluated from the experimental results in Table 2.

The maximum deviation of model-predicted values of the weldment HAZH from the experimental values was evaluated by comparing HAZH of cast iron as evaluated from experiment and derived model.

Table 3: Variation of Log ϑ with $(\text{Log } V + \text{Log } \text{ƀ})^{0.648}$

Log ϑ	$(\text{Log } V + \text{Log } \text{ƀ})^{0.648}$
2.9395	2.9507
2.9638	2.9557
3.0043	2.9858
2.9138	2.9246

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 1000cm^3 of palm oil, groundnut oil, water which were maintained at 25°C. Some samples were cooled in air 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. 1-6 indicate a comparative analysis of HAZ hardness of cast iron, 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 and similarly covered area of shapes 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.

Deviational Analysis: Analysis of the HAZH sincast iron, mild steel and aluminium weldments as obtained from the experiment and derived model revealed a maximum deviation <4.5% (of model-predicted results from the experiment). This invariably translates to over 95% model confidence level and also over 0.95 Reliability Equivalence Coefficients (REC) of cast iron weldment HAZH relative to weldment HAZHs of mild steel and aluminium. The deviation was basically attributed to non-consideration of some experimental process conditions which actually influenced the research results, but were not considered 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;

$$Dv = \left(\frac{W_p - W_{ex}}{W_{ex}}\right) \times 100 \quad (6)$$

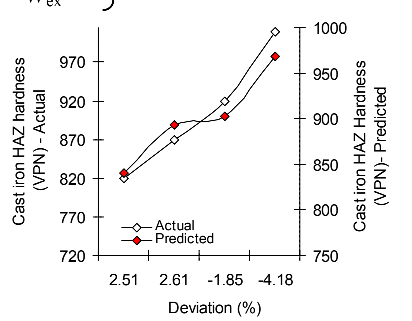

Fig. 1: Comparison of cast iron weldment HAZ hardness (relative to deviation of predicted result) as obtained from actual and model-prediction

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

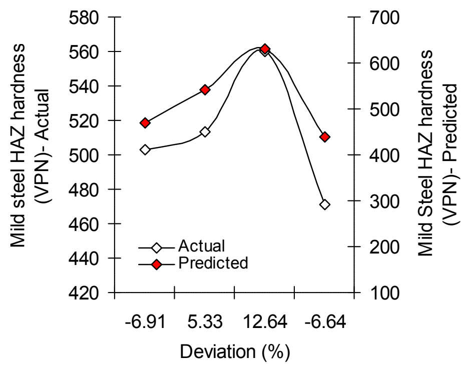

Fig. 2: Comparison of mild steel weldment HAZ hardness (relative to deviation of predicted result) as obtained from actual and model-prediction

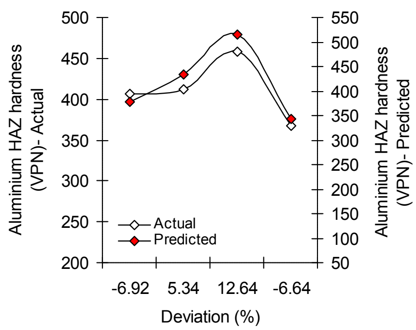

Fig. 3: Comparison of aluminium weldment HAZ hardness (relative to deviation of predicted result) as obtained from actual and model-prediction

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

$$Cr = -Dv \quad (7)$$

Therefore

$$Cr = -\left(\frac{W_p - W_{ex}}{W_{ex}}\right) \times 100 \quad (8)$$

where

Dv = Deviation (%)

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

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

Cr = Correction factor (%)

It is strongly believed that on introducing the values of Cr from equation (8) into the model, the exact corresponding experimental based weldment HAZH would be obtained.

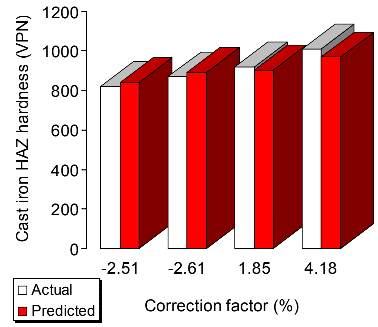

Fig. 4: Comparison of cast iron weldment HAZ hardness (relative to correction factor to predicted result) as obtained from actual and model-prediction

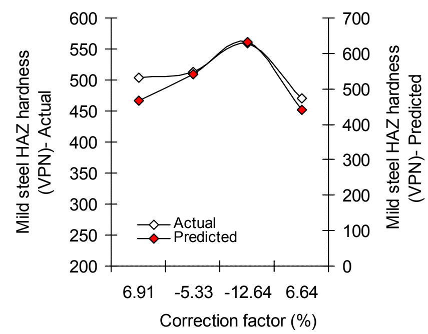

Fig. 5: Comparison of mild steel weldment HAZ hardness (relative to correction factor to predicted result) as obtained from actual and model-prediction

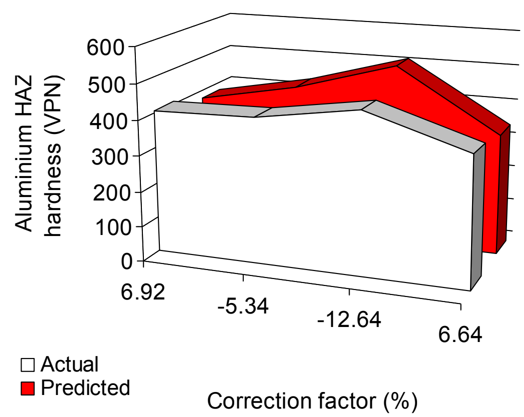

Fig. 6: Comparison of aluminium weldment HAZ hardness (relative to correction factor to predicted result) as obtained from actual and model-prediction

CONCLUSIONS

Logarithmic analysis of heat affected zone hardness (HAZH) of cast iron weldment similarly cooled with mild steel and aluminium weldments in palm oil, groundnut oil, air and water was carried out. An empirical model; $\vartheta \approx$ antilog (Log V + Log ƅ)$^{0.648}$ being derived from experimental results, predicts the

HAZ hardness of cast iron as equivalent of mild steel and aluminium weldments HAZH on cooling them altogether similarly in any of the cooling medium; palm oil, groundnut oil, air and water. The validity of the model is rooted in the core model expression $\text{Log } \vartheta = (\text{Log } V + \text{Log } \text{ƀ})^{0.648}$ where both sides of the expression are approximately equal. The maximum deviation of model-predicted results from the actual was < 4.5%. This invariably translated to over 95% model confidence levels as well as over 0.95 Reliability Equivalence Coefficients (REC) of cast iron weldment HAZH relative to weldment HAZHs of mild steel and aluminium.

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