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Implicit Analysis of Heat Affected Zone Hardness (HAZH) of Aluminum Weldment As a Function of HAZH of Similarly Cooled Metals

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Abstract

This paper presents an implicit analysis of the heat affected zone hardness of aluminum weldment cooled in air as a function of the heat affected zone hardness of similarly cooled mild steel and cast iron weldments. This evaluation resulted to model derivation; $\beta = 1.2279\ (\gamma\alpha /(\alpha + \gamma))$. The empirical model predicted the heat affected zone hardness (HAZH) of the aluminium weldment as a function of the HAZH of similarly cooled rmild steel and cast iron weldments. The HAZHs of mild steel and cast iron were also respectively predicted following evaluation of generated results on re-arranging the model. The maximum deviation of the model-predicted HAZHs (from experimental values) was less than 0.01% indicating a model confidence and reliability level above 99.99% and reliability coefficient of above 0.9999.

Key words- Hardness, Heat Affected Zone, Aluminum Weldments, Mild Steel, Cast Iron.

1. Introduction

The unavoidable need for intensive studies geared towards research and development of better welding techniques, cooling media and rates stems from abrupt failure of welded metal and alloy materials during service. Heating and cooling cycle of the weld zone brings about considerable and significant changes in the microstructure of weldments, which in turn is directly related to the welding process and techniques employed. The microstructure of heat affected zone (HAZ) affects the properties of a welded joint. Therefore any changes in the microstructure of HAZ invariably results to changes in the welded joint. Research [1] has shown that the characteristics, microstructure and invariably, hardness, toughness, and cracking susceptibility of the HAZ in steel fusion welds are influenced by a number of welding process variables and applied operating conditions. High heat-input submerged arc welds is exclusively characterized by wide HAZ with low impact strength. Aluminium alloys such as antimony-modified A356-type Al-Si-Mg alloy on their part show tremendous increase in the tensile properties and hardness with thermal ageing treatment, while the impact energy and elongation decreased upon ageing [2].

A study [3] on the divisions of the heat affected zone clearly revealed that supercritical, intercritical, and subcritical zones are the three divisions of the heat-affected zone of a fusion weld in steel. The supercritical region in turn, divides to give two regions: grain growth and grain refinement. The properties of the weld joint are significantly influenced by the microstructure of the grain growth and grain refinement regions of the HAZ's supercritical zone. The amount and extent of grain growth and the weld thermal cycle need be known, in order to predict the properties of this zone accurately. It is a good practice to ensure that heat input from the welding process is limited so that the width of the HAZ's supercritical zone becomes narrow. Also, the supercritical zone undergoes significantly greater microstructural changes compare to what is obtainable in the HAZ's intercritical and subcritical zones. The mechanical and metallurgical properties of the weldment have since been discovered to be affected by these microstructural changes [4]. This implies that the size of the HAZ is an indication of the extent of structural changes. Interestingly, HAZ dimensions are controlled by process variables and heat input, and so there is reality in correlating them through development of mathematical models.

Assessment and computational analysis of heat affected zone hardness (HAZH) of water cooled aluminum weldment were carried out using a different model. The general model:

$$\gamma = 1.2714[(\alpha\beta/\alpha + \beta)] \quad (1)$$

showcases the tendency of predicting the HAZ hardness of aluminum weldment cooled in water as a function of the HAZ hardness of both mild steel and cast iron welded and cooled under the same conditions. The maximum deviations of the model-predicted HAZ hardness values γ, α and β from the corresponding experimental values γexp, αexp and β exp were less than 0.02% respectively.

Empirical analysis of results generated from studies [5] indicates that the heat-affected zone (HAZ) hardness of cast iron weldment cooled in water could be predicted using quadratic and linear models. Analysis of generated results were carried out in relation to the combined and respective values of the heat-affected zone hardness of aluminum and mild steel welded and cooled under the same conditions. The quadratic model is expressed as:

$$\theta = [3.0749\beta - \gamma]/2 + \sqrt{[((\gamma - 3.0749\beta)/2)^2 - \gamma\beta]} \quad (2)$$

The validity of the quadratic model was rooted on the fractional expression; $\gamma/3.0749\theta + \gamma/3.0749\beta + \theta/3.0749\beta = 1$. Evaluations indicate that the respective deviations of the model-predicted heat-affected zone hardness values of aluminum, cast iron and mild steel from the corresponding experimental values were less than 0.01% which is quite insignificant, indicating reliability of the model. The linear models expressed as: $\theta = 2.2051\gamma$ and $\theta = 1.8035\beta$, on the other hand predict the HAZ hardness of cast iron weldment cooled in water given the values of the HAZ hardness of aluminum or/and mild steel welded and cooled under the same conditions are known.

A successful derivation of a predictive model for analysis of the heat affected zone hardness of aluminum weldment cooled in groundnut oil has been carried out [6]. The general model;

$$\beta = 0.5997\sqrt{(\gamma\alpha)} \quad (3)$$

shows that HAZ hardness in aluminium weldment was dependent on the hardness of the heat affected zone (HAZ) in mild steel and cast iron weldments cooled in same media. Re-arrangement of the subject of the model evaluated the HAZ hardness of mild steel α, or cast iron γ respectively as in the case of aluminum.

$$\alpha = \frac{\beta^2}{0.3596\gamma} \quad (4)$$

$$\gamma = \frac{\beta^2}{0.3596\alpha} \quad (5)$$

The respective deviations of the model-predicted HAZ hardness values β, γ and α from the corresponding experimental values was less 0.02%.

Intensive research and computational analysis of experimental results have been carried out to understand how HAZ hardness of weldment is affected on cooling the weldments in groundnut oil [7]. Empirical models were derived [8] (based the results of the research) for the evaluation of the HAZ hardness of cast iron weldment cooled in groundnut oil in relation to the respective and combined values of HAZ hardness of aluminum and mild steel welded and cooled under the same conditions. The linear models; $\alpha = 2.2330\gamma$, $\alpha = 1.7934\beta$ and $\beta = 1.2451\gamma$, were found to predict the HAZ hardness of cast iron weldment cooled in groundnut oil as a function of the HAZ hardness of aluminum or mild steel welded and cooled under the same conditions. The results of the research [7] also shows that the derived model;

$$\alpha = 1.7391\gamma + 0.3967\beta \quad (6)$$

can predict the HAZ hardness of cast iron weldment cooled in groundnut oil as a function of the HAZ hardness of both aluminum and mild steel welded and cooled under the same conditions. The respective deviations of the model-predicted HAZ hardness values γ, β and α from the corresponding experimental values γexp, βexp, and αexp, was less 0.8% indicating the reliability and validity of the model.

Similar research [9] to the previous work [5] was carried out to ascertain the possibility of predicting the HAZ hardness of air cooled weldments of the same materials. Quadratic and linear models were also derived [9], validated and used for predicting the HAZ hardness of air cooled cast iron weldment in relation to the combined and respective values of HAZ hardness of aluminum and mild steel welded and cooled under the same conditions. The basic difference in both studies [5] and [9] is the cooling medium. The general model;

$$\theta = [2.9774\beta - \gamma]/2 + \sqrt{[((\gamma - 2.9774\beta)/2)^2 - \gamma\beta]} \quad (7)$$

predicted the HAZ hardness of cast iron weldment cooled in air as a function of the HAZ hardness of both aluminum and mild steel welded and cooled under the same conditions. The linear models; θ = 2.2391γ and θ = 1.7495β on the other hand predict the HAZ hardness of cast iron weldment cooled in air as a function of the HAZ hardness of aluminum or mild steel welded and cooled under the same conditions. The validity of the model is rooted on the fractional expression; γ/2.9774θ + γ/2.9774β + θ/2.9774β = 1 since the actual computational analysis of the expression was also equal to 1, apart from the fact that the expression comprised the three metallic materials. The respective deviations of the model-predicted HAZ hardness values θ, γ, and β from the corresponding experimental values θexp, γexp, and βexp was less than 0.003%.

The present study aims at carrying out an implicit analysis of the heat affected zone hardness of aluminum weldment cooled in air as a function of the heat affected zone hardness of similarly cooled mild steel and cast iron weldments. An empirical model will be derived and used as a tool for the predictive analysis of experimental and model-predicted results.

2. Materials and methods

Mild steel, aluminum and cast iron were cut and welded using the shielded metal arc welding technique and the hardness of the HAZ cooled in air (maintained at room temperature) tested. Ten other samples from each of the three materials were also welded, cooled in air and their respective HAZ hardness tested. Table 1 shows the welding current and voltage used.

Table 1: Variation of materials with 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

3. Results and discussion

The average HAZ hardness for the weldments of each of the three materials investigated are as presented in Table 2.

Table 2: Hardness of HAZ in weldments

Material	HAZ Hardness (VHN)
Aluminium	368
Cast Iron	824
Mild Steel	471

3.1 Model Formulation

Experimental data obtained from the highlighted research work were used for this work. Computational analysis of these data shown in Table 2, gave rise to Table 3 which indicate that;

$$\beta = 0.4466\gamma \quad (8)$$
$$\gamma = 1.7495\alpha \quad (9)$$
$$\beta = 0.7813\alpha \quad (10)$$

Multiplying equations (8) and (10) as arranged in Table 2;

$$\frac{\beta}{\gamma} + \frac{\beta}{\alpha} = 0.4466 + 0.7813 \qquad (11)$$

$$\frac{\alpha\beta + \gamma\beta}{\gamma\alpha} = 1.2279 \qquad (12)$$

$$\alpha\beta + \gamma\beta = 1.2279\,\gamma\alpha \qquad (13)$$

$$\beta(\alpha + \gamma) = 1.2279\,\gamma\alpha \qquad (14)$$

$$\beta = 1.2279\,(\gamma\alpha/(\alpha + \gamma)) \qquad (15)$$

Following re-arrangement of the model equation; (15), the values of γ and α were also evaluated as;

$$\gamma = \left(\frac{1.2279}{\beta} - \frac{1}{\alpha}\right)^{-1} \qquad (16)$$

$$\alpha = \left(\frac{1.2279}{\beta} - \frac{1}{\gamma}\right)^{-1} \qquad (17)$$

The derived models are equations (15), (16) and (17)

Where
(β) = Model-predicted hardness of HAZ in aluminum weldment cooled in air (VPN)
(α) = Model-predicted hardness of HAZ in mild steel weldment cooled in air (VPN)
(γ) = Model-predicted hardness of HAZ in cast iron weldment cooled in air (VPN)

Table 3: HAZ Hardness ratio between aluminum, mild steel, and cast iron weldments cooled in air.

Ratios			S/No
β/γ	368/824	0.4466	1
γ/α	824/471	1.7495	2
β/α	368/471	0.7813	3

3.2 Boundary and Initial Conditions

The welding process was carried out under atmospheric condition. After welding, weldments were also maintained at atmospheric condition. In put welding current and voltage range are 120-180A and 220-280V respectively. SiO_2-coated electrodes were used to avoid oxidation of weld spots. Welded samples were cooled in air which was maintained at 25^0C. 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.

Table 2 shows the variation of materials with the input welding current type (C/Type), welding current (W/C) and voltage (W/V). The result of hardness of the HAZ obtained from aluminium, cast iron and mild steel weldments similarly cooled in air (as presented in Table 2) shows that HAZ hardness is greatest in cast iron followed by mild steel, while that of aluminium is lowest.

Tables 4 and 5 show that on comparing the HAZ hardness values from experiment and those of the model, model values were found to be very much within the range of the experimental values. Model values of β evaluated from equations (8) and (10) and tabulated in Table 4 show that all the equations are valid since all of them gave almost the same corresponding experimental values. The value of γ in equation (9) was evaluated to establish the validity of the model. It was found that the model-predicted γ value was also almost the same as the corresponding experimental value. This is a clear indication that the HAZ hardness of any of aluminum, mild steel and cast iron weldments cooled in air can be predicted as a function of the HAZ hardness of any of the other two materials, providing each pair was cooled in air. Table 5 also indicates that the model-predicted value of α is approximately the same as the corresponding experimental value. It can also be seen from Table 5 that the model-predicted values of γ and α are also almost the same as the corresponding experimental values of γ and α respectively. Tables 4 and 5 indicate that the respective deviations of the model-predicted HAZ hardness values β, γ and α from those of the corresponding experimental values are all less than 0.01% which is quite negligible and within the acceptable model deviation range from experimental results. Furthermore, the values of γ and α (from equations (16) and (17) respectively) evaluated to be approximately equal to the respective corresponding experimental values confirm the validity of the model. This also implies that the general model; equation (15) can predict the HAZ hardness of any of aluminum, mild steel and cast iron weldments cooled in air as a function of the HAZ hardness of the other two materials, providing the three materials constituting the model (aluminum, mild steel and cast iron) were cooled in air. Equation (15) is regarded as the general model equation because it comprises of the HAZ hardness of all the materials considered for the model formulation. Based on the foregoing, the models in equations (8), (10) and (15) are valid and very useful for predicting HAZ hardness of aluminum, mild steel and cast iron weldments cooled in air depending on the material of interest and the given HAZ hardness values for the other materials.

Table 4: Comparison of the hardness of HAZ in aluminum, mild steel and cast iron weldments cooled in air as obtained from experiment and as predicted by derived model (each material as a function of 1- material).

N	Models derived	M_H	E_H	Dv (%)	Cf (%)
1	$\beta = 0.4466\gamma$	368.00	368.00	0	0
1	$\beta = 0.7813\alpha$	367.99	368.00	-0.0027	+0.0027
1	$\gamma = 1.7495\alpha$	824.01	824.00	+0.0012	-0.0012

Table 5: Comparison of the hardness of HAZ in aluminum, mild steel and cast iron weldments cooled in air as obtained from experiment and as predicted by derived model (each material as a function of 2-materials).

N	Models derived	M_H	E_H	Dv (%)	Cf (%)
2	$\beta = 1.2279\,[\gamma\alpha/(\alpha+\gamma)]$	367.99	368.00	-0.0015	+0.0015
2	$\gamma = [(1.2279/\beta - 1/\alpha)]^{-1}$	819.67	824.00	-0.0053	+0.0053
2	$\alpha = [(1.2279/\beta - 1/\gamma)]^{-1}$	469.48	471.00	-0.0032	+0.0032

Where N = No. of materials constituting the corresponding model as independent variables

3.3 Model Validation

The validity of the derived model, was tested by comparing the weldment HAZ hardness of the three materials as evaluated from experiment and derived model. Analysis and comparison between the model-predicted values β, γ, α and the respective corresponding experimental values β_{exp}, γ_{exp} and α_{exp} reveal deviations of model data from the experimental data. This is attributed to the non-consideration of the chemical properties of the coolant and the physiochemical interactions between the materials (aluminum, mild steel and cast iron) and the coolant which is believed to have played vital roles in modifying the microstructure of the HAZ during the coolant process. These deviations necessitated the introduction of correction factor to bring the model-predicted values to exactly that of the corresponding experimental values.

3.4 Deviational Analysis

A comparative analysis of HAZ Hardness from the experiment and derived model revealed very insignificant deviations on the part of the model-predicted values relative to values obtained from the experiment. This is attributed to the fact that the experimental process conditions which influenced the research results were not considered during the model formulation. This necessitated the introduction of correction factor, to bring the model-predicted HAZ hardness results to those of the corresponding experimental values.
Deviation (De) of model-predicted HAZ hardness from that of the experiment is given by

$$De = \left(\frac{P_H - E_H}{E_H}\right) \times 100 \quad (18)$$

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

$$Cf = -De \tag{19}$$

Therefore

$$Cf = -\left(\frac{P_H - E_H}{E_H}\right) \times 100 \tag{20}$$

Where

De = Deviation (%)

P_H = Model-predicted HAZ hardness (VHN)

E_H = HAZ hardness from experiment (VHN)

Cf = Correction factor (%)

Introduction of the corresponding values of Cf from equation (20) into the model gives exactly the corresponding experimental HAZ hardness.

Table 4 indicates clearly that the maximum deviation of model-predicted HAZ hardness (from experimental values) is less than 0.01 %. This is insignificant and very much within the acceptable range of deviation from experimental results. The evaluated maximum deviation translates to over 99.99 % operation confidence and reliability level for the derived models.

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

Conclusion

The heat affected zone hardness of aluminum weldment cooled in air has been implicitly analyzed as a function of the heat affected zone hardness of similarly cooled mild steel and cast iron weldments. The resultant empirical model derivation predicted the heat affected zone hardness (HAZH) of aluminium weldment based on the (HAZH) of similarly cooled mild steel and cast iron weldments. Evaluation of generated results shows that on re-arranging the model, the HAZH of mild steel and cast iron were also respectively predicted. The maximum deviation of the model-predicted HAZHs (from experimental values) was less than 0.01% indicating a model confidence and reliability level above 99.99% as well as a reliability coefficient of 0.9999.

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