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Response of Heat Affected Zone Hardness of Air Cooled Aluminium, Cast Iron and Mild Steel Weldments to the Welding Voltage

[1]C.I. Nwoye, [2]H.C. Otamiri, [3]T.G. Okafor, [4]M.K. Edojah and [5]I.C.C. Iloabachie

[1]Chemical Systems and Data Research Laboratory, Department of Metallurgical and
Materials Engineering, Nnamdi Azikiwe University, Awka, Nigeria
[2]Department of Mechanical Engineering Technology,
Akanu Ibiam Federal Polytechnic, Afikpo, Ebonyi, State, Nigeria
[3]Department of Mechanical Engineering Technology,
Federal Polytechnic, Oko, Anambra State, Nigeria
[4]Department of Mechanical Engineering,
Delta State Polytechnic, Otefe-Oghara, Delta State, Nigeria
[5]Department of Mechanical Engineering,
Institute of Management and Technology, Enugu, Enugu State, Nigeria

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Abstract: Response of heat affected zone hardness of air cooled aluminium, cast Iron and mild steel weldments to the welding voltage carried out. The materials were weldedusing the shielded metal arc technique and the HAZ hardness of their respective weldmentsevaluated following cooling in air. Three multi-factorial models were derived and used as empirical analytical tools for the predictive evaluation of the HAZ hardness resulting from mathematical input of welding voltage influence. The results of the evaluation indicate that the HAZ hardness of these weldments are significantly affected by the input welding voltage. On similarly cooling aluminium, cast iron and mild steel weldments in air followingwelding,the derivedmodel expressed as:

$$\vartheta_a = \left(\frac{\vartheta_m + \vartheta_c}{\vartheta_m + \vartheta_c} \left(\frac{\varepsilon_a \varepsilon_m + \varepsilon_a \varepsilon_c}{\varepsilon_c \ \varepsilon_m} \right)^{0.2197} \right)$$

evaluates aluminium weldment HAZ hardness by multiplying the computedgeneral voltage product rule (GVPR) $((\varepsilon_a\varepsilon_m+\varepsilon_a\varepsilon_c)/\varepsilon_c\varepsilon_m)^{0.2197}$ with the ratio; HAZ hardness product of cast iron and mild steel/ HAZ hardness sum of cast iron and mild steel $(\vartheta_m\vartheta_c /(\vartheta_m + \vartheta_m))$. Other derived models show that the weldment HAZ hardness of each of cast iron and mild steel relative to the others is significantly dependent on the GVPR which is a collective function of their respective welding voltages. The validity of the model was found to be rooted in the core model expression; $(\varepsilon_a / \varepsilon_c + \varepsilon_a / \varepsilon_m) = (\vartheta_a / \vartheta_c + \vartheta_a / \vartheta_m)$ where both sides of the expression are correspondingly equal.Comparative evaluationof results from experiment and derived model shows that aluminium weldment HAZ hardness per unit welding voltageare 1.3143 and 1.3142(VHN)V^{-1} respectively. Similarly, cast iron weldment HAZ hardness per unit welding voltage as evaluated from experiment and derived model are 3.7455 and 3.7463 (VHN) V^{-1} respectively. Furthermore, mild steel weldment HAZ hardness per unit welding voltage evaluated from experiment and derived model are 2.1409 and 2.1412 (VHN) V^{-1} respectively. The maximum deviation of model-predicted HAZ hardness from the experimental results is less than 0.03%, translating to over 99.97 % operation confidence level for the derived models.

Key words: Response · Heat affected zone hardness · Air cooled aluminium · Cast Iron and mild steel weldments · Welding voltage

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Corresponding Author: C.I. Nwoye, Chemical Systems and Data Research Laboratory, Department of Metallurgical and Materials Engineering, NnamdiAzikiwe University, Awka, Nigeria.

INTRODUCTION

The failure of metallic structures including tanks and pipelines, deduced to result from cracks at welded areas has seriously awakened the need to expedite intensive and extensive research and development in the areas of welding techniques, cooling rates, cooling media, fluxes and filler rods used with the aim ofimproving on the grain structures within the confines of weld beads and invariably ensuring durability of the associated structures during service delivery.

Successful welding of components at a low cost compared with replacement costs especially when the component is large and/or expensive is referred to as ultimate achievement of restoration.

Consideration and applicability of suitable welding procedures as well asfulfilling the metallurgical requirements have been found to be the first two vital factors for successful repairs [1, 2].

Research [3] carried out over the years has shown that restoration of worn-out industrial componentsis achievable by weld surfacing. The researcher reported that the wide range of consumables available for use with the many welding processes significantly require careful selection to suit a given working environment.

Report [4] has shown that a number of welding processvariables and applied operating conditions influence the toughness andcracking susceptibility of the HAZ in steel fusion weldsas well as themicrostructure which invariably affects hardness.It is therefore believed that the properties of a welded joint can only be significantly improved by improving the microstructure of the heat affected zone (HAZ).

Extensive studies [5] on the heat affected zone of a fusion weld insteel reveal three significant zones: supercritical, intercritical andsubcritical zones. The supercriticalregion further divides to givetwo regions: grain growth andgrain refinement. The properties of the weld joint are significantly influenced by the microstructure of the grain growthand grain refinement regions of the HAZ’s supercritical zone. Accurate prediction ofthe properties of this zone, requires the knowledge of the weld thermal cycle as well as the amount and extent of graingrowth. Heat input from the welding process is expected to be limited, so as to maintain a narrow width for the HAZ’s super critical zone. Furthermore, the supercritical zone undergoes considerable micro structural changes and reformation unlike the comparatively small and significantly negligible structural changes in the HAZ’s intercritical and subcritical zones. Similar studies [6] reported that these micro structural changes affect significantly the mechanical and metallurgical properties of the weldment. Based on the forgoing, thesize of the HAZ is evaluated as an indication of extentof structural changes.

Researchers [7-9] have carried out studies on HAZ hardness of weldments and models derived for predictive analysis of hardness of the heat affectedzone in aluminum, cast iron and mild steel weldmentssimilarly cooled in groundnut oil. The general model;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 modelevaluated the HAZ hardness of mild steel α, or cast iron γ respectively as in the case of aluminum.The respective deviations of the model-predicted HAZ hardness values β, γ and α from thecorresponding experimental values was less 0.02%.

Investigations [10, 11] on the studies of HAZ hardness of water cooled cast iron, aluminiumand mild steel weldmentscame up with quadratic and linear models which predicted HAZ hardness of each of the materials relative to other two. The validity of the quadratic model was rooted on the fractional expression; $\gamma/3.0749\theta + \gamma/3.0749\beta + \theta/3.0749\beta = 1$. Computational analysis of model-predicted results indicate that the respective deviations of the model-predictedheat-affected zone hardness values of aluminum, cast iron and mild steel from thecorresponding experimental values were less than 0.01% which is quite insignificant,indicating reliability of the model. Furthermore, the linear models predicted the HAZ hardness of cast iron weldment cooled in watergiven the values of the HAZ hardness of aluminum or/and mild steel welded and cooledunder the same conditions are known.

Similar research work [12], succeeded in predicting the HAZ hardness of aluminum, cast iron and mild steel weldments cooled in air. The quadratic and linear modelsderived were able to predict the HAZ hardness of air cooled cast iron weldment in relation to the combined and respectivevalues of HAZ hardness of aluminum and mild steel welded and cooled under the sameconditions. This is indeed similar to the previous model [10] except that the weldments in this case were cooled in air, while those of the previous model [10] were cooled in water. The general model predicted the HAZ hardness of cast iron weldment cooled in air as a function of the HAZhardness of both aluminum and mild steel welded and cooled under the same conditions. Thelinear models; $\theta = 2.2391\gamma$ and $\theta = 1.7495\beta$ on the other hand predict the

HAZ hardness ofcast iron weldment cooled in air as a function of the HAZ hardness of aluminum or mild steelwelded and cooled under the same conditions. The validity of the model isrooted on the fractional expression; $\gamma/2.9774\theta + \gamma/2.9774\beta + \theta/2.9774\beta = 1$ since the actual computational analysis of the expression was also equal to 1, apart from the fact that theexpression comprised the three metallic materials. The respective deviations of the model-predicted HAZ hardness values θ, γ and β from the corresponding experimental values θ_{exp}, γ_{exp} and β exp was less than 0.003%.

The present work aimed at reliability assessment of welding voltage dependence ofheat affected zone (HAZ) hardness inaluminium, cast iron and mild steel weldments cooled in air. Models will be derived and used as a tool for the predictive evaluation.

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 airtested. Ten other samples from each of the three materials were also welded, cooled in air and their respective HAZ hardness tested. The average HAZ hardness for the weldments of each of the three materials investigated are as presented in Table 2. 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

Table 2: Hardness of HAZ in weldments

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

RESULTS AND DISCUSSIONS

Table 1 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.

Model Formulation: Experimental data obtained from the highlighted research workwere used for this work. Computational analysis of these data shown in Tables 1 and 2, gave rise to Table 3 which indicate that;

$$\left(\frac{\varepsilon_a}{\varepsilon_c} + \frac{\varepsilon_a}{\varepsilon_m}\right) \approx \left(\frac{\vartheta_a}{\vartheta_c} + \frac{\vartheta_a}{\vartheta_m}\right)^N \tag{1}$$

Introducing the value of N into equation (1).

$$\left(\frac{\varepsilon_a}{\varepsilon_c} + \frac{\varepsilon_a}{\varepsilon_m}\right) \approx \left(\frac{\vartheta_a}{\vartheta_c} + \frac{\vartheta_a}{\vartheta_m}\right)^{4.5508} \tag{2}$$

$$\left(\frac{\varepsilon_a\varepsilon_m + \varepsilon_a\varepsilon_c}{\varepsilon_c\varepsilon_m}\right) = \left(\frac{\vartheta_a\vartheta_m + \vartheta_a\vartheta_c}{\vartheta_c\vartheta_m}\right)^{4.5508} \tag{3}$$

Dividing the indices of both sides of equation (3) by 4.5508;

$$\left(\frac{\varepsilon_a\varepsilon_m + \varepsilon_a\varepsilon_c}{\varepsilon_c\varepsilon_m}\right)^{1/4.5508} = \left(\frac{\vartheta_a\vartheta_m + \vartheta_a\vartheta_c}{\vartheta_c\vartheta_m}\right) \tag{4}$$

$$\left(\frac{\varepsilon_a\varepsilon_m + \varepsilon_a\varepsilon_c}{\varepsilon_c\varepsilon_m}\right)^{0.2197} = \left(\frac{\vartheta_a\vartheta_m + \vartheta_a\vartheta_c}{\vartheta_c\vartheta_m}\right) \tag{5}$$

$$\vartheta_a = \left(\frac{\vartheta_c\vartheta_m}{\vartheta_c + \vartheta_m}\left(\frac{\varepsilon_a\varepsilon_m + \varepsilon_a\varepsilon_c}{\varepsilon_c\varepsilon_m}\right)^{0.2197}\right) \tag{6}$$

Evaluating the value of ϑ_m from the derived model in equation (6) gives;

$$\vartheta_m = \vartheta_a\left(\left(\frac{\varepsilon_a\varepsilon_m + \varepsilon_a\varepsilon_c}{\varepsilon_c\varepsilon_m}\right)^{0.2197} - \frac{\vartheta_a}{\vartheta_c}\right)^{-1} \tag{7}$$

Similarly, from equation (7), ϑ_c is evaluated as;

$$\vartheta_c = \vartheta_a\left(\left(\frac{\varepsilon_a\varepsilon_m + \varepsilon_a\varepsilon_c}{\varepsilon_c\varepsilon_m}\right)^{0.2197} - \frac{\vartheta_a}{\vartheta_m}\right)^{-1} \tag{8}$$

The derived models are equations (6), (7) and (8)

where,

(ϑ_a) = HAZ hardness of aluninium weldment cooled in air (VHN)

(ϑ_c) = HAZ hardness of cast iron weldment cooled in air (VHN)

(ϑ_m) = HAZ hardness of mild steel weldment cooled in air (VHN)
N = 4.5508; equalizing constant (determined using C-NIKBRAN [13]
(ε_a) = Welding voltage for welding of aluninium (V)
(ε_c) = Welding voltage for welding of cast iron (V)
(ε_m) = Welding voltage for welding of mild steel (V)

Boundary and Initial Conditions: The welding process was carried out under atmospheric condition. Following the welding process, 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°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.

The derived models are equations (6), (7) and (8). Computational analysis of Tables 1 and 2 gave rise to Table 3. The precision andvalidity of the model is rooted on this table (Table 3).

It could be seen from equation (6) that on similarly cooling aluminium, cast iron and mild steel in air following welding, the HAZ hardness in aluminium weldment is evaluated by multiplying the ratio of HAZ hardness product of cast iron and mild steel to their HAZ hardness sum with the general voltage product rule (GVPR) (involving aluminium, cast iron and mild steel). This implies that $((\varepsilon_a\varepsilon_m + \varepsilon_a\varepsilon_c)/\varepsilon_c\varepsilon_m)^{0.2197}$ is the general current product rule and acts as multiplying factor to $\vartheta_c\vartheta_m/(\vartheta_c + \vartheta_m)$. Equations (7) and (8) also evaluate the HAZ hardness of mild steel and cast iron based on the GVPR. Based on the foregoing, the weldment HAZ hardness of each of the three materials relative to the others is significantly dependent on the GVPR which is a collective function of their respective welding voltages. The highlighted analysis therefore shows that the HAZ hardness of weldments is significantly affected by the input welding voltage.

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. This was done using computational and deviational analysis. The validity of the model was found to be rooted in equation (2) (core of the model) where both sides of the equation are correspondingly equal.

Table 3: Variation of $(\varepsilon_a/\ \varepsilon_c + \varepsilon_a/\ \varepsilon_m)$ with $(\vartheta_a / \vartheta_c + \vartheta_a / \vartheta_m)^{4.5508}$

$\varepsilon_a/\varepsilon_c + \varepsilon_a/\ \varepsilon_m$	$(\vartheta_a / \vartheta_c + \vartheta_a / \vartheta_m)^{4.5508}$
2.5454	2.5454

Table 3 also agrees with equation (2) following the values of $(\varepsilon_a/\ \varepsilon_c + \varepsilon_a/\ \varepsilon_m)$ and $(\vartheta_a / \vartheta_c + \vartheta_a / \vartheta_m)^{4.5508}$ evaluated from the experimental results in Tables 1 and 2.

Computational Analysis: A comparative computational analysis of the experimental and model-predicted weldment HAZ hardness per unit welding voltage were carried outfor the three materials to ascertain the degree of validity of the derived model. These were evaluated from calculations involving experimental results and derived model.

Aluminium HAZ hardness per unit welding voltage ϑ_a^V; was calculated from the equation;

$$\vartheta_a^v = \vartheta_a / V \tag{9}$$

Dividing the HAZ hardness of aluminium weldment; 368 VHN (as shown in Table 2) with the input welding voltage V; 280 V gives the HAZ hardness per unit welding voltage as 1.3143 (VHN) V^{-1}. This is the experimentally obtained aluminium weldment HAZ hardness per unit welding voltage. Also, dividing the model-predicted HAZ hardness of aluminium weldment; 367.9789 VHN with the input welding voltage; 280V, the model-predicted aluminiumHAZ hardness per unit welding voltage is given as 1.3142 (VHN) V^{-1}.

Cast iron HAZ hardness per unit welding voltage; ϑ_c^V; was calculated from the equation;

$$\vartheta_c^v = \vartheta_c / V \tag{10}$$

On dividing the HAZ hardness of cast iron weldment; 824 VHN (as shown in Table 2) with the input welding voltage; 220 V gives the HAZ hardness per unit welding voltage as 3.7455 (VHN) V^{-1}. This is the experimentally obtained cast iron weldment HAZ hardness per unit welding voltage.

Furthermore, dividing the model-predicted HAZ hardnessof cast iron weldment; 824.1881 VHN with the input welding voltage; 220 V gives 3.7463 (VHN) V^{-1}as the model-predicted cast iron HAZ hardness per unit welding voltage.

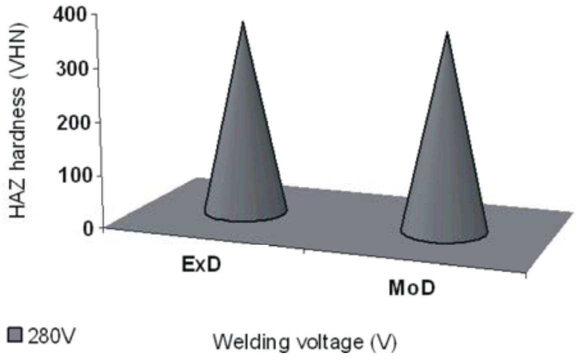

Fig. 1: Comparison of aluminium HAZ hardness of weldments as obtained from experiment and derived model

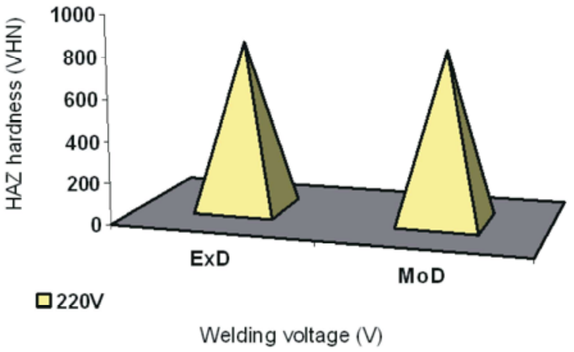

Fig. 2: Comparison of cast iron HAZ hardness of weldments as obtained from experiment and derived model

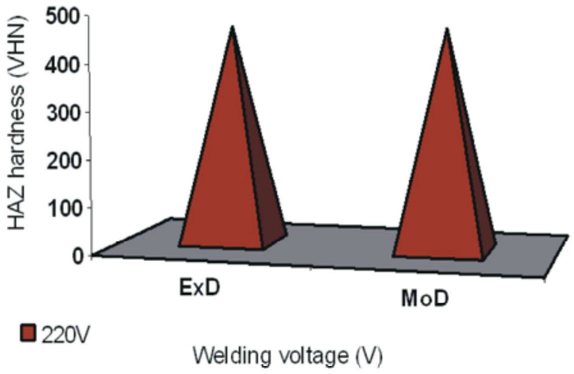

Fig. 3: Comparison of mild steel HAZ hardness of weldments as obtained from experiment and derived model

Mild steel HAZ hardness per unit welding voltage ϑ_m^V; was calculated from the equation;

$$\vartheta_m^V = \vartheta_m / V \tag{11}$$

Dividing the HAZ hardness of mild steel weldment; 471 VHN (as shown in Table 2) with the input welding voltage; 220 V gives 2.1409 (VHN) V^{-1} as the HAZ hardness per unit welding voltage as obtained from experiment. Similarly, dividing the model-predicted HAZ hardness of mild steel weldment; 471.0701 VHN with the input welding voltage; 220 V gives 2.1412 (VHN) V^{-1} as the model-predicted mild steel HAZ hardness per unit welding voltage.

An analysis of Figs. 1-3 shows proximate agreement between HAZ hardness as evaluated from experiment and derived model. A comparison of these three corresponding sets of HAZ hardness values per unit welding voltageshows proximate agreement and invariably a high degree of validity for the derived model.

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 experimentis given by;

$$De = \left(\frac{P_H - E_H}{E_H}\right) \times 100 \tag{12}$$

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

$$\text{Cf} = -\text{ De} \tag{13}$$

Therefore,

$$Cf = -\left(\frac{P_H - E_H}{E_H}\right) \times 100 \tag{14}$$

where,

De = Deviation (%)

P_H = Model-predicted HAZ hardness (VHN)

E_H = HAZ hardness from experiment (VHN)

Cf = Correction factor (%)

Table 4: Variations of model predicted HAZ hardness with deviations and correction factors

Material	MoD	Dv (%)	Cf (%)
Aluminium	367.9789	-0.0057	+0.0057
Cast Iron	824.1881	+0.0228	-0.0228
Mild Steel	471.0701	+0.0149	-0.0149

Introduction of the corresponding values of *Cf* from equation (14) into the model gives exactly the corresponding experimental HAZ hardness.

Table 4 indicates that the maximum deviation of model-predicted HAZ hardness (from experimental values) is less than 0.03 %. This is insignificant and very much within the acceptable range of deviation from experimental results.The evaluated maximum deviation translates to over 99.97 % operation confidence 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).

CONCLUSIONS

Response of heat affected zone hardness of air cooled aluminium, cast Iron and mild steel weldments to the welding voltage was carried out. The three multi-factorial models derived gave a predictive evaluation of the HAZ hardness resulting from welding voltage input. The results of the evaluation indicate that the HAZ hardness of these weldments is significantly affected by the input welding voltage. On similarly cooling aluminium, cast iron and mild steel weldments in air following welding, the derived model evaluates aluminium weldment HAZ hardness by multiplying the computed general voltage product rule (GVPR) $((\varepsilon_a\varepsilon_m+\varepsilon_a\varepsilon_c)/\varepsilon_c\varepsilon_m)^{0.2197}$ with the ratio; HAZ hardness product of cast iron and mild steel/ HAZ hardness sum of cast iron and mild steel $(\vartheta_m\vartheta_c/(\vartheta_m+\vartheta_m))$. Other derived models show that the weldment HAZ hardness of each of cast iron and mild steel relative to the others is significantly dependent on the GVPR which is a collective function of their respective welding voltages. Comparative evaluation of results from experiment and derived model shows that aluminium weldment HAZ hardness per unit welding voltage are 1.3143 and 1.3142 (VHN)V^{-1} respectively. Similarly, cast iron weldment HAZ hardness per unit welding voltage as evaluated from experiment and derived model are 3.7455 and 3.7463 (VHN) V^{-1} respectively. Furthermore, mild steel weldment HAZ hardness per unit welding voltage evaluated from experiment and derived model are 2.1409 and 2.1412 (VHN) V^{-1} respectively. The maximum deviation of model-predicted HAZ hardness from the experimental results is less than 0.03%, translating to over 99.97 % operation confidence level for the derived models.

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