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Response of Weldment Heat Affected Zone Hardness to the Operational Welding Current Resistance

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Abstract This paper presents the welding of selected engineering materials: aluminium, mild steel and cast iron using the shielded metal arc technique and evaluation of the heat affected zone (HAZ) hardness of their respective weldments similarly cooled in palm oil. The weldment HAZ hardness for aluminium, mild steel and cast iron were 407, 503 and 870 VPN respectively. Three models were derived, validated and used for evaluating the dependency of HAZ hardness of the materials on the welding current resistance. The results of the analyses clearly revealed that the HAZ hardness of these weldments are significantly affected by the resistance to the welding current flow. It was discovered that on welding aluminium, cast iron and mild steel, and similarly cooling their respective weldments in palm oil, the model; $\varepsilon_a = 1000\,ƅ^{9.6831}\,(\varepsilon_c\,\varepsilon_m)^{-1}$ predicts aluminium weldment HAZ hardness by multiplying a thousand of the evaluated Welding Current Resistance Product Rule (WCRPR); $(R_a\,R_cR_m)^{9.6831}$ or Welding Current Resistance Equivalent (WCRE); $ƅ^{9.6831}$ with reciprocal of the product of cast iron and mild steel weldment HAZ hardness $(\varepsilon_c\,\varepsilon_m)^{-1}$. Other derived models reveal that the HAZ hardness of weldments of each of cast iron and mild steel relative to the others is also significantly dependent on the WCRPR or WCRE which is the resultant operational input of their respective welding current resistance. The validity of the model was found to be rooted in the core model expression; $0.001(\varepsilon_a\,\varepsilon_c\,\varepsilon_m) = (R_a\,R_c\,R_m)^{9.6831}$ where both sides of the core model expression are correspondingly equal. Computational analysis of experimental and model predicted results indicate that aluminium, cast iron and mild steel weldment HAZ hardness per unit welding current resistance as evaluated from experiment and derived model are 174.431 & 174.433, 711.831 & 711.839 and 411.553 & 411.557 (VHN) Ω^{-1} respectively. Deviational analysis shows that the maximum deviation of model-predicted HAZ hardness from the experimental results is less than 0.0012%. This invariably implies over 99.99 % confidence level for the derived models as well as over 0.99 reliability response coefficients of aluminum, cast iron and mild steel weldment HAZ hardness to the operational influence of welding current resistance.

Keywords: *response, heat affected zone hardness, aluminum, mild steel, cast iron weldment, welding current resistance, palm oil cooling*

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1. Introduction

Abrupt catastrophic failures of steel and alloy structures in industrial plants and at different service environments has raised the need for intensive studies aimed at improving the corrosion resistance and durability of welded joints serving at different environment as well as withstanding loads from various sources. This stems from the fact that most structural failures in steel and allied alloys start with crack formation at the welded joint, followed by crack coalesces, crack propagation before failure.

In any welding process, the heating and cooling cycle of the weld zone leads to considerable changes in the microstructure of the weldment. This depends directly on the welding process and techniques employed. Therefore, it is only by improving the microstructure of the HAZ that the properties of a welded joint be improved.

Studies [1] have indicated that a number of welding process variables and operating conditions influence the characteristics of the microstructure, and, therefore affects hardness, toughness, and cracking susceptibility of the HAZ in steel fusion welds.

Research [2] has classified the heat affected zone of a fusion weld in steel into three zones: supercritical, intercritical, and subcritical. The supercritical region may, in turn, be divided into two regions - grain growth and grain refinement. The research indicated that the properties of the weld joint are largely influenced by the microstructure of the grain growth and grain refinement regions of the HAZ's supercritical zone. Accurate prediction of the properties of this zone requires knowledge of the amount and extent of grain growth as well as the weld thermal cycle. Therefore, it is expected that the heat input from the welding process must be limited so as to ascribe and maintain a narrow width for the HAZ's supercritical zone. Comparative analysis of these HAZ zones by the researcher [2] shows that the supercritical zone undergoes more significant microstructural changes compared to small, negligible, structural changes in the HAZ's intercritical and subcritical zones. These microstructural changes affect the mechanical and metallurgical properties of the weldment [3]. Therefore, the size of the HAZ is an indication of the extent of structural changes.

Some researchers [4] have reported that achievement of a good control of heat affected zone (HAZ) dimensions, getting the required bead size and quality requires a selection of appropriate values for process variables. The scientists opined that experimental conditions must be selected, such that weld bead would not only be predictable but also reproducible. This ensures a high quality level.

Mathematical models have been developed [4] to study the effects of process variables and heat input on various metallurgical aspects, namely, the widths of the HAZ, weld interface, and grain growth and grain refinement regions of the HAZ. The color metallography technique and response surface methodology were also used. Direct and interaction effects of the process variables and heat input on the characteristics of the HAZ were presented in graphical forms.

Results of the study reveal that the heat input and wire feed rate have a positive effect, but welding speed has a negative effect on all HAZ characteristics. The width of grain growth and grain refinement zones increased and weld interface decreased with an increase in arc voltage. Also the width of HAZ is maximum (about 2.2 mm) when wire feed rate and welding speed are at their minimum limits.

Earlier mathematical models [5] found application in selecting correct process variables for achieving the desired weld bead HAZ characteristics and mechanical properties and in predicting HAZ dimensions for the given process variables. These models also helped to improve understanding of the effect of process parameters on bead quality, for quantitative evaluation of the interaction effects of process variables on HAZ characteristics, and 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

Empirical models [7-12] have been derived for predictive analysis of the HAZ hardness of the weldments in selected engineering materials; mild steel, cast iron and aluminum. The materials used were welded using Shielded Metal Are Welding (SMAW) technique and similarly cooled (for each research) in palm oil, air, water and groundnut oil. Each of these models recorded a maximum deviation less than 0.5%. These are deviations of model-predicted weldment HAZ hardness values from the corresponding experimental values.

The present work aims at establishing the dependence of heat affected zone hardness of palm oil cooled aluminium, cast iron and mild steel weldments on welding current resistance.

2. 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 was selected as the cooling medium because it confers greater hardness than air [5]. 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 three materials were welded, similarly cooled in palm oil and their respective weldment HAZ hardness tested. The average HAZ hardness for the weldments of each of the three materials investigated were evaluated and 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	W/CR
Aluminium	D.C	120	280	2.3333
Cast Iron	A.C	180	220	1.2222
Mild Steel	A.C	180	220	1.2222

2.1. Model Formulation

Experimental data generated from the highlighted research work were used for the model formulation. Computational analysis of these data shown in Table 1, gave rise to Table 2 which indicate that;

$$\mathrm{K}\left(\varepsilon_{\mathrm{a}}\varepsilon_{\mathrm{c}}\varepsilon_{\mathrm{m}}\right)=\left(\frac{V_a}{I_a}\times\frac{V_c}{I_c}\times\frac{V_m}{I_m}\right) \tag{1}$$

Electrical resistance to current flow is given by a relationship:

$$R=\left(\frac{V}{I}\right) \tag{2}$$

Therefore equation (1) reduces to

$$\mathrm{K}\left(\varepsilon_{\mathrm{a}}\varepsilon_{\mathrm{c}}\varepsilon_{\mathrm{m}}\right)=\left(\mathrm{R_a R_c R_m}\right)^{\mathrm{N}} \tag{3}$$

Introducing the values of K and N into equation (3), reduces it to

$$0.001\left(\varepsilon_{\mathrm{a}}\varepsilon_{\mathrm{c}}\varepsilon_{\mathrm{m}}\right)=\left(\mathrm{R_a R_c R_m}\right)^{9.6831} \tag{4}$$

$$\left(\varepsilon_{\mathrm{a}}\varepsilon_{\mathrm{c}}\varepsilon_{\mathrm{m}}\right)=1000\left(\mathrm{R_a R_c R_m}\right)^{9.6831} \tag{5}$$

From equation (5), $R_aR_cR_m$ is precisely expressed as ƅ to be referred to as Conjugated Welding Current

Resistance Product (CWCRP). This is because ƅ involves all the respective electrical resistances to welding current flow during welding of the selected materials. Based on the forgoing,

$$\text{ƅ} = R_a\, R_c\, R_m \qquad (6)$$

Substituting equation (6) in equation (5) reduces it to:

$$(\varepsilon_a\, \varepsilon_c\, \varepsilon_m) = 1000\ \text{ƅ}^{9.6831} \qquad (7)$$

$$\varepsilon_a = 1000\ \text{ƅ}^{9.6831}\ (\varepsilon_c\, \varepsilon_m)^{-1} \qquad (8)$$

On re-arranging equation (8), the HAZ hardness of cast iron ε_c and mild steel ε_m are similarly evaluated as:

$$\varepsilon_c = 1000\ \text{ƅ}^{9.6831}\ (\varepsilon_a\, \varepsilon_m)^{-1} \qquad (9)$$

and

$$\varepsilon_m = 1000\ \text{ƅ}^{9.6831}\ (\varepsilon_a\, \varepsilon_c)^{-1} \qquad (10)$$

Where
(ε_c) = HAZ hardness of aluminium weldment cooled in palm oil (VHN)
(ε_c) = HAZ hardness of cast iron weldment cooled in palm oil (VHN)
(ε_c) = HAZ hardness of mild steel weldment cooled in palm oil (VHN)
(R_a)= Welding current resistance during welding of aluminium (Ω)
(R_c) = Welding current resistance during welding of cast iron (Ω)
(R_m)= Welding current resistance during welding of mild steel (Ω)
V = Welding voltage (V)
I = Welding current (A)
K = 0.001; N = 9.6831. These are equalizing constants (determined using C-NIKBRAN [12]).

The derived models are equations (8), (9) and (10)

2.2. 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 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.

3. Results and Discussions

Table 2 shows the variation of materials with the input welding current type (C/Type), welding current (W/C), voltage (W/V) and current resistance (W/CR). The result of hardness of the HAZ obtained from aluminium, cast iron and mild steel weldments similarly cooled in palm oil (as presented in Table 2) shows that the weldment HAZ hardness for aluminium, mild steel and cast iron were 407, 503 and 870 VPN respectively.

Computational analysis of results in the 3rd and 4th column of Table 1 as well as 2nd column of Table 2 gave rise to Table 3. It is strongly believed that the precision and validity of the model is rooted on this table (Table 3).

Table 2. Hardness of HAZ in weldments

Material	HAZ Hardness (VHN)
Aluminium	407
Cast Iron	870
Mild Steel	503

Table 3. Variation of with 0.001$(\varepsilon_a\, \varepsilon_c\, \varepsilon_m)$ with $(R_a\, R_c\, R_m)^{9.6831}$

0.001$(\varepsilon_a\, \varepsilon_c\, \varepsilon_m)$	$(R_a\, R_c\, R_m)^{9.6831}$
178107.27	178109.22

Following welding of aluminium, cast iron as well as mild steel and similarly, cooling their respective weldments in palm oil, the HAZ hardness of aluminium weldment was evaluated (using equation (8)) by multiplying a thousand of the evaluated Welding Current Resistance Product Rule (WCRPR); $(R_aR_cR_m)^{9.6831}$ or Welding Current Resistance Equivalent (WCRE); $\text{ƅ}^{9.6831}$ with reciprocal of the product of cast iron and mild steel weldments HAZ hardness; $(\varepsilon_c\, \varepsilon_m)^{-1}$. Other derived models in equations (9) and (10) also evaluate the HAZ hardness of cast iron and mild steel respectively based on the WCRPR or WCRE. This implies that the HAZ hardness of weldments of each of the materials relative to the two others is significantly dependent on the WCRPR or WCRE which is the resultant operational input of their respective welding current resistance.

3.1. Model Validation

The validity of the derived model was tested through precise computational and deviational analysis of both the experimental and model-predicted results. This was actually done by carefully comparing results evaluated from the weldment HAZ hardness of the three materials as evaluated from experiment and derived model. The validity of the model was found to be rooted in equation (4) (core of the model) where both sides of the equation are correspondingly equal. Table 3 also agrees with equation (4) following the values of 0.001$(\varepsilon_a\, \varepsilon_c\, \varepsilon_m)$ and $(R_a\, R_c\, R_m)^{9.6831}$ evaluated from the experimental results in Table 1 and Table 2.

3.2. Computational Analysis

Computational analysis of the experimental and model-predicted weldment HAZ hardness per unit welding current resistance were carried out for the three materials to ascertain the degree of validity of the derived model. These were evaluated from calculations involving experimental results, and derived model.

3.3. Aluminium HAZ Hardness Per Unit Welding Current Resistance

Aluminium HAZ hardness per unit welding current resistance $\varepsilon_R{}^A$; was calculated from the equation;

$$\varepsilon_R{}^A = \varepsilon_a / R_a \qquad (11)$$

Dividing the HAZ hardness of aluminium weldment; 407 VHN (as shown in Table 2) with the welding current resistance; 2.3333Ω gives the HAZ hardness per unit welding current resistance as 174.431 (VHN) Ω^{-1}. This is the experimentally obtained aluminium weldment HAZ hardness per unit welding current resistance.

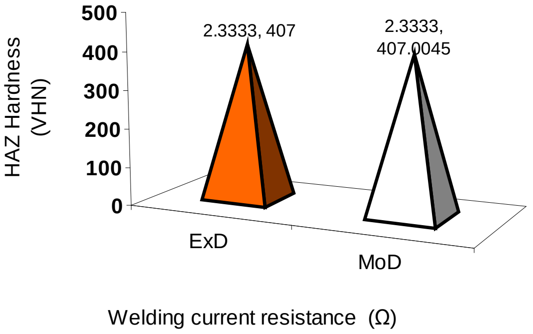

Figure 1. Comparison of aluminium HAZ hardness of weldments as obtained from experiment and derived model

Also, dividing the model-predicted HAZ hardness of aluminium weldment; 406.0045 VHN with the welding current resistance; 2.3333 Ω, the model-predicted aluminium HAZ hardness per unit welding current resistance is given as 174.433 (VHN) Ω^{-1}.

3.4. Cast iron HAZ Hardness Per Unit Welding Current Resistance

Cast iron HAZ hardness per unit welding current resistance $\varepsilon_R{}^C$; was calculated from the equation;

$$\varepsilon_R{}^C = \varepsilon_c / R_c \tag{12}$$

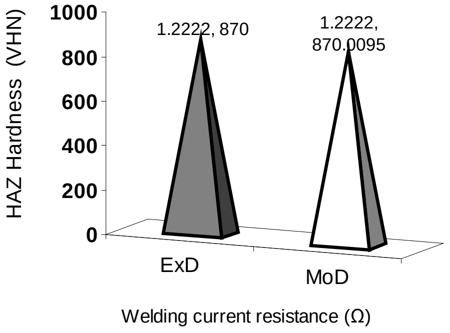

Figure 2. Comparison of cast iron HAZ hardness of weldments as obtained from experiment and derived model

On dividing the HAZ hardness of cast iron weldment; 870 VHN (as shown in Table 2) with the welding current resistance; 1.2222 Ω gives the HAZ hardness per unit welding current resistance as 711.831 (VHN) Ω^{-1}. This is the experimentally obtained cast iron weldment HAZ hardness per unit welding current resistance.

Furthermore, dividing the model-predicted HAZ hardness of cast iron weldment; 870.0095 VHN with the welding current resistance; 1.2222 Ω gives 711.839 (VHN) Ω^{-1} as the model-predicted cast iron HAZ hardness per unit welding current resistance.

3.5. Mild Steel HAZ Hardness Per Unit Welding Current Resiatance

Mild steel HAZ hardness per unit welding current resistance $\varepsilon_R{}^M$; was calculated from the equation;

$$\varepsilon_R{}^M = \varepsilon_m / R_m \tag{13}$$

Dividing the HAZ hardness of mild steel weldment; 503 VHN (as shown in Table 2) with the welding current resistance; 1.2222 Ω gives 411.553 (VHN) Ω^{-1} as the HAZ hardness per unit welding current resistance as obtained from experiment.

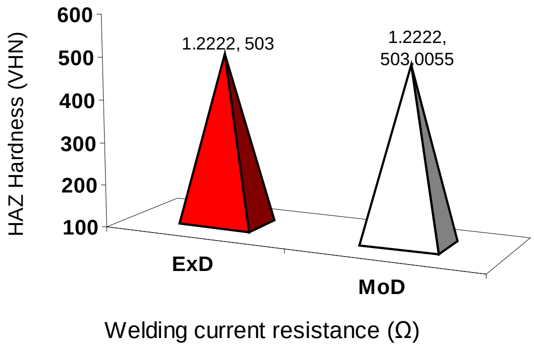

Figure 3. Comparison of mild steel HAZ hardness of weldments as obtained from experiment and derived model

Similarly, dividing the model-predicted HAZ hardness of mild steel weldment; 503.0055 VHN with the welding current resistance; 1.2222 Ω gives 411.557 (VHN) Ω^{-1} as the model-predicted mild steel HAZ hardness per unit welding current resistance.

Figure 1-Figure 3 show proximate agreement between three corresponding sets of HAZ hardness values (for alumunium, cast iron and mild steel weldments) per unit welding current resistance as evaluated from experiment and derived model, indicating a high degree of validity for the derived model.

3.6. Deviational Analysis

Comparative analysis of weldment 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 was 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 (Dv) of model-predicted HAZ hardness from that of the experiment is given by

$$\mathrm{Dv} = \frac{\varepsilon_p - \varepsilon_{ex}}{\varepsilon_{ex}} \times 100 \tag{14}$$

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

$$\mathrm{Cr} = -\mathrm{Dv} \tag{15}$$

Therefore

$$\mathrm{Cr} = -\left(\frac{\varepsilon_p - \varepsilon_{ex}}{\varepsilon_{ex}}\right) \times 100 \tag{16}$$

Where

Dv = Deviation (%)

ε_p = Model-predicted HAZ hardness (VHN)

ε_{ex} = HAZ hardness from experiment (VHN)

Cr = Correction factor (%)

It is strongly believed that on introduction of the values of Cr from equation (16) into the model, exact corresponding experimental HAZ hardness would be obtained.

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

Material	MoD	Dv (%)	Cr (%)
Aluminium	407.0045	+0.0011	-0.0011
Cast Iron	870.0095	+0.0011	-0.0011
Mild Steel	503.0055	+0.0011	-0.0011

Deviational analysis of Table 4 indicates clearly that the maximum deviation of model-predicted HAZ hardness (from experimental values) is less than 0.0012 %. This is insignificant and very much within the acceptable range of deviation from experimental results. This invariably implies over 99.99 % confidence level for the derived models as well as over 0.99 reliability response coefficients of aluminum, cast iron and mild steel weldment HAZ hardness to the operational influence of welding current resistance.

It is pertinent 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).

4. Conclusions

The HAZ hardness of aluminum, mild steel and cast iron weldments are significantly affected by the electrical resistance to the welding current flow during the welding process. The weldment HAZ hardness for aluminium, mild steel and cast iron were 407, 503 and 870 VPN respectively. The derived model predicts aluminium weldment HAZ hardness by multiplying a thousand of the evaluated Welding Current Resistance Product Rule (WCRPR); $(R_a \ R_c \ R_m)^{9.6831}$ or the Welding Current Resistance Equivalent (WCRE); $ƀ^{9.6831}$ with reciprocal of the product of cast iron and mild steel weldment HAZ hardness $(\varepsilon_c \varepsilon_m)^{-1}$. Similarly, the HAZ hardness of each of cast iron and mild steel weldment relative to the others is also significantly dependent on the WCRPR or WCRE which is the resultant operational input of their respective welding current resistance. The validity of the model was found to be rooted in the core model expression; $0.001(\varepsilon_a \varepsilon_c \varepsilon_m) = (R_a \ R_c \ R_m)^{9.6831}$ where both sides of the core model expression are correspondingly equal. Computational analysis of experimental and model predicted results indicate that aluminium, cast iron and mild steel weldment HAZ hardness per unit welding current resistance as evaluated from experiment and derived model are 174.431 & 174.433, 711.831 & 711.839 and 411.553 & 411.557 (VHN) Ω^{-1} respectively. Deviational analysis shows that the maximum deviation of model-predicted HAZ hardness from the experimental results is less than 0.0012%. This invariably implies over 99.99 % confidence level for the derived models as well as over 0.99 reliability response coefficients of aluminum, cast iron and mild steel weldment HAZ hardness to the operational influence of welding current resistance.

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