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# Models for assessment and prediction of the hardness of the heat affected zone in aluminum weldment cooled in groundnut oil in relation to similarly cooled mild steel and cast iron weldments

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**Abstract**

Models have been derived for assessing and predicting the heat affected zone hardness of aluminum weldment cooled in groundnut oil in relation to the respective and combined values of HAZ hardness of mild steel and cast iron welded and cooled under the same conditions have been derived. The derived single models; $\beta = 0.4478\gamma$, $\beta = 0.8031\alpha$, and $\gamma = 1.7934\alpha$ as well as general model; $\beta = 1.2509[(\gamma\alpha/\gamma + \alpha)]$ were found to predict the HAZ hardness of aluminum weldment cooled in groundnut oil as a function of the HAZ hardness of mild steel or cast iron welded and cooled under the same conditions. The maximum deviation of the model-predicted HAZ hardness values β, γ and α from the corresponding experimental values $\beta_{exp}$, $\gamma_{exp}$ and $\alpha_{exp}$ was less 0.02% indicating the reliability and validity of the model.

*Keywords:* Model; hardness; heat affected zone; aluminum weldments; mild steel; cast iron

## 1. Introduction

Weldment cracking has been reported (Nnuka, 2008) as one of the reasons for low mechanical properties such as hardness and impact strength in welded parts. Heat affected zone (HAZ) is the adjacent to the immediate welded area or fusion zone. The mechanical property of main importance in HAZ is the hardness since it gives an indication of the degree of embrittlement. Studies by Lancaster (1987) show that the heat affected zone hardness produced by any given welding operation depends on the cooling rate experienced by the HAZ. Rapid cooling results to the formation of hard and brittle martensite in all the sub zones of the HAZ or increase in the martensite region in size relative to the other regions. The presence of martensite in the HAZ results in a very high hardness value for the heat affected zone. Slow cooling favours a better microstructure needed for engineering applications. Moreso, the more rapid the quenching rate, the greater the HAZ hardness.

The hardness of HAZ in aluminum, cast iron and mild steel cooled in kerosine was found to be exactly the same as the hardness value of the same materials cooled in groundnut oil (Nwoye, 2008). This implies that

$$H_G = H_K \qquad (1)$$

Nwoye (2008) reported that 8-10% less hardness than that from water occurs when kerosine or groundnut oil is used as quenchant for HAZ. He discovered that quenching the HAZ with kerosine or groundnut oil gives approximately 8-10.7% more hardness than that from quenching with air. He found that palm oil gave the lowest hardness and cooling rate on the HAZ.

Model for predictive analysis of hardness of the heat affected zone in aluminum weldment cooled in groundnut oil has been derived (Nwoye et al., 2009). The general model;

$$\beta = 0.5997\sqrt{(\gamma\alpha)} \qquad (2)$$

is dependent on the hardness of the heat affected zone (HAZ) in mild steel and cast iron weldments cooled in same media. Furthermore, re-arrangement of these models could be done to evaluate the HAZ hardness of mild steel or cast iron respectively as in the case of aluminum. The respective deviations of the model-predicted HAZ hardness values β, γ and α from the corresponding experimental values was less 0.02% indicating the reliability and validity of the model.

(Nwoye (2009a) derived quadratic and linear models for predicting the heat-affected zone (HAZ) hardness of water cooled cast iron weldment 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 model;

$$\theta = \left(\frac{3.0749}{2} - \gamma\right) + \sqrt{\gamma - \left(\frac{3.0749\beta^2}{2}\right)} - \gamma\beta \quad (3)$$

was found to be the solution to a quadratic equation; $\gamma\beta + \gamma\theta + \theta^2 = 3.07490\beta$

Where

$\gamma$ = Model-predicted hardness of HAZ in aluminum weldment cooled in water (VPN).

$\beta$ = Model-predicted hardness of HAZ in mild steel weldment cooled in water (VPN).

$\theta$ = Model-predicted hardness of HAZ in cast iron weldment cooled in water (VPN).

It was found that the validity of the model is rooted on the fractional expression; $\gamma/3.07490 + \gamma/3.0749\beta + \theta/3.0749\beta = 1$. 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.

Similarly attempt has been made (Nwoye,2009b) to derive quadratic and linear models 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. It was discovered that the general model;

$$\theta = [2.9774\beta - \gamma]/2 + \sqrt{[((\gamma - 2.9774\beta)/2)^2 - \gamma\beta]} \quad (4)$$

predicts 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; $\theta = 2.2391\gamma$ and $\theta = 1.7495\beta$ 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. Re-arrangement of the general model also resulted to the evaluation of the corresponding HAZ hardness in aluminum and mild steel weldments. It was found that the validity of the model is rooted on the fractional expression; $\gamma/2.97740 + \gamma/2.9774\beta + \theta/2.9774\beta = 1$ since the actual computational analysis of the expression was also equal to 1, apart from the fact that the expression comprised the three metallic materials. The respective deviations of the model-predicted HAZ hardness values $\theta$, $\gamma$, and $\beta$ from the corresponding experimental values $\theta_{exp}$, $\gamma_{exp}$, and $\beta_{exp}$ was less than 0.003% indicating the validity and reliability of the model.

The present study aims at deriving models for assessing and predicting hardness of the heat affected zone (HAZ) in cast iron weldment cooled in groundnut oil, as a function of the respective and combined values of HAZ hardness of aluminum and mild steel welded and cooled under the same conditions.

## 2. Materials and methods

Aluminum, mild steel and cast iron were cut and welded using the shielded metal arc welding technique and the hardness of the HAZ (cooled in groundnut oil maintained at room temperature) tested. The hardness of the HAZ is as presented in Table 2. The full details of the experimental procedures and equipment used are presented in the previous report (Nwoye, 2008). Table 1 shows the welding current and voltage used.

## 3. Model formulation

Experimental data obtained from research work (Nwoye,2008) carried out at Metallurgical and Materials Engineering Department of Federal University of Technology, Owerri were used for this work. Results of the experiment as presented in the report (Nwoye, 2008) and used for the model formulation are as shown in Table 2. Computational analysis of the experimental data (Nwoye, 2008) shown in Table 2 resulted in Table 3.

Table 3 shows that the hardness of HAZ in aluminum weldment cooled in groundnut oil is a function of the hardness of HAZ in cast iron and mild steel weldment also cooled in groundnut oil. Therefore,

$$\beta = 0.4478\gamma \quad (5)$$

$$\beta = 0.8031\alpha \quad (6)$$

$$\gamma = 1.7934\alpha \quad (7)$$

Adding eqns. (5) and (6) as arranged in Table 2;

$$\frac{\beta}{\gamma} + \frac{\beta}{\alpha} = 0.4478 + 0.8031 \quad (8)$$

$$\frac{\alpha\beta + \gamma\beta}{\gamma} = 1.2509 \quad (9)$$

$$\alpha\beta + \gamma\beta = 1.2509\gamma\alpha \quad (10)$$

$$\beta(\alpha + \gamma) = 1.2509\gamma\alpha \quad (11)$$

$$\beta = 1.2509\left(\frac{\gamma\alpha}{\gamma + \alpha}\right) \quad (12)$$

The derived model (general model) is equation (12).

## 4. Boundary and initial conditions

The welding was carried out under atmospheric condition. After welding, weldments were also maintained under atmospheric condition. Welding current and voltage used are 180A and 220V respectively. $SiO_2$-coated electrodes were used to avoid oxidation of weld spots. The coolants used were maintained at $25^0$C (room temperature). Volume of coolants used; $1000cm^3$. 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.

## 5. Model validation

The derived model was validated by evaluating the model-predicted values of HAZ hardness in aluminum weldment cooled in groundnut oil β and comparing them with the corresponding values obtained from the experiment $\beta_{exp}$ (Nwoye,2008). Following re-arrangement of the model equation; (12), the values of γ and α were also evaluated as;

$$\gamma = \left( \frac{1.2509}{\beta} - \frac{1}{\alpha} \right)^{-1} \tag{13}$$

$$\alpha = \left( \frac{1.2509}{\beta} - \frac{1}{\gamma} \right)^{-1} \tag{14}$$

and compared with their respective corresponding experimental values $\gamma_{exp}$ and $\alpha_{exp}$ to further establish the validity of the model. The model-predicted values of β, γ and α are shown in Table 3.

Analysis and comparison between the model-predicted values β, γ, α and the respective corresponding experimental values $\beta_{exp}$, $\gamma_{exp}$ and $\alpha_{exp}$ 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.

Deviation (Dv) of the model-predicted HAZ hardness values (β, γ and α) from the corresponding experimental values $\beta_{exp}$, $\gamma_{exp}$ and $\alpha_{exp}$ is given by

$$Dv = \left( \frac{M_H - E_H}{E_H} \right) \tag{15}$$

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

$$Cf = -Dv \tag{16}$$

Therefore

$$Cf = -100\left( \frac{M_H - E_H}{E_H} \right) \tag{17}$$

Introduction of the value of Cf from equation (17) into the models give exactly the corresponding experimental values $\beta_{exp}$, $\gamma_{exp}$ and $\alpha_{exp}$ (Nwoye,2008).

## 6. Results and discussion

A comparison of the HAZ hardness values from experiment and those of the model show model values very much within the range of the experimental values. Results of this comparison are presented in Tables 4 and 5. Model values of β evaluated from equations (5) and (6) and tabulated in Table 4 show that all the equations are valid since all of them gave almost the same corresponding experimental values $\beta_{exp}$. The value of γ in equation (7) 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 $\gamma_{exp.}$ This is a clear indication that the HAZ hardness of any of aluminum, mild steel and cast iron weldments cooled in groundnut oil can be predicted as a function of the HAZ hardness of any of the other two materials, providing each pair was cooled in groundnut oil. 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 $\gamma_{exp}$ and $\alpha_{exp}$ 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 $\beta_{exp}$, $\gamma_{exp}$ and $\alpha_{exp}$ are all less than 0.02% which is quite negligible and within the acceptable model deviation range from experimental results. Furthermore, the values of γ and α (from equations (13) and (14) respectively) evaluated to be approximately equal to the respective corresponding experimental values $\gamma_{exp}$ and $\alpha_{exp}$ confirm the validity of the model. This also implies that the general model; equation (12) can predict the HAZ hardness of any of aluminum, mild steel and cast iron weldments cooled in groundnut oil 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 groundnut oil. Equation (12) 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 (5), (6) and (12) are valid and very useful for predicting HAZ hardness of aluminum, mild steel and cast iron weldments cooled in groundnut oil depending on the material of interest and the given HAZ hardness values for the other materials.

## 7. Conclusion

The derived models; $\beta = 0.4478\gamma$, $\beta = 0.8031\alpha$, and $\gamma = 1.7934\alpha$, can predict the HAZ hardness of aluminum weldment cooled in groundnut oil as a function of the HAZ hardness of mild steel or cast iron welded and cooled under the same conditions. Similarly, the general model; $\beta = 1.2509[(\gamma\alpha/\gamma + \alpha)]$ can predict the HAZ hardness of aluminum weldment cooled in groundnut oil as a function of the HAZ hardness of both mild steel and cast iron welded and cooled under the same conditions. Furthermore, re-arrangement of these models could be done to evaluate the HAZ hardness of mild steel or cast iron respectively as in the case of aluminum. The respective deviations of the model-predicted HAZ hardness values β, γ and α from the corresponding experimental values $\beta_{exp}$, $\gamma_{exp}$ and $\alpha_{exp}$ was less 0.02% indicating the reliability and validity of the model.

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Table 1
Variation of materials with welding current and voltage (Nwoye,2008)

| Materials | Current Type | Welding current (A) | Welding Voltage (V) |
|---|---|---|---|
| Aluminum | Direct (d.c) | 120 | 280 |
| Cast Iron | Alternating (a.c) | 180 | 220 |
| Mild Steel | Alternating (a.c) | 180 | 220 |

Table 2
Hardness of HAZ in weldments (Nwoye,2008)

| Materials | HAZ Hardness (VHN) |
|---|---|
| Aluminum | 412 |
| Cast Iron | 920 |
| Mild Steel | 513 |

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

| | | |
|---|---|---|
| *β/γ* | *412/920* | *0.4478* |
| *β/α* | *412/513* | *0.8031* |
| *γ/α* | *920/513* | *1.7934* |

Table. 4
Comparison of the hardness of HAZ in aluminum, mild steel and cast iron weldments cooled in groundnut oil as obtained from experiment (Nwoye,2008) and as predicted by derived model ( each material as a function of 1- material)

| *N* | *Models derived* | $M_H$ | $E_H$ | *Dv (%)* | *Cf (%)* |
|---|---|---|---|---|---|
| 1 | $\beta = 0.4478\gamma$ | 411.9760 | 412.00 | -0.0058 | +0.0058 |
| 1 | $\beta = 0.8031\alpha$ | 411.9903 | 412.00 | -0.0024 | +0.0024 |
| 1 | $\gamma = 1.7934\alpha$ | 920.0142 | 920.00 | +0.0015 | -0.0015 |

Table 5
Comparison of the hardness of HAZ in aluminum, mild steel and cast iron weldments cooled in groundnut oil as obtained from experiment (Nwoye,2008) and as predicted by derived model (each material as a function of 2- materials).

| N | Models derived | $M_H$ | $E_H$ | Dv (%) | Cf (%) |
|---|---|---|---|---|---|
| 2 | $\beta = 1.2509[(\gamma\alpha/\gamma + \alpha)]$ | 411.9852 | 412.00 | -0.0036 | +0.0036 |
| 2 | $\gamma = [(1.2509/\beta - 1/\alpha)]^{-1}$ | 919.9632 | 920.00 | -0.0040 | +0.0040 |
| 2 | $\alpha = [(1.2509/\beta - 1/\gamma)]^{-1}$ | 513.0836 | 513.00 | +0.0163 | -0.0163 |

## List of Symbols

$H_G$ = Hardness of HAZ cooled in groundnut oil
$H_K$ = Hardness of HAZ cooled kerosine
β = Model-predicted hardness of HAZ in aluminum weldment cooled in groundnut oil (VPN)
α = Model-predicted hardness of HAZ in mild steel weldment cooled in groundnut oil (VPN)
γ = Model-predicted hardness of HAZ in cast iron weldment cooled in groundnut oil (VPN)
Dv = Deviation (%)
Cf = Correction factor (%)
$M_H$ = Model-predicted HAZ hardness values
$E_H$ = HAZ hardness values from the experiment (Nwoye, 2008)
HAZ= Heat affected zone
N = No. of materials constituting the corresponding model as independent variable.