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Research Article

Factorial Analysis of Welding Current Influence on Heat Affected Zone Hardness of Cast Iron, Aluminium, and Mild Steel Weldments Cooled in Palm Oil

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Factorial analysis of heat affected zone hardness of some metals was evaluated. Three models were derived and used as tools for evaluating the welding current influence on the predictability of HAZ hardness in aluminium, cast iron, and mild steel weldments similarly cooled in palm oil. It was discovered that on welding these materials, and similarly cooling their respective weldments in palm oil, the model $\alpha_w = (\gamma_w\beta_w/(\beta_w+\gamma_w))((i_\alpha i_\beta + i_\alpha i_\gamma)/i_\gamma i_\beta)^{0.8498}$ predicts aluminium weldment HAZ hardness by multiplying the determined general current product rule (GCPR) $((i_\alpha i_\beta + i_\alpha i_\gamma)/i_\gamma i_\beta)^{0.8498}$ with the ratio: HAZ hardness product of cast iron and mild steel/HAZ hardness sum of cast iron and mild steel $(\gamma_w\beta_w/(\beta_w+\gamma_w))$. Computational analysis of experimental and model-predicted results indicates that aluminium, cast iron, and mild steel weldment HAZ hardness per unit welding current as evaluated from experiment and derived model are 3.3917, 4.8333, and 2.7944 and 3.3915, 4.8335, and 2.7946 (VHN) A^{-1}, respectively. Deviational analysis shows that the maximum deviation of model-predicted HAZ hardness from the experimental results is less than 0.007%. This invariably implies over 99.99 % confidence level for the derived models.

1. Introduction

In many industries today, engineers are concerned with ways or how to prolong the life of the structure, with the repair and reclamation of its worn-out surface on its broken components [1]. Interestingly, in some cases, the extent of damage or worn is so small and localized that the components involved are repaired economically by welding [1].

In the past, restoration of worn-out industrial components has been achieved by weld surfacing. And so the wide range of consumables available for use with the many welding processes requires careful selection to suit a given working environment [2]. Restoration is ultimately achieved when welding is done at a low cost compared with replacement costs especially when the component is large and/or expensive.

Studies [1, 3] have revealed consideration and applicability of suitable welding procedures as well as fulfilling the metallurgical requirements as the first two vital factors for successful repair.

Analytical and numerical models for the prediction of the thermal fields induced by the stationary or the moving heat sources are useful tools for studying the fore mentioned problems [4]. In some laser beam applications, such as surface heat treatment, the contribution of convective heat transfer must also be taken into account [5]. Quasi-steady state thermal fields induced by moving localized heart sources have been widely investigated [6], whereas further attention seems to be devoted to the analysis of temperature distribution in transient heat conduction because temperature distribution has a significant influence on the residual stresses, distortion, and hence the fatigue behavior of welded structures. Welding is accompanied with considerable changes in the microstructure of the weldment due to the heating and cooling cycle of the weld zone, which in turn is directly related to the welding process and techniques employed.

The properties of a welded joint can only be improved by improving the microstructure of the HAZ. It has been generally reported [7] that a number of welding process variables and applied operating conditions influence the characteristics and microstructure, and, invariably, hardness, toughness, and cracking susceptibility of the HAZ in steel fusion welds. Excessive heat input has been known to result in a wide HAZ with low impact strength, particularly in high heat-input submerged arc welds. Rosenthal fails to predict the temperature in the vicinity of the heat source [8]. Eager and Tsai [9] modified Rosenthal's theory to include a two-dimensional (2-D) surface Gaussian distributed heat source with a constant distribution parameter (which can be considered as an effective solution of arc radius) and found that an analytical solution for the temperature of a semi-infinite body subjected this moving heat source. Their solution is a significant step for the improvement of temperature prediction in the near heat source regions.

Heat-affected zone of a fusion weld in steel may be divided into three zones, supercritical, intercritical, and subcritical zones [10]. The supercritical region, in turn, is divided into two regions: grain growth and grain refinement. The microstructure of the grain growth and grain refinement regions of the HAZ's supercritical zone has been reported [11] to influence significantly the properties of the weld joint. Accurate prediction of the properties of this zone stems from the amount and extent of grain growth apart from knowing the weld thermal cycle. The width of the HAZ's supercritical zone is expected to be as narrow as possible and so heat input from the welding process must be limited. Also, the supercritical zone undergoes considerable microstructural changes that are compared to small, negligible, and structural changes in the HAZ's intercritical and subcritical zones. The mechanical and metallurgical properties of the weldment are affected by these microstructural changes [12]. This invariably implies that the size of the HAZ is an indication of the extent of structural changes. The sizes of the HAZ are controlled by process variables and heat input, and so correlating them through development of mathematical models is significantly needful.

A model has also been derived [13] for assessment and computational analysis of the hardness of the heat-affected zone (HAZ) in aluminum weldment. The general model

$$\gamma = 1.2714\left[\left(\frac{\alpha\beta}{\alpha} + \beta\right)\right] \tag{1}$$

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 $\gamma\exp$, $\alpha\exp$, and $\beta\exp$ were less than 0.02%, respectively.

Studies have been carried out to understand how HAZ hardness of weldment is affected on cooling the weldments in groundnut oil [14]. Models were derived [15] (using the results of the study) 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. It was also discovered that the general model:

$$\alpha = 1.7391\gamma + 0.3967\beta \tag{2}$$

was able to 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 $\gamma\exp$, $\beta\exp$, and $\alpha\exp$, was less than 0.8% indicating at the reliability and validity of the model.

A model [16] has successfully been derived for the predictive analysis of hardness of the heat affected zone in aluminum weldment cooled in groundnut oil. The general model

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

shows that HAZ hardness in aluminium weldment was dependant on the hardness of the heat-affected zone (HAZ) in mild steel and cast iron weldments cooled in same media. Rearrangement 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

$$\alpha = \frac{\beta^2}{0.3596\gamma}, \tag{4}$$

$$\gamma = \frac{\beta^2}{0.3596\alpha}. \tag{5}$$

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

Quadratic and linear models [17] were also derived 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. This is similar to the previous model [18] except that the weldments in this case were cooled in air, while those of the previous model [18] were cooled in water. It was discovered that the general model

$$\theta = \frac{[2.9774\beta - \gamma]}{2} + \sqrt{\left[\left(\frac{(\gamma - 2.9774\beta)}{2}\right)^2 - \gamma\beta\right]} \tag{6}$$

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. The validity of the model is rooted 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 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 $\theta\exp$, $\gamma\exp$, and $\beta\exp$ were less than 0.003%.

The heat-affected zone (HAZ) hardness of water cooled cast iron weldment has been predicted by quadratic and linear models [18]. This was done 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

$$\theta = \frac{[3.0749\beta - \gamma]}{2} + \sqrt{\left[\left(\left(\frac{\gamma - 3.0749\beta}{2}\right)^2 - \gamma\beta\right]}. \quad (7)$$

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 the 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 that the values of the HAZ hardness of aluminum or/and mild steel welded and cooled under the same conditions are known.

The present work aims at determination of the HAZ hardness of aluminium, cast iron, and mild steel weldments, similarly cooled in palm oil as well as achieving a factorial analysis of the welding current influence on HAZ hardness of the aforementioned metals.

2. Materials and Methods

The welding operations were carried out using samples of aluminum, cast iron, and mild steel obtained from the First Aluminum Company Ltd. Port Harcourt. Two parts of each standard sample of these materials were butt welded end to end at the interface of separation prior to welding. The joints were prepared by chamfering the edges to be joined to create a “double V” kind of groove. The welding technique employed here was the shielded metal arc welding (SMAW) process because of its commonness and versatility and also because the process gives a moderately sized heat-affected zone. Also this 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]. This is what the experimental condition demands. Consumable electrodes of length 230–240 mm 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 was determined using Vickers hardness testing machine. Ten samples from each of the three materials were welded and similarly cooled in palm oil, and their respective weldment HAZ hardness was tested. The average HAZ hardness for the weldments of each of the three materials investigated was evaluated 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	407
Cast iron	870
Mild steel	503

3. 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 indicates that

$$\left(\frac{i_\alpha}{i_\gamma} + \frac{i_\alpha}{i_\beta}\right) \approx \left(\frac{\alpha_w}{\gamma_w} + \frac{\alpha_w}{\beta_w}\right)^N. \quad (8)$$

Introducing the value of N into (8)

$$\left(\frac{i_\alpha}{i_\gamma} + \frac{i_\alpha}{i_\beta}\right) \approx \left(\frac{\alpha_w}{\gamma_w} + \frac{\alpha_w}{\beta_w}\right)^{1.1768}, \quad (9)$$

$$\left(\frac{i_\alpha i_\beta + i_\alpha i_\gamma}{i_\gamma i_\beta}\right) = \left(\frac{\alpha_w\beta_w + \alpha_w\gamma_w}{\gamma_w\beta_w}\right)^{1.1768}. \quad (10)$$

Dividing the indices of both sides of (10) by 1.1768,

$$\left(\frac{i_\alpha i_\beta + i_\alpha i_\gamma}{i_\gamma i_\beta}\right)^{1/1.1768} = \left(\frac{\alpha_w\beta_w + \alpha_w\gamma_w}{\gamma_w\beta_w}\right),$$
$$\left(\frac{i_\alpha i_\beta + i_\alpha i_\gamma}{i_\gamma i_\beta}\right)^{0.8498} = \left(\frac{\alpha_w\beta_w + \alpha_w\gamma_w}{\gamma_w\beta_w}\right), \quad (11)$$

$$\alpha_w = \left(\frac{\gamma_w\beta_w}{\beta_w + \gamma_w}\left(\frac{i_\alpha i_\beta + i_\alpha i_\gamma}{i_\gamma i_\beta}\right)^{0.8498}\right). \quad (12)$$

Evaluating the value of β_w from the derived model in (12) gives

$$\beta_w = \alpha_w\left(\left(\frac{i_\alpha i_\beta + i_\alpha i_\gamma}{i_\gamma i_\beta}\right)^{0.8498} - \frac{\alpha_w}{\gamma_w}\right)^{-1}. \quad (13)$$

Table 3: Variation of $((i_\alpha/i_\gamma) + (i_\alpha/i_\beta))$ with $((\alpha_w/\gamma_w) + (\alpha_w/\beta_w))^{1.1768}$.

$i_\alpha/i_\gamma + i_\alpha/i_\beta$	$(\alpha_w/\gamma_w + \alpha_w/\beta_w)^{1.1768}$
1.3333	1.3333

Similarly, from (13), γ_w is evaluated as

$$\gamma_w = \alpha_w\left(\left(\frac{i_\alpha i_\beta + i_\alpha i_\gamma}{i_\gamma i_\beta}\right)^{0.8498} - \frac{\alpha_w}{\beta_w}\right)^{-1}, \quad (14)$$

where (α_w) = HAZ hardness of aluminium weldment cooled in palm oil (VHN), (γ_w) = HAZ hardness of cast iron weldment cooled in palm oil (VHN), (β_w) = HAZ hardness of mild steel weldment cooled in palm oil (VHN), (i_α) = welding current for aluminium (A), (i_γ) = welding current for cast iron (A), and (i_β) = welding current for mild steel (A), $N = 1.1768$, equalizing constant (determined using C-NIKBRAN [13].

The derived models are (12), (13), and (14).

4. Boundary and Initial Conditions

The welding process was carried out under atmospheric condition. After welding, weldments were also maintained at atmospheric condition. Input welding current and voltage range are 120–180 A and 220–280 V, respectively. SiO_2-coated electrodes were used to avoid oxidation of weld spots. The range of electrode length was used: 230–240 mm. Welded samples were cooled in 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.

5. Results and Discussions

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 palm oil (as presented in Table 2) shows that HAZ hardness is the greatest in cast iron followed by mild steel, while that of aluminium is the lowest.

The derived models are (12), (13), and (14). Computational analysis results in the 3rd column of Table 1 and 2nd column of Table 2 gave rise to Table 3. The precision and validity of the model are stemmed on this table (Table 3).

Equation (12) indicates that on welding aluminium and cast iron as well as mild steel and then cooling their respective weldments similarly in palm oil, the HAZ hardness in aluminium weldment will be evaluated by multiplying the ratio of HAZ hardness product of cast iron, and mild steel to their HAZ hardness sum with the general current product rule (GCPR) (involving aluminium, cast iron, and mild steel). This implies that $((i_\alpha i_\beta + i_\alpha i_\gamma)/i_\gamma i_\beta)^{0.8498}$ is the general current product rule and acts as a multiplying factor to $\gamma_w\beta_w/(\beta_w + \gamma_w)$, a way of influencing the value of α_w in (12). Equations (13) and (14) also evaluate the HAZ hardness of mild steel and cast iron based on the GCPR. Based on the foregoing, the weldment HAZ hardness of each of the three materials relative to the other materials is significantly dependant on the GCPR which is a collective function of their respective welding currents. The highlighted analysis therefore shows that the HAZ hardness of weldments is significantly affected by the input welding current.

6. Model Validation

The validity of the derived model was tested by comparing between the weldment HAZ hardnesses 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 (8) (core of the model) where both sides of the equation are correspondingly equal. Table 3 also agrees with (8) following the values of $(i_\alpha/i_\gamma + i_\alpha/i_\beta)$ and $((\alpha_w/\gamma_w) + (\alpha_w/\beta_w))^{1.1768}$ evaluated from the experimental results in Tables 1 and 2.

7. Computational Analysis

Computational analysis of the experimental and model-predicted weldment HAZ hardness per unit welding current was 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.

7.1. Aluminium HAZ Hardness per Unit Welding Current. Aluminium HAZ hardness per unit welding current ${H_Z}^A$ was calculated from

$${H_Z}^A = \frac{{}_A H_Z}{I}. \quad (15)$$

Dividing the HAZ hardness of aluminium weldment; 407 VHN (as shown in Table 2) with the input welding current of 120 A, gave 3.3917 (VHN) A^{-1} as the HAZ hardness per unit welding current.

Also, dividing the model-predicted HAZ hardness of aluminium weldment, 406.98 VHN with the input welding current, 120 A, the model-predicted aluminium HAZ hardness per unit welding current, is given as 3.3915 (VHN) A^{-1}.

7.2. Cast Iron HAZ Hardness per Unit Welding Current. Cast iron HAZ hardness per unit welding current ${H_Z}^C$, was calculated from

$${H_Z}^C = \frac{{}_C H_Z}{I}. \quad (16)$$

On dividing the HAZ hardness of cast iron weldment; 870 VHN (as shown in Table 2) with the input welding current of 180 A, gave 4.8333 (VHN) A^{-1} as the HAZ hardness per unit welding current. This is the experimentally obtained cast iron weldment HAZ hardness per unit welding current.

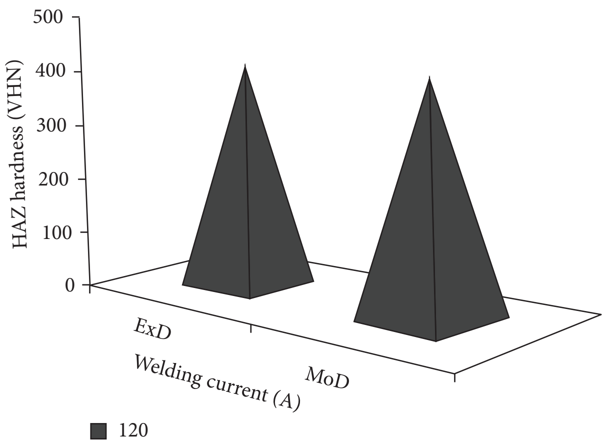

Figure 1: Comparison of aluminium HAZ hardness of weldments as obtained from experiment and derived model.

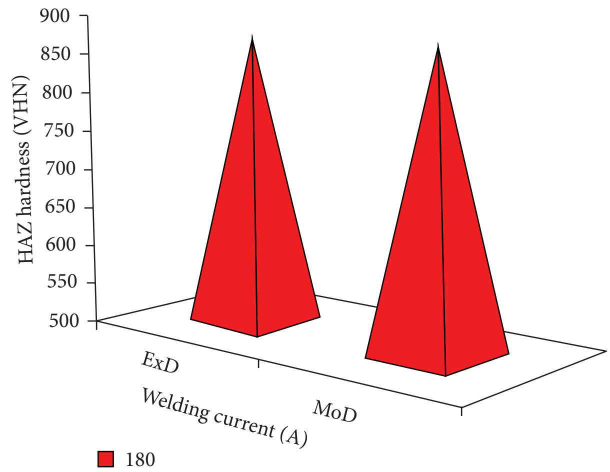

Figure 2: Comparison of cast iron HAZ hardness of weldments as obtained from experiment and derived model.

Furthermore, dividing the model-predicted HAZ hardness of cast iron weldment, 870.03 VHN with the input welding current, 180 A gives 4.8335 (VHN) A^{-1} as the model-predicted cast iron HAZ hardness per unit welding current.

7.3. Mild Steel HAZ Hardness per Unit Welding Current. Mild steel HAZ hardness per unit welding current ${H_Z}^M$ was calculated from

$$ {H_Z}^M = \frac{{}_M H_Z}{I}. \quad (17) $$

Dividing the HAZ hardness of mild steel weldment, 503 VHN (as shown in Table 2) with the input welding current, 180 A gives 2.7944 (VHN) A^{-1} as the HAZ hardness per unit welding current as obtained from experiment.

Similarly, dividing the model-predicted HAZ hardness of mild steel weldment, 503.03 VHN with the input welding current, 180 A gives 2.7946 (VHN) A^{-1} as the model-predicted mild steel HAZ hardness per unit welding current.

An analysis of Figures 1, 2, and 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 current shows proximate agreement and invariably a high degree of validity for the derived model.

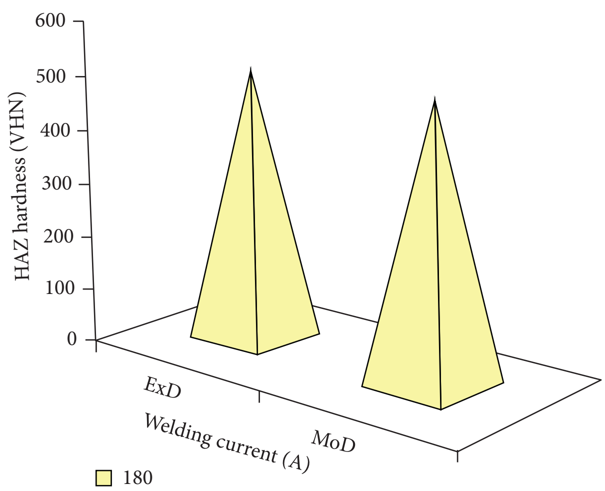

Figure 3: Comparison of mild steel HAZ hardness of weldments as obtained from experiment and derived model.

8. 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 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 (Dv) of model-predicted HAZ hardness from that of the experiment is given by

$$ \mathrm{Dv} = \left(\frac{P_R - E_R}{E_R} \right) \times 100. \quad (18) $$

Correction factor (Cf) is the negative of the deviation that is

$$ \mathrm{Cf} = -\mathrm{Dv}. \quad (19) $$

Therefore

$$ \mathrm{Cf} = -\left(\frac{P_R - E_R}{E_R} \right) \times 100, \quad (20) $$

where Dv = deviation (%), P_R = model-predicted HAZ hardness (VHN), E_R = HAZ hardness from experiment (VHN), and Cf = correction factor (%).

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

Material	MoD	Dv (%)	Cf (%)
Aluminium	406.98	−0.0049	+0.0049
Cast iron	870.03	+0.0034	−0.0034
Mild steel	503.03	+0.0060	−0.0060

It is strongly believed that on introduction of the values of Cf from (20) into the model, exact corresponding experimental HAZ hardness would be obtained.

Deviational analysis indicates clearly in Table 4 that the maximum deviation of model-predicted HAZ hardness (from experimental values) is less than 0.007%. This is insignificant and very much within the acceptable range of deviation from experimental results. This implies over 99.99% operation confidence level for the derived models.

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).

9. Conclusions

The factorial analysis of welding current influence on the HAZ hardness of aluminium, cast iron, and mild steel weldments similarly cooled in palm oil, carried out using three derived models, reveals that the HAZ hardness of the weldments was significantly affected by the input welding current. On welding aluminium, cast iron, and mild steel and cooling their respective weldments similarly in palm, the model evaluates aluminium weldment HAZ hardness by multiplying the determined general current product rule (GCPR) $((i_\alpha i_\beta + i_\alpha i_\gamma)/i_\gamma i_\beta)^{0.8498}$ with the ratio, HAZ hardness product of cast iron and mild steel/HAZ hardness sum of cast iron and mild steel $(\gamma_w \beta_w/(\beta_w + \gamma_w))$.

Furthermore, weldment HAZ hardness of each of cast iron and mild steel relative to the others is significantly dependant on the GCPR which is a collective function of their respective welding currents. The validity of the model was found to be rooted in the core model expression $((i_\alpha/i_\gamma) + (i_\alpha/i_\beta)) = ((\alpha_w/\gamma_w) + (\alpha_w/\beta_w))^{1.1768}$, where both sides of the core model expression are correspondingly equal.

Computational analysis of experimental and model predicted results indicates that aluminium weldment HAZ hardness per unit welding current as evaluated from experiment and derived model are 3.3917 and 3.3915 (VHN) A^{-1}, respectively. Similarly, cast iron weldment HAZ hardness per unit welding current as evaluated from experiment and derived model are 4.8333 and 4.8335 (VHN) A^{-1}, respectively. Furthermore, mild steel weldment HAZ hardness per unit welding current evaluated from experiment and derived model are 2.7944 and 2.7946 (VHN) A^{-1}, respectively. Deviational analysis shows that the maximum deviation of model-predicted HAZ hardness from the experimental results is less than 0.007%. This invariably implies over 99.99% confidence level for the derived models.

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