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Predictability of Operational Welding Voltage Affecting the Heat Affected Zone Hardeness of Metal Weldments Similarly Cooledin Palm Oil

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Abstract: Predictability of the operational welding voltage affecting heat affected zone hardness of metal weldments, similarly cooled in palm oil has been ascertained. Metals such as aluminium, mild steel and cast iron were welded using shielded metal arc technique, at different welding voltages, and their respective weldments similarly cooled in palm oil to obtain their corresponding hardnesses. Results of the study revealed that the HAZ hardness for aluminium, mild steel and cast iron weldments were 407, 503 and 870 VPN respectively. Derived and validated empirical models; $V_a= K(\vartheta_a \vartheta_c\vartheta_m)^{1.3583} \varepsilon^{-1}$, $V_m= K(\vartheta_a\vartheta_c\vartheta_m)^{1.3583}$ Ƅ$^{-1}$ and $V_c= K(\vartheta_a\vartheta_c\vartheta_m)^{1.3583}$ Ä$^{-1}$ predicted the welding voltages of aluminium, mild steel and cast iron as 280.0021, 220.0016 and 220.0016V respectively with maximum deviation (from experimental values) < 0.0008%. This invariably translates to over 99.99% model confidence level. The validity of the models are rooted in the core model expression $(V_aV_cV_m)^{0.7362} = 0.001(\vartheta_a \vartheta_c \vartheta_m)$ where both sides of the expression are very close. The predicted results confirmed widely reported knowledge that the operational welding voltage for metal weldments varies with materials, since their respective hardnesses are different, even though they are similarly cooled.

Key words: Prediction - Operating welding voltage - Heat Affected Zone Hardness - metal Weldments - Palm oil cooling

INTRODUCTION

In welding, very sound structural consideration were based on depth of heat affected zone, weld metal hardness and microstructure of weldment. These are significantly affected by welding method, cooling rate, grain structure, structural integrity, strength and rusting probability of weldment.

Research [1] has shown that proper control of process parameters such as feed rate, arc length, cooling process, welding current, voltage, electrode wire materials and diameter will give positive and accurate results during welding. During MIG welding process, parameters such arc length, welding current, electrode wire diameter and electrode wire feed rate have been observed [1] to exert profound influence on hardness, depth of heat affected zone and microstructure of weldment.

Results of investigation [2] which concentrated on the form of the hardness gradient in the heat affected zones (HAZs) produced by submerged arc welding of two low-carbon Q & T steels show unequivocally that the gradient differs from that found in steels of lower carbon equivalent in that the peak HAZ hardness is displaced from the grain coarsened heat affected zone (GCHAZ) into the grain refined heat affected zone (GRHAZ). The scientists used thermal cycle simulation to confirm the results obtained from actual welds and then clarify the cause of this unexpected phenomenon.

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Results [3] of welding a lean super martensitic stainless steel under different heat input of 7.97, 8.75 and 10.9 kJ/cm by gas tungsten arc welding process indicates that the tensile strength of the weld joint decreased with rise in the heat input and temperature. The researchers also observed that rise in the heat input very slightly affected the hardness of weld joint while the toughness of weld deposit was enhanced. This was attributed to increased ferrite content in the matrix of martensite resulting from increased heat input. The scientists concluded that the resulting microstructure consists of mixed phase of martensite, austenite and some amount of ferrites while larger and more elongated bright phase of banded delta ferrite in a matrix of martensite are within the HAZ near to the fusion line irrespective of change in heat input.

The effects of process variables and heat input on various metallurgical aspects, namely, the widths of the HAZ, weld interface, grain growth and grain refinement regions of the HAZ have been studied [4] using mathematical models. The color metallography technique and response surface methodology were also used. Results of the investigation 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 while weld interface decreased with an increase in arc voltage. Futhermore, the width of HAZ is maximum (about 2.2 mm) when wire feed rate and welding speed are at their minimum limits.

Successful selection of correct process variables for achieving the desired weld bead HAZ characteristics and mechanical properties, and in predicting HAZ dimensions for the given process variables have all been achieved by mathematical models [5]. These models have greatly 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. The models have also helped 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.

The patterns of results obtained from the experiments have been successfully realized using ANN based modeling of the experiment [6].It had been observed that the microstructures obtained in these weldments were distinctly different from that of the base metal. Microstructures, hardness and depth of heataffected zone of weldment depended on the process parameters. ANN model also shows good agreement with the experimental results in case of hardness and depth of heat affected zone of weldment.

Empirical models [7-13] 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 predicting theoperational welding voltage affecting the heat affected zone hardness of metal weldments similarly cooled in palm oil.

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. 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.

Table 1 shows the variation of materials with the input welding current type (C/Type), welding current (W/C) and voltage (W/V). The results of HAZ hardness of aluminium, mild steel and cast iron weldments similarly cooled in palm oil (as presented in Table 2) were 407, 503 and 870 VPN respectively.

Table 1: Variation of materials with their 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

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.

Table 3 shows that the power of the effective operational welding voltage $(V_a\ V_c\ V_m)^{0.7362}$ is proportional to the effective HAZ hardness of aluminium, mild steel and cast iron $0.001(\vartheta_a \vartheta_c \vartheta_m)$.

Table 3: Variation ofwith $(V_a\ V_c\ V_m)^{0.7362}$ with $0.001(\vartheta_a \vartheta_c \vartheta_m)$

$(V_a\ V_c\ V_m)^{0.7362}$	$0.001(\vartheta_a \vartheta_c \vartheta_m)$
178065.96	178107.27

Both sides of the table show values of very close proximity. This is the basis for the empirical models that will predict the welding voltages affecting HAZ hardness of the metal weldments.

Model Formulation: Results from the experiment were used for the model formulation. Computational analysis of results shown in Tables 1 and 2, gave rise to Table 3 which indicate that;

$$(V_aV_cV_m)^N = S(\vartheta_a \vartheta_c \vartheta_m) \tag{1}$$

Introducing the values of N and S into equation (1) gives;

$$(V_aV_cV_m)^{0.7362} = 0.001(\vartheta_a \vartheta_c \vartheta_m) \tag{2}$$

Multiplying the indices of both sides of equation (2) by the reciprocal of 0.7362 gives;

$$V_aV_cV_m = (0.001(\vartheta_a \vartheta_c \vartheta_m))^{1.3583} \tag{3}$$

$$V_a\ V_c\ V_m = 8.4159 \times 10^{-5}(\vartheta_a \vartheta_c \vartheta_m)^{1.3583} \tag{4}$$

$$V_a\ V_c\ V_m = K(\vartheta_a \vartheta_c \vartheta_m)^{1.3583} \tag{5}$$

From equation (5), $V_a\ V_c$; product of welding voltages of cast iron and aluminium precisely expressed as Ƅ, and referred to as Conjugated HAZ Product $(CHP)_{AC}$ or HAZ Equivalent $(HE)_{AC}$ for aluminium and cast iron similarly cooled in palm oil.

Based on the forgoing,

$$Ƅ = V_aV_c \tag{6}$$

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

$$V_m = \frac{K(\vartheta_a \vartheta_c \vartheta_m)^{1.3583}}{Ƅ} \tag{7}$$

On re-arranging equation (7), the welding voltage of cast iron V_c and aluminium V_a are similarly evaluated as:

$$V_c = \frac{K(\vartheta_a \vartheta_c \vartheta_m)^{1.3583}}{Ä} \tag{8}$$

and

$$V_a = \frac{K(\vartheta_a \vartheta_c \vartheta_m)^{1.3583}}{\varepsilon} \tag{9}$$

where

(ϑ_c) = HAZ hardness of aluminium weldment cooled in palm oil (VHN)

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

(ϑ_c) = HAZ hardness of mild steel weldment cooled in palm oil (VHN)

(V_a) = Welding voltage during welding of aluminium (V)

(V_c) = Welding voltage during welding of castiron (V)

(V_m) = Welding voltage during welding of mildsteel (V)

(Ä) = Conjugated HAZ Product $(CHP)_{AM}$ or HAZ Equivalent $(HE)_{AM}$

(ε) = Conjugated HAZ Product $(CHP)_{CM}$ or HAZ Equivalent $(HE)_{CM}$

N = 0.7362, S = 0.001 equalizing constant.

K = 8.416×10^{-5}, e = 1.3583;empirical constant (determined using C-NIKBRAN [14]).

The derived models are equations (7), (8) and (9)

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.

Model Validation: The validity of the models were rooted in the core model expression $(V_a\ V_c\ V_m)^{0.7362} = 0.001(\vartheta_a\ \vartheta_c\ \vartheta_m)$ where both sides of the expression are very close. Table 3 also agrees with equation (2) following the values $(V_a\ V_c\ V_m)^{0.7362}$ and $0.001(\vartheta_a\ \vartheta_c\ \vartheta_m)$ evaluated from the experimental results in Tables 1 and 2. Maximum deviation of model-predicted values of the welding voltages from the experimental values was evaluated. This was done by comparing results of welding voltage of the three materials as evaluated from experiment and derived model.

Analysis of Experimental and Model-Predicted Welding Voltage: Comparative analysis of welding voltages of metal weldments as evaluated from the experiment and model-prediction were carried.

Figs. 1-3 show operational welding voltages of aluminium, mild steel and cast iron as 280.0021 &280, 220.0016 & 220 and 220.0016 & 220V as obtained from model-prediction and experiment respectively. Critical comparative analysis of Figs. 1-3 shows in each case almost same height of shapes. These translated into significantly similar trend of data points distribution for the experiment and model-predicted values.

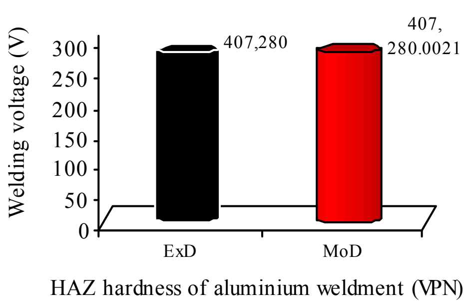

Fig. 1: Comparison of operational welding voltage for aluminium weldment relative its HAZ hardness as obtained from experiment and derived model

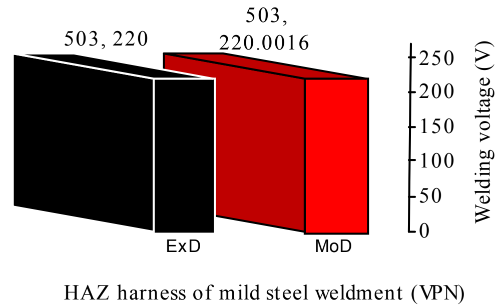

Fig. 2: Comparison of operational welding voltage for mild steel weldment relative its HAZ hardness as obtained from experiment and derived model

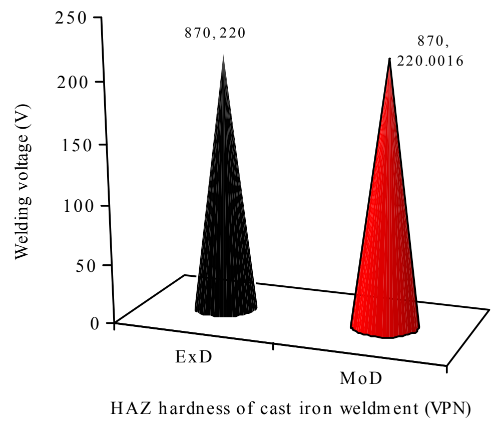

Fig. 3: Comparison of operational welding voltage for cast iron weldment relative its HAZ hardness as obtained from experiment and derived model

Figs. 1-3 show proximate agreement between each of the three sets of operational welding voltages relative to the HAZ hardness of respective metal weldments.

Deviational Analysis: Comparative analysis of the operational welding voltages for the metal weldments as obtained 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 welding voltage to those of the corresponding experimental values.

Deviation (Dv) of model-predicted welding voltage from that of the experiment is given by;

$$Dv = \left(\frac{W_p - W_{ex}}{W_{ex}} \right) \times 100 \qquad (10)$$

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

$$Cr = - Dv \qquad (11)$$

Therefore

$$Cr = - \left(\frac{W_p - W_{ex}}{W_{ex}} \right) \times 100 \qquad (12)$$

where

Dv = Deviation (%)
W_p = Model-predicted welding voltage (V)
W_{ex} = Welding voltage from experiment (V)
Cr = Correction factor (%)

It is strongly believed that on introducing the values of Cr from equation (12) into the model, the exact corresponding experimental based welding voltage would be obtained.

Table 4: Variations of model predicted welding voltages with deviations and correction factors

Material	MoD	Dv (%)	Cr (%)
Aluminium	280.0021	+0.0007	-0.0007
Cast Iron	220.0016	+0.0007	-0.0007
Mild Steel	220.0016	+0.0007	-0.0007

Fig. 4 clearly shows that the maximum deviation of model-predicted welding voltage (from experimental values) for each metal weldment was < 0.0008%. This invariably translates to over 99.99% model confidence level and over 0.9999. Reliability dependency voltage on the metal type and its weldment HAZ hardness coefficients of the operational welding.

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).

CONCLUSIONS

The predictability of operational welding voltage affecting heat affected zone hardness of metal weldments has been ascertained. Weldment HAZ hardness for aluminium, mild steel and cast iron weldments were 407, 503 and 870 VPN respectively. Derived and validated empirical models; $V_a = K(\vartheta_a\, \vartheta_c\, \vartheta_m)^{1.3583}\, \varepsilon^{-1}$, $V_m = K(\vartheta_a\, \vartheta_c\, \vartheta_m)^{1.3583}\, \text{ƀ}^{-1}$ and $V_c = K(\vartheta_a\, \vartheta_c\, \vartheta_m)^{1.3583}\, \ddot{A}^{-1}$ predicted the welding voltages of aluminium, mild steel and cast iron as 280.0021, 220.0016 and 220.0016V respectively with maximum deviation (from experimental values) < 0.0008%. This invariably translates to over 99.99% model confidence level. The validity of the models are rooted in the core model expression $(V_a\, V_c\, V_m)^{0.7362} = 0.001(\vartheta_a\, \vartheta_c\, \vartheta_m)$ where both sides of the expression are very close. The predicted results confirmed widely reported knowledge that the operational welding voltage for metal weldments varies with materials, since their respective hardnesses are different, even though they are similarly cooled.

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