Selection of Process Variables Used for Gas Metal Arc Welding of Low Carbon Steel Plates by Metallographical Method

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Abstract

Many methods have been employed by various researchers to determine the quality of the weld made from either varying the welding process parameters or altering the chemical composition of the weldment by selecting an appropriate filler metal and shielding gas mixtures. This study has taken a step further, to also evaluate the quality of the welds by applying the metallographical method to select process variables used for gas metal arc welding of low carbon steel plates. An average of 64welds was obtained by varying the process variables developed by a matrix design presented in Table 1 through Table 3.

The welds were classified by a metallographical method as either very good, bad or very bad. The corresponding impact strengths were also obtained. Standard deviation of the responses was obtained and the selection criteria was established and was used to select weld sample number 56 which had the highest weld factor of 0.87, as the weld with the best microstructure, strength and quality. The mechanical properties of the selected weld showed that the UTS and BHN values conformed to those from reported literature.

Keywords: Brinell Hardness Number (BHN), Heat Affected Zone (HAZ), Metallography, Ultimate Tensile Strength (UTS), Weld Factor.

1. INTRODUCTION

Heat input can alter the chemical composition of a weld metal different from the parent metal. This is possible because atoms or elements present in the weld metal are affected differently when under the influence of heat. Some elements are reduced in proportion due to evaporation and others gained due to oxidation or a combination of similar elements in the weld pool during the welding process.

The proportion of the melted electrode and base metal, coupled with their mixture and the shielding gas, as a result of the welding process form the weld pool. After the welding process, as the weld pool begins to cool, the elements nuclei together as their movement becomes more restricted, especially when the cooling process is complete the weld pool therefore had formed crystals containing elements in fixed positions. The formation and arrangement of these crystals cannot be entirely controlled but reveals a detailed view of the quality of the weld metal. The microstructural view of the weld metals becomes a strong quality criteria for the classification of the weldments by employing the evaluation of experts. Achebo [1] was of the opinion that the strength of the weld metal can be enhanced by altering its composition by adding those elements that enhance strength. Since the alteration of weld chemical composition is strongly related to its microstructure. Hence, this study finds a way of enhancing strength by metallographic method. Metallography is the study of structure of metals and alloys by means of microscopy.

In this study, the weld metal becomes the heat affected zone (HAZ), as this portion has undergone thorough heat treatment. The impact energy absorbed by the HAZ is a measure of its ductility and was used here to select the optimum process variables.

Other investigators who have researched in this area are Pluphrach [2] studied the effect of solidification on graphite flakes microstructure and mechanical properties, such as hardness and ultimate tensile strength of an ASTM a - 48 grey cast iron. Topolska and Labanowski [3] studied the effect of microstructure on impact toughness of duplex and super duplex stainless steels. Chen et al. [4] worked on the effect of high temperatures on microstructure stability and toughness property in a 2205 Duplex stainless steel. Kuzueu et al. [5] investigated the microstructures of iron based wrought Cr - Ni - Mo Duplex alloy. Lu et al. [6] studied the microstructure and wear property of Fe-Mn-Cr-Mo-V alloy cladding by submerged arc welding process.

In this study, the microstructure of test specimens were used to classify the quality of the welds and the impact absorbed energy was used to determine the selection criteria for obtaining the optimum process variables. A step by step approach is shown for the selection of these variables.

2. MATERIALS AND METHODS

2.1 Materials

2.1.1 Baldwin Universal Testing Machine

An Avery Dennison Baldwin Universal Testing machine consists of two vital units – a loading frame and an indicator. The machine has a capacity range of 2.25 – 25000 kg and operated on a 220v.50Hz single phase power. The machine was used to carry out tensile tests of the welded specimen.

2.1.2 V-Notch Impact Testing Machine

A material that exhibits good tensile strength properties may not be able to withstand sudden loading. Notched bar impact testing measures the toughness of a notched bar i.e. the ability to absorb energy. The Avery impact testing machine was used.

2.1.3 Brinell Hardness Tester

An Avery Brinell hardness tester was used to carry out the hardness test. The machine consists of a hydraulic pump, which applies a load of 3000 kg on the etched and polished specimen.

2.1.4 Grinding Machine

A locally made grinding machine was used to prepare the weld for metallographical examination. This machine is operated manually and is partitioned into four sections of a rectangular shape. The first to the fourth sections occur in the order of 240, 320, 400 and 600 emery paper respectively.

2.1.5 Polishing Machine

An automated Polisher Econet II Cinder made from Buehler United Kingdom was used. It consists of an electric motor, a polishing rotating circular flat plate, 1.0 µm emery cloth used for initial polishing and 0.5 µm emery cloth used for the final polishing with the gradual application of silicon carbide solutions.

2.1.6 Weld Metallographical Method

An Econet II weld metallurgical microscope was used. It is a digital microscope used to physically examine and take the microstructural view of the weld specimen when magnified to about 100 times.

2.2 Methods

This study was carried out following the steps below:
Step 1: A matrix design was developed;
Step 2: The process parameters and their values in their various ranges were identified;
Step 3: The process parameters were inputted into the matrix design and used to conduct welding Processes and metallographical examination was used to determine the microstructure of the welds produced.
Step 4: The impact strength of the welds were tested and the average values recorded
Step 5:The standard deviation of the responses was obtained and the selection criteria established
Step 6: The welds that conform to the standards set by the selection criterion were selected
Step 7: By employing the weld factor analysis, the weld with the best strength factor was finally selected.

3. RESULTS

The Process parameters were inputted into the matrix design that was developed and their corresponding responses that were obtained for the 64 welds are shown in Table 1.

Trial No.	A	B	C	D	E	F	G	H	I	J	K	L	Condition of Microstructure		Charpy Impact Test Results, $J(X_i)$	$(X_i - \bar{X})^2$
1	1	0	0	0	0	0	1	1	0	1	1	1	Very bad	-1	75	243.36
2	1	1	0	0	0	0	0	0	1	0	1	0	Very good	+1	82	73.96
3	1	1	1	0	0	0	0	0	0	0	1	1	Bad	0	60	936.36
4	1	1	1	1	0	0	0	0	1	0	1	1	Very good	+1	100	88.36
5	1	1	1	1	1	0	0	1	0	0	0	1	Bad	0	96	29.16
6	1	1	1	1	1	1	1	1	1	1	1	1	Bad	0	75	234.36
7	0	1	1	1	1	1	0	0	1	0	0	0	Very good	+1	108	302.76
8	1	0	1	1	1	1	0	0	0	0	1	0	Very good	+1	65	655.36
9	0	1	0	1	1	1	0	0	0	0	0	1	Bad	0	89	2.56
10	1	0	1	0	1	1	0	0	0	1	0	0	Very bad	-1	118	750.76
11	0	1	0	1	0	1	0	1	0	1	0	1	Very good	+1	105	207.36
12	1	0	1	0	1	0	1	0	1	0	1	0	Bad	0	69	466.56
13	1	1	0	1	0	1	1	0	0	0	1	0	Bad	0	87	12.96
14	0	1	1	0	1	0	1	0	0	0	0	0	Very good	+1	73	309.76
15	0	0	1	1	0	1	1	0	0	0	0	1	Very bad	-1	84	43.56
16	1	0	0	1	1	0	1	0	0	1	0	1	Bad	0	97	40.96
17	1	1	0	0	1	1	1	1	0	0	0	0	Very good	+1	114	547.56
18	0	1	1	0	0	1	0	1	1	0	1	0	Bad	0	64	707.56
19	1	0	1	1	0	0	1	1	1	0	0	0	Very good	+1	88	6.76
20	1	1	0	1	1	0	0	1	1	0	0	0	Very good	+1	92	1.96
21	1	1	1	0	1	1	1	1	1	0	0	1	Bad	0	74	275.56
22	0	1	1	1	0	1	0	1	1	1	0	0	Very good	+1	100	88.36
23	1	0	1	1	1	0	1	0	1	1	0	0	Very good	+1	86	21.16
24	1	1	0	1	1	1	1	1	0	1	1	0	Very bad	-1	98	54.76
25	0	1	1	0	1	1	0	0	1	1	1	0	Very good	+1	120	864.36
26	1	0	1	1	0	1	0	1	0	1	1	0	Very good	+1	109	338.56
27	0	1	0	1	1	0	1	0	1	1	1	1	Very bad	-1	85	31.36
28	0	0	1	0	1	1	1	1	0	0	1	1	Very good	+1	110	376.36
29	1	0	0	1	0	1	0	1	1	1	1	1	Very bad	-1	68	510.76
30	0	1	0	0	1	0	1	0	1	0	0	1	Bad	0	98	54.76
31	0	0	1	0	0	1	1	0	0	1	1	1	Very good	+1	106	237.16

32	1	0	0	1	0	0	1	1	0	0	0	1	Bad	0	86	21.16
33	1	1	0	0	1	0	0	1	1	1	1	0	Very good	+1	72	345.96
34	1	1	1	0	0	1	1	0	1	1	0	1	Very good	+1	68	510.76
35	0	1	1	1	0	0	1	1	0	0	1	0	Bad	0	98	54.76
36	0	0	1	1	1	0	0	1	1	0	1	1	Very good	+1	100	88.36
37	0	0	0	1	1	1	1	1	1	1	0	0	Very bad	-1	109	338.56
38	1	0	0	0	1	1	0	0	1	1	0	1	Bad	0	67	556.96
39	0	1	0	0	0	1	0	1	0	0	1	1	Bad	0	63	761.76
40	1	0	1	0	0	0	1	1	1	1	1	0	Very good	+1	79	134.56
41	1	1	0	1	0	0	0	0	1	1	0	0	Very good	+1	120	864.36
42	1	1	1	0	1	0	0	1	0	1	1	1	Very bad	-1	76	213.16
43	1	1	1	1	0	1	1	0	1	0	1	1	Bad	0	95	19.36
44	0	1	1	1	1	0	1	0	0	1	1	0	Very bad	-1	76	213.16
45	0	0	1	1	1	1	1	1	0	1	0	1	Very bad	-1	80	112.36
46	1	0	0	1	1	1	0	0	1	0	1	1	Very good	+1	92	1.96
47	0	1	0	0	1	1	0	0	0	1	1	1	Bad	0	100	88.36
48	1	0	1	0	0	1	0	1	0	0	0	0	Very good	+1	116	645.16
49	0	1	0	1	0	0	1	1	1	0	1	1	Very good	+1	89	2.56
50	0	0	1	0	1	0	0	1	1	1	0	1	Bad	0	97	40.96
51	0	0	0	1	0	1	1	0	1	0	0	0	Very bad	-1	100	88.36
52	1	0	0	0	1	0	1	0	0	0	1	1	Very bad	-1	86	21.16
53	1	1	0	0	0	1	1	0	0	1	0	0	Bad	0	98	54.76
54	0	1	1	0	0	0	1	1	0	1	0	0	Very good	+1	86	21.16
55	0	0	1	1	0	0	0	0	1	1	1	1	Very good	+1	98	54.76
56	0	0	0	1	1	0	0	1	0	0	1	0	Very good	+1	102	129.96
57	0	0	0	0	1	1	1	1	1	0	1	0	Very good	+1	118	750.76
58	1	0	0	0	0	1	0	1	1	0	0	1	Very bad	-1	99	70.56
59	0	1	0	0	0	0	1	1	1	1	0	1	Bad	0	65	655.36
60	0	0	1	0	0	0	0	0	1	0	0	1	Very good	+1	74	275.56
61	0	0	0	1	0	0	0	0	0	1	1	0	Bad	0	87	12.96
62	0	0	0	0	1	0	0	1	0	1	0	0	Very good	+1	98	54.76
63	0	0	0	0	0	1	1	0	1	1	1	0	Very good	+1	117	696.96
64	0	0	0	0	0	0	0	0	0	0	0	0	Very good	+1	92	1.96
∑															**5798**	**16427.44**

TABLE 1: First matrix Design of Input Parameters and the corresponding Responses.

3.1 Matrix Design Parameters

The parameters in Table 2 are randomly allocated for a more unbiased judgment. The parameters were used to prepare and process the specimens used in this study. In this study, it is intended to optimally allocate these parameters to the finally selected weldment. For the finally selected weldment, the distribution of the matrix design in Table1, where 0 indicates low value and 1 indicates high value are used to allocate the parameters in Table 2. The analysis of the optimal distribution of these parameters is expressed in the discussion of results.

A	Type of material	Low carbon steel – medium carbon steel
B	Welding temperature	1128^{o}C – 1400^{o}C
C	Preheat temperature	200^{o}C – 250^o C
D	Welding time	60 sec – 120 sec
E	Etching reagent	Hydrofluoric – hydrochloric
F	Emery cloth for smoothness	0.5μm – 1.0 μm
G	Material hardness	250 – 330 BHN
H	Machined specimen size	40mm x 40mm – 60mm x 60mm
I	Ultimate tensile strength	450MPa – 600MPa
J	Current	220A – 360A
K	Voltage	20V – 22V
L	Welding speed	100mm/s – 125mm/s

TABLE 2: Parameters Used for Matrix Design.

3.2 Variance and Standard Deviation of the Mean Absorbed Energy Response

Table 3 shows the mean responses obtained from Table 1 above, relating to Hadamard matrix design.

A	B	C	D	E	F	G = ABF	H = ABE	I = BCF	J = ABDEF	K = ADF	L =ABC
$\frac{-184}{32}$	$\frac{-146}{32}$	$\frac{-102}{32}$	$\frac{130}{32}$	$\frac{82}{32}$	$\frac{234}{32}$	$\frac{-60}{32}$	$\frac{4}{32}$	$\frac{-62}{32}$	$\frac{72}{32}$	$\frac{-156}{32}$	$\frac{-284}{32}$
-5.75	-4.56	-3.19	4.06	2.56	7.31	-1.88	-0.13	-1.94	-2.25	-4.88	-8.88

TABLE 3: Mean Responses Relating to Hadamard Matrix Design.

The variance was calculated from the values in Table 1, using equation (1):

$$Variance = S^2 = \frac{\sum_{i=1}^{n=1}\left(X_i - \overline{X}\right)^2}{n-1} \tag{1}$$

Where i = 1, 2, 3, ------ n. The denominator (n - 1) is called the degree of freedom [7]

$$\text{where } \overline{X} = \frac{\sum X_i}{n} = 90.6$$

Therefore,

$$\text{variance} = S^2 = \frac{16427.44}{64-1} = 260.753$$

$$\text{Standard deviation}=S = \sqrt{260.753} = 16.15$$

Since the degree of freedom, df = φ = 63, α = 0.5 and the variance is now known, the probability point of the normal distribution single sided, U_x would be 1.645 [7].

The criterion for impact strength response at 95% confidence level is calculated as

$$\left|\overline{X}_{high} - \overline{X}_{low}\right| * = U_\alpha S\sqrt{\frac{1}{32}+\frac{1}{32}} = 1.645x16.15x0.25 = 6.64 \; at \; 95\% \; confidence$$

3.3 Selection Process

$$Since \left|\overline{X}_{high}F - \overline{X}_{low}F\right| = 7.31 \succ 6.64, \; high \; F \; is \; required$$

and $Since \left|\overline{X}_{high}L - \overline{X}_{low}L\right| = -8.88 \succ 6.64, \; but \; negative, \; Low \; L \; is \; required$

The parameters with values below the critical value of 6.64 were disregarded.

From the above, the welds with very good microstructural properties that contain the required elements (that is high F and low L) are presented in Table 4.

Sample No.	*Weldment UTS, MPa*	*Basemetal UTS, MPa*	Weld Factor, $F_w = \frac{Weldment\ UTS, \sigma_W}{Basemetal\ UTS, \sigma_b}$ (Balkan et al, [8])	*Rank*
7	310	620	0.5	8
8	365		0.59	7
17	283		0.46	10
22	480		0.78	2
25	375		0.61	6
26	384		0.62	5
48	432		0.70	3
56	540		0.87	1
57	420		0.68	4
63	296		0.48	9

TABLE 4: Weld Factor Determination.

Table 4 shows that Sample 56 has the highest weld factor of 0.87. This indicates that Sample 56 has the highest strength value. Since Sample 56 is chosen as the weld with the best qualities, some mechanical and chemical tests were carried out to validate this claim [9].

3.4 Mechanical Test

The Brinell Hardness Number (BHN) and Ultimate Tensile Strength (UTS) of the weld produced by sample 56 (see Fig 1) was evaluated to validate the reason for selecting it as the optimum process parameter.

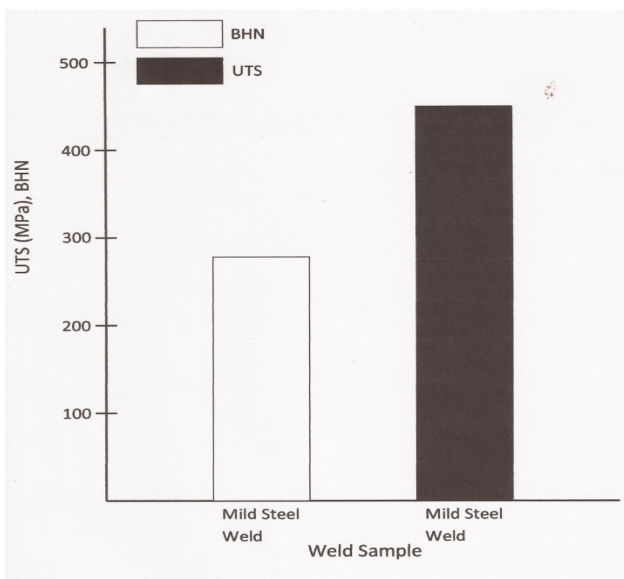

FIGURE 1: UTS, BHN Vs Weld Sample.

The microstructural view as obtained from the Econet II metallurgical microscope of the Mild Steel Weld is shown in figure 2.

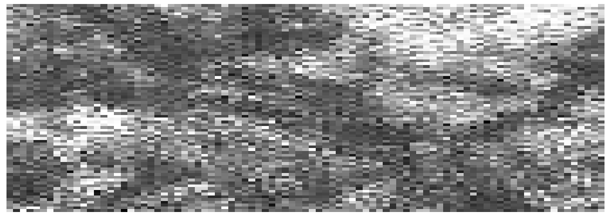

FIGURE 2: Microstructural View of the Mild Steel Weld.

4. DISCUSSION OF RESULTS

Optimum process variables were selected for welding a low carbon steel plate based on the state of the microstructure of its weld. A 64 experimental matrix design developed from the Hadamard multivariate design [7] was used in this study (see Table 1). The contents of the matrix design are presented in Table 1 where 0 signifies low level whereas, 1 signifies high level. The variables in Table 2 were allocated randomly, because, which way these variables are allocated would eventually produce the expected results.

Each of the process variables as presented in Table 2 were used in the experimental process producing three weld samples, the microstructure and impact absorbed energy were obtained. This process was conducted for the 64 experimental trials. The absorbed energies were recorded whereas, there was an expert evaluation of the microstructures and an acceptable verdict was given either as very good, bad or very bad. An average of 64 results was obtained for both the microstructure and the corresponding absorbed impact energy. Since the absorbed impact energy is quantified, it was absorbed into the matrix design which was used for the study analysis.

A standard deviation from the mean of the absorbed energy response was obtained as 16.15. The criterion for absorbed energy response (impact strength) which is the threshold value for selecting the relevant variables was calculated as 6.64 at 95% confidence level. This criterion value was used to compare with the values of each of the process variables as presented in Table 3. From the comparison, only process variables with high level of variable F and low level of variable L are required. Process variables F and L were selected from welds with very good microstructure. This match were found in only 10 welds which are presented in Table 4 and from the weld factor analysis, it was found that sample No. 56 has the best weld factor. This indicates that the weld of sample 56 has the highest strength value that can absorb impact energies without fracturing. From the study conducted, Sample 56 should comprise of low carbon steel of the size of 60mm x 60mm and this low carbon steel sample is expected to be preheated to a temperature of 200^oC to relieve the internal stresses resident in the steel sample and at the same time raises the sample to a weldable temperature. A welding temperature of 1128^oC is therefore recommended to make weld deposits, as temperature above this threshold value may cause weld spatter, that is, the weld metal should be too light or liquid to be controlled or localised in order to achieve deep weld penetration.

However, a current of 220A, voltage of 22V, welding speed of 100mm/s and welding time of 80 seconds would be adequate to conduct a desirable welding process. As the weld cools and solidifies, it would be machined with a semi-automatic lathe machine and polished using a 0.5μm emery cloth to achieve excellent smoothness. The 0.5μm emery cloth would give a smoother surface of the weld than a 1.0μm emery cloth. The smoothened weld was recommended to be etched with Hydrochloric acid before conducting a metallographic test using a microscopy. The etched welds should also be tested for their hardness and UTS, and a 220 BHN and 420MPa UTS are recommended.

Further analyses were carried out to validate this claim by investigating the mechanical properties of the selected weld sample 56. Fig. 1 shows both the Brinell Hardness Number (BHN) and Ultimate Tensile Strength. From Fig. 1, it was shown that the weld of sample 56 has a BHN of

280 and the UTS is 450MPa. The value of the BHN of 280 obtained is higher than the proposed value of 250, this could be better explained by the analysis of the microstructural arrangement of Sample 56 as presented in Fig. 2. The higher BHN has finer grains and denser microstructure. The UTS of 540 MPa obtained is higher than the proposed value of 450 MPa but falls within the range of values suggested for UTS, which indicated that the proposed value is not the expected threshold value for the low carbon steel plate considered in this study. The higher BHN value of the weldment, could influence the determination of higher UTS. Comparing these mechanical properties with those found in literature, it is observed that Achebo and Odinikuku [10] conducted a tensile test on mild steel welds and determined the UTS to be between the range of 220MPa and 520 MPa. Achebo and Omoregie [11] carried out both tensile and Brinell hardness tests on mild steel welds and obtained UTS in the range of 300MPa and 600MPa as well as BHN in the range of 150 and 350. Kumar and Kumar [12] conducted a study of mechanical properties of mild steel and found the UTS to be within the range of 328MPa and 482.2 MPa. Achebo [13] determined the BHN and UTS of carburized mild steel welds to be within the ranges of 282 and 382, and 480MPa and 720MPa respectively. The Author also determined the BHN and UTS of uncarburized mild steel welds to be within the ranges of 156 and 220, and 286MPa and 485MPa respectively. From the results of BHN and UTS obtained in this study, it can be seen that they compare well with those obtained from the results of other researchers.

Fig. 2 shows the microstructural view of Sample 56 weld. The weld sample is made of low carbon steel alloy. Baliman and Alialhosseini [14] wrote that low carbon steel has its carbon content between 0.17 and 0.2% wt. Its low carbon makes its weldability appropriate. From Fig. 2, it is the white grains that form the ferrite elements whereas the black grains form the cementite elements. Ferrite is a body centered cubic iron (α – iron) with a small amount of dissolved carbon. Ferrite is soft and ductile and gives steel good cold working properties. Cementite is iron carbide, Fe_3C; it is very hard and brittle at room temperature. The microstructure in Fig. 2 corresponds to the claim made by Ren et al [15], who said that microstructure mainly consist of acicular ferrite which can be obtained in weld metals using the wires with a low carbon content and appropriate contents of Mn, Mo, Ti, B, Cu and Ni, resulting in the high low-temperature impact toughness of weld metals. Cavaliere and Perrone [16] wrote that Yield strength is strongly inversely dependent on ferritic and perlitic microstructure and less from bainitic or austenitic microstructure, it is also dependent inversely from heat input and residual stresses. Impact strength seem to be influenced by pearlitic microstructure and which is inversely proportional to heat input. High impact strength, they said can be obtained from martensite - ferrite – austenite microstructure. Pearlite is a lamellar structure of ferrite and cementite whereas, Bainite is a structure of ferrite and cementite, its cementite is present in a needlelike form. Austenite is a face centered cubic iron (γ – iron) with a maximum of 2% carbon in solution, austenite begins to form at 723^{o}C. Martensite is a supersaturated solution of carbon in iron. It is produced by rapid cooling steel from above the upper critical temperature. Martensite has a body centered tetragonal crystal and is hard, strong and brittle. Below the lower critical temperature (723^{o}C), the microstructure is either ferrite plus pearlite, or pearlite and cementite. Above the lower critical temperature, austenite begins to form. From the above explanation, it can be deduced that because of the high strength properties of the weld microstructure of Sample 56 weld, the obtained BHN is higher than the proposed BHN.

Pluphrach [2] wrote that hardness and UTS are the most commonly specified properties of iron castings. Hardness as expressed by the author is relatively a good indication of machinability and hinted that increase in carbon as revealed by metallographical examination can reduce machinability. Topolska and Labanowski [3] wrote that light microscope examinations, hardness measurements and impact toughness tests are used to reveal the microstructure and changes observed in mechanical properties in metals. However, Singh et al. [17] cited the work of Lu et al. [6] who observed that the presence of increased content of retained austenite in the microstructure could results in lower hardness. Summarily, the weld microstructure shows that there is no presence of voids; therefore the weld is of very good quality.

5. CONCLUSION

The process variables appropriate for welding low carbon steel plates have been selected considering some suggested variables expected to enhance the quality of the weld. These selected variables are those of Sample trial number 56. The weld microstructure was found to consist of both ferrites and cementites elements and contained no void, it is regarded as being of very high quality. This explains the reason why the obtained BHN is greater than the proposed BHN. From the study conducted it was seen that the proposed value of UTS is adequate and this further confirms the adequacy of this selection process. Both the obtained BHN and UTS in this study compared well with those found in literature.

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