WELDING SEQUENCE EFFECT ON THE MECHANICAL PROPERTIES OF BS460B MEDIUM STRENGTH OFFSHORE STEEL

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Abstract

In this paper the optimum welding sequence to enhance the mechanical performance of offshore structure fabricated with medium carbon steel was presented. This was achieved by investigating the influence of altering the sequence of welding on the mechanical properties of three welded separate thick plate of dimension 120 x 120 x 120 mm from the same material. Double "V" edged preparation, the same electrode, manual metal arc welding process (SWAM) with the same welding parameters were used for weld plate manufacture. The first plate tag welding sequence one was fully welded in the upper groove before the down groove while the second plate (welding sequence two) was welded half way in the upper groove and halfway in the down groove. Both grooves were then completely filled simultaneously. The third plate (welding sequence three) was welded half way in the upper groove followed by complete filling up of the down groove before the upper groove was then completed. Specimens for tensile, compressive, impact and hardness strength test were extracted from the weld metal zone and the heat affected zone. The result of the mechanical tests carried out on these specimens revealed that welding sequence two possess the highest tensile strength of 686(Mpa) and 421 Mpa in un-weld metal region (HAZ). The weld metal regions of the same welding sequence two possess the optimal performance in compressive and impact strength but with the least average hardness value. This experimental investigation revealed that welding sequence two is the best welding sequence for the offshore steel used.

Keywords - Welding sequence; Mechanical properties; Medium strength steel; Offshore structure.

1.0 INTRODUCTION

Steel is the mostly used engineering material. The areas of application include automobile industry, civil engineering, manufacturing, oil and gas. Steel has wide area of application due to the variation of its carbon content (6). The complexity of steel arises as result of addition alloy element to iron-carbon alloy system. Steel with carbon content varying from 0.25 and 0.65 are classified as medium carbon steel while those with carbon content up to 0.25% C are classified as low carbon steel. Between 0.65-1.5% C are termed high carbon steel. Medium carbon steel is used for fabrication of fixed platform in oil and gas industry as a result of its low cost and ease of fabrication (5). Mechanical structure in offshore consist of varying steel component in term of size and geometry which are joined together mostly by welding. Welding has been identified as the preferred method of joining steel as most steels are weldable (18). Welding process is classified as either pressure welding or fusion welding. Pressure welding process is a suitable welding process of thin plate ranging from 0.5-6.0mm thick. (4). These welding processes are further classified in (17). Fusion welding process is a preferred welding method of fabricating offshore platform because of its flexibility, versatility and efficiency in welding thick plate. Prominent among the fusion welding of offshore is the shield metal arc welding (SMAW). When steel is welded, the weld portion, the heat affected zone (HAZ) and the unaffected parent material have different microstructure which depend on several factors which includes material type, heat input, welding type, and type of electrode.

Weld induced residual stress is another factor that affects the integrity of weldments depending on the residual stress (tensile or compressive) type. Residual stress distribution in welds depend plate thickness as well as local melting or fusion process (3, 5). Welding sequence has also been mentioned in (3) as one of the factors that affect residual stresses in welds. Welding sequence is defined by American welding society (AWS) as the order of carrying out weld in a weldment. It is classified by number of passes into single pass and multiple pass welding sequence. Single pass welding sequence is used to perform welding on a thin component by dividing the weld head into short section. Consideration is given to order of filling the weld. The common single pass welds are progressive, backstep, symmetry and jump. Welding sequence for multiple pass includes: Build-up edge in which the first layer is completed along the entire weld length through single pass sequence (progressive, backstep, symmetry and jump) (8). This is followed by first, second, third or the number of desired welding sequence. Build-up edge is applied in large diameter butt welded pipe joints frequently used in boiling water reactors, oil pipe line transport system and steam piping system. Another welding sequence is the Block welding type. In this sequence, a given block of the joint is welded completely and then the next block is welded. Cascade welding sequence is similar to block welding sequence; the main difference is that in the block welding type, the block overlap in cascade.

Previous literatures have revealed that in welding medium carbon steel with carbon content greater than 0.3 percent, pre-heating is required to archive a satisfactory weld. The differential cooling rate between the core and the surface of thick plate during welding has been reported to enhance the weld crack (7). Preheating and the use of low hydrogen electrode have been suggested to reduce the tendencies of weld crack (5). The appropriate temperature ranges for pre-heating before welding medium carbon steel with combine thickness greater than 40 mm according to sources have been suggested to be 250 ^{O}C (10, 11, 17). Unlike in thin plates, welding of thick plate require edge preparation which include shapes like V, U, J and square. These shapes can be single or double edge preparation depending on the thickness of the material. The V groove preparation has the advantage of welding accessibility as well as ease of machining, but it is prone to residual stresses if the right welding methods are not employed (3). In references 2 and 3, the range of groove angle for material thickness greater than 19 mm was mentioned to be 60^{o}-75^{o}.

In references 1 and 14, certain fundamental problems that should be addressed pertinent to weldments were outlined for designers and fabricators of engineering structure. Such structures include offshore structures which are designed for 20 to 25-year service lives (9). Offshore structures are subjected to highly dynamic fatigue loads in harsh marine environments throughout their service lives. These loads result into origination of cracks, which could lead to propagation and failure of such structures. Since fatigue cracks usually originate from the weld

HAZ and grow into the parent material, the variation of the mechanical properties of such weldments needs to be understood in order to establish the optimum welding sequence that will ensure reliability, safety and efficiency of the structures. In this paper, three different welding sequences have been employed to weld BS460 medium strength offshore steels. Mechanical tests which include, tensile, compressive and hardness were carried out on samples that were extracted from the three weld sections. These are discussed in the following section.

2.0 MATERIALS AND METHODS

2.1 Materials

The material that was used for this research was a BS460B rectangular steel block of dimension 500 mm x 120 mm x 120 mm. The material was sourced from the Ajaokuta Steel Company Kogi State, Nigeria and the material composition is shown in table 1. The electrode that was used for welding was a 4 mm thick, 350 mm gauge length low hydrogen electrode designated E7018.

Table 1: Chemical Composition of BS460B steel

Element	Composition (%)
C	0.33
SI	0.289
S	0.003
P	0.005
Mn	0.029
Cr	0.090
Mo	0.05
Ni	0.027
V	0.03
Fe	0.147

2.2 Methods

The rectangular steel block was cut into three square blocks of 120 x 120 x 120 mm using a power arc saw. Figure 1 shows one of the square blocks. During the cutting operation, it was ensured that adequate lubrication was used in order to get a satisfactory output from the cutting blade.

Figure 1: 120 x 120 x 120 mm steel block

2.2.1 Edge preparations

The edge preparations were carried out cutting each of the three blocks into two equal halves of dimension 120 mm x 120 mm x 60 mm on milling machine using the slating saw. Each of the halve block was further milled to 35 mm in order to achieve a 70^{0} grove angle. The two halve milled plate were then brazed to ensure the desire angle is maintained and to allow for safe handling during pre- heating and welding. Electrode of 3 mm thickness was inserted between milled plate before brazing to serve as weld. Also 4 mm weld root face was left on the milled surface according to (ISO Standard design). The brazed plates were then pre-heated to 250 ^{0}c before welding to prevent cracking of the weld metal.

2.2.2 Welding Sequences of the plates

The model for welding thick plate developed by (8) was used to fill weld each of the double "V" groove in which each of the two grooves of each block were divided into two portions using the height of each groove as a reference point. The welding sequence that was adopted was similar to the one designed for thick butt welds in reference 8 as shown in Figure 2. Each of the portion was labeled 1 ,2 ,3 and 4. Each of these portions of the steel block were weld filled in different order with the same electrode, current, voltage setting and the same preheating temperature of 250 ^{0}c.

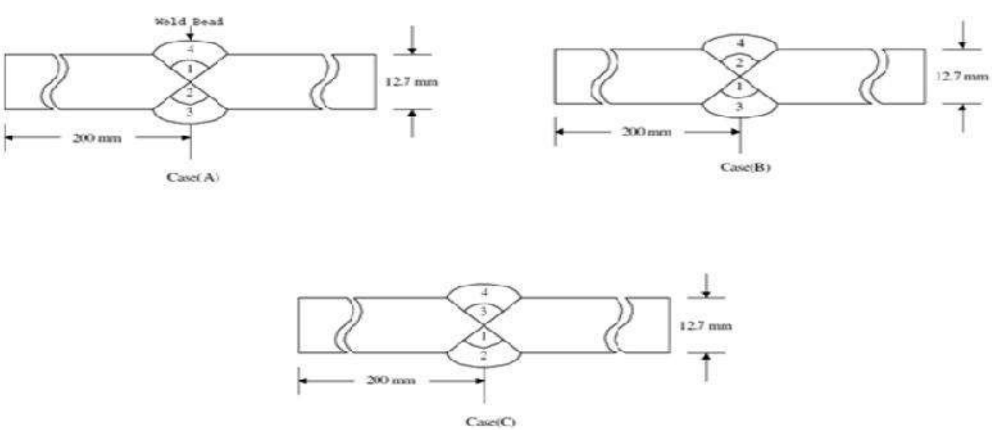

Figure 2: Different welding sequence for butt weld

(i) In welding sequence one, portion one and two was completely welded before portion 3 and 4

(ii) In welding sequence two the filling of upper and lower groove were done interchangeably. That is half of the lower grove followed by half of upper groove. The welding sequence was completed by filling the lower groove and lastly the upper groove.

(iii) In welding sequence 3, half of lower groove was filled first, followed by completely filling the upper grove and finally the last portion of the lower groove. Figure 3 shows the sample of the complete welded plate

Figure 3: Sample of welded steel plate (block)

2.2.3 Slicing of the welded steel block into plates:

In order to extract specimens from different zones of the weld for mechanical tests and for etching so as to reveal the weld, the welded blocks were sliced into different thickness according to the requirement of thickness and dimensions of the test piece. The slicing was carried out on universal milling machine while the etching was done with 2% Nital.

2.2.4 **Design and Extraction of Specimens from the sliced plates**

Specimens to be used for tensile, compressive and impact tests were extracted within the weld metal and outside the weld metal regions of each welded block as shown in Figure 4 and Figure 5. The figures show standard tensile test specimen design. The black portion on Figure 4 and 5 is the weld metal portion while the remaining portion contain the heat affected zone and the un-affected base metal. The designs of impact and hardness test specimens are shown in Figures 6 and Figure 7.

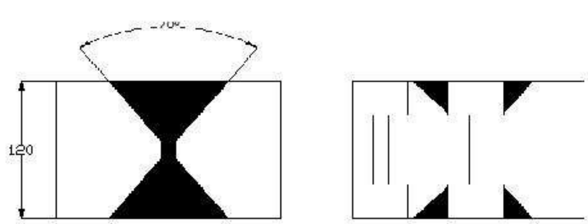

Figure 4: Positions of tensile and compressive specimens on weld block

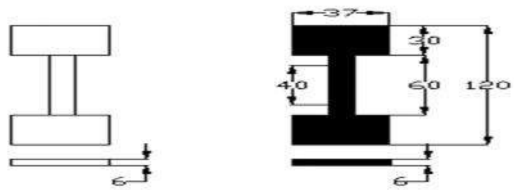

Figure 5: Tensile and compressive specimens design

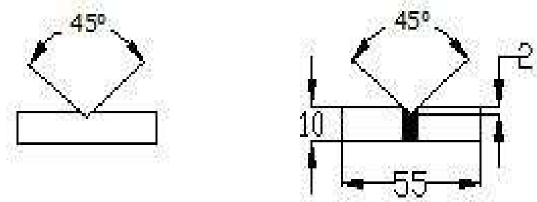

Figure 6: design of the impact test specimen

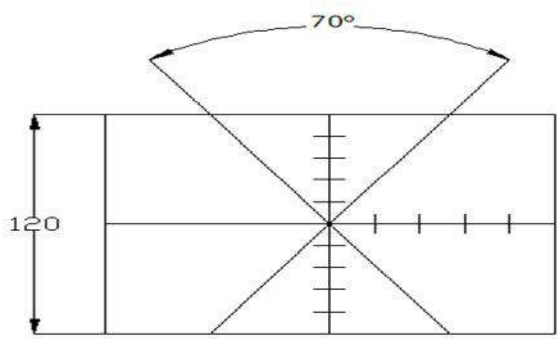

Figure 7: Design of the hardness test specimen

2.3 Mechanical Tests

For tensile tests, twelve numbers of specimens were used; four specimens were extracted from each welding sequence; two each from un-weld metal/(HAZ) and weld metal region. Monsanto tensometer was used to carry out the tensile and compressive tests. The initial gauge lengths, original widths, original thickness of specimens were measured and recorded. The tensile specimen was clamped on the Monsanto tensometer. The load was gradually applied to the specimen by turning the hand wheel gradually and steadily. The applied load readings at the hand wheel at every 0.2 mm interval of extension on the dial gauge were observed and recorded until the specimen fractured. The fractured test pieces (specimen) as well as the extensometer were carefully removed from the machine. Thereafter, the two pieces of fractured specimen were joined together, the final gauge length was measured and recorded, the final width and thickness of fractured point were also measured and recorded. The graph of the load against extension was automatically plotted by the machine. For compressive tests, the same number of specimens as those used for tensile tests was selected. The compressive specimen was firmly clamped on the tensometer vial a suitable compression gauge, after which the load gauge was reset to zero. The machine is equipped with a compression device that reverses the tensile pull of the machine to compressive load on the specimen. The load was gradually applied on the specimen by turning the hand wheel of the tensometer until it buckled. The load which buckles the specimen was observed and recorded. The buckled specimen and compression gauge were gently removed from the machine.

An Avery Birmingham impact testing machine was used to carry out the impact tests. The pendulum arm of the machine was allowed to swing freely to ensure freedom of movement after which it was positioned to its rest. The room ambient temperature of 35^{o}c was observed via the thermometer. The specimen was firmly clamped such that the notch faces the striker, after which it was engaged by clamped lever. The loose pointer was then adjusted to the fixed point's position. Thereafter, the striking medium was set in such that the flat surface was facing the release direction. The release lever was carefully disengaged which allow the pendulum arm to swing and strike the specimen and fractured it. The final energy reading on the scale as registered by the loose pointer was observed and recorded. The clamping lever was unlocked and the fractured specimen was removed from the vice. The above procedures were repeated for other specimen. Hardness test was carried out using Brinell hardness tester. The hardness was carried out on different portion (phases) of the plates. A was applied load to the surface of the material to be tested via a hardened steel ball of known diameter (Indenter). The diameter of the resulting permanent indentation in the tested metal was measured and the Brinell hardness number was calculated using the relationship in equation 1.

$$BHN = \frac{2P}{\pi D(D - \sqrt{D^2 - d^2})} \qquad (1)$$

Where;
BHN = Brinell Hardness Number,
P = Applied Load (kgf)
D = Diameter of indenter (mm) = 2 mm, d = Diameter of Indentation (mm)

The three etched plates, one each from each of the welding sequence ware used as specimens for the test. Each of the plates was marked at equal intervals within the weld metal portion and across the heat affected zone and the un-affected base metal. A hardened steel ball of 2 mm diameter indenter was selected and was firmly fixed on the indenter's holder. The specimen was gently positioned on the anvil and a required load of 115 kg was added to the weight hangers of 5 kg which sum up the load to 120 kg. The load lever was released to apply the load on the plate and a stop watch was simultaneously started from zero to 15 seconds. After which the load lever was used to retract the specimen from the indenter. The process was repeated for different marked positions on the plate. The hardness values of each portion were calculated using equation 1. These procedures were repeated for the other two plates.

3.0 Result of the Mechanical Test

The result of tensile and compressive properties of three welding sequence studied are tabulated in table 2. From table 2, it can be seen that the result of the tensile strength shows variation of mechanical properties of specimen extracted at different portion of the welded plate. This variation is similar to those reported in reference 3. Differential cooling rate between the surface and core of the thick plate material been welded has been attributed to this variation. Welding sequence 2 has the highest ultimate tensile strength of 686.38 Mpa and 431.30 Mpa in HAZ and weld metal region respectively. Also from table 2 the same welding sequence two has the highest strength of 342 Mpa in compression along the weld metal region. However, welding sequence one has the highest compressive strength of 388.12 along HAZ region. The tensile properties obtained from welding sequence 2 agree with the study carried out on welded joint of similar medium carbon steel (12). Welding sequence one has the least yield strength of 318.50 Mpa in weld metal region and lowest % elongation of 7.00 in weld metal region. Generally, the weld metal portion exhibited higher percentage elongation, more ductile but lower yield strength compared to un-weld metal region.

The results of impact tests are displayed in table 3 where it can be seen that welding sequence one has the highest impact energy of 30 joules in un-weld metal portion (HAZ). Tensile test result shows that this region has the highest percentage elongation among the three sequence in un-weld metal region. These results agree with those reported in references 13 and 16. The weld metal of welding sequence 2 has the highest impact strength of 177 joules with highest percentage elongation of 30 %. The weld metal region of welding sequences 1 ,2 and 3 have higher impact energy than the un-weld metal region unlike the tensile test result. This may attribute to differences in composition of weld to base metal as reported by (5 and 6). From table 4 and 5 the result of hardness value across the weld metal show that the hardness values across the three w/s vary significantly as a result of different cooling rate and re-melting after solidification as suggested by (3 ,6). Welding sequence one has the highest average hardness value 171 BHN, which may be as a result of formation of coarse grain due to high cooling rate. The center of the weld has close hardness values which may be as result of rooting that was done in a similar way before sequence filling of the groove. Figure 7 shows the hardness curve along the weld metal region

Table 2: Tensile and compressive test result of welding sequence one, two and three

Tensile Properties	Yield strength (N/mm^2)	Tensile Strength (N/mm^2)	Breaking Strength (N/mm^2)	% Elongation	% Reduction in area	Compressive strength (N/mm^2)
Plate 1&2: W/S 1 weldment	318.50 302.89	380.61 302.89	369.81 292.07	7.00 7.00	19.00 18.00	327 326
Plate 1&2: W/S 1 un-weld metal	389.08 420.00	520.12 510.20	520.18 510.20	7.00 6.00	29.00 28.00	386 388
Plate 1&2: W/S 2 weldment	331.32 320.30	431.70 412.20	317.32 355.85	13.70 11.25	60.93 43.89	342 306
Plate 1&2: W/S	589.62 506.50	686.23 633.12	686.38 633.12	6.00 7.50	13.00 17.00	570 347

2 un-weld metal						
Plate	342.48	420.16	363.20	6.40	20.89	327
1&2:	353 .98	353.98	353.98	9.50	34.23	
W/S 3						302
weldment	542.30	542.30	538.90	4.50	20.80	344
Plate1& 2: W/S 3 Un-weld metal						
	543.98	543.98	540.98	4.50	27.00	308

W/S: Welding sequence

Table 3: Impact test result of welding sequence 1, 2 and 3

W/S 1-3	PORTION OF EXTRACTION OF SPECIMEN	IMPACT ENERGY ABSORBED (J)	% ELONGATION
WELDING	weldment of plate 1	175.3	7.9
SEQUENCE 1	and 2	158	7
	un-weld metal plate	25.6	3.5
	1 and 2	30	7
WELDING	weldment of plate 1	159	13.7
SEQUENCE 2	and 2	177	11.25
	un-weld metal of plate	27	6
	1 and 2	24	7.5
WELDING	weldment of plate 1	122	6.4
SEQUENCE 3	and 2	131	9.5
	un-weld metal of plate	29.5	4.15
	1 and 2	25.6	4.75

W/S: Welding sequence

Table 4: Hardness Test Result across the Weldment of W/S 1-3

Distance from etched plate edge (mm)	W/S 1 Hardness value (BHN)	W/S 2 Hardness Value (BHN)	W/S 3 Hardness Value (BHN)
5	159	143	159
10	159	143	159
15	179	143	168
20	179	143	168
25	179	179	179
30	229	229	229
35	168	159	179

40	143	159	179
45	143	151	143
50	143	143	143

W/S: Welding sequence

Table 5 Variation of hardness of base metal close to center of the fusion zone

Distance from center of the plate to base metal (mm)	W/S One Hardness Value (BHN)	W/S Two Hardness Value (BHN)	W/S Three Hardness Value (BHN)
3	229	229	229
6	229	2277	228
9	228	225	220
12	220	227	219

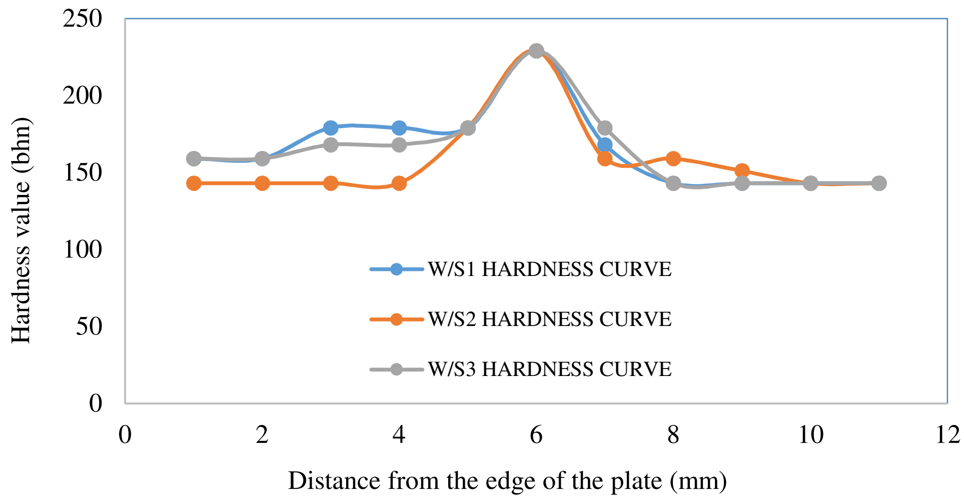

Figure 7: Variation of hardness value along the weld metal of sequence 1, 2 and 3

4. Conclusion

The following conclusion can be drawn from the result obtained;

1. Welding sequence two has the best performance in term of tensile strength having the highest strength of 430 Mpa in the weld metal region and 686 Mpa un-weld metal region. Also welding sequence two possess the highest strength in compression especially along the weld metal where failure can emanate easily and is therefore the best welding sequence where tensile and compressive strength are desirable.
2. Welding sequence one possess the highest hardness value along the weld metal and the HAZ region and is therefore the welding sequence that has the best performance in hardness.
3. Welding sequence two also has the best value of impact energy absorbed during the impact test having the impact energy of 177 joules in weld metal region.

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