ADVANCED TECHNOLOGIES AND MATERIALS VOL. 44, NO. 2 (2019)
DOI: 10.24867/ATM-2019-2-003

ADVANCED TECHNOLOGIES & MATERIALS

http://journal-atm.org

Distinctiveness of Welding Joints Design Based on Mechanical and Corrosion Environmental Influence on Low Carbon Steel

Isiaka O. Oladele,[a] Davies B. Alonge,[a,b] Timothy O. Betiku,[a,c], Abel A. Barnabas[a], S. A. Shittu[a]

[a]Department of Metallurgical and Materials Engineering, Federal University of Technology, PMB, 704, Akure
[b]Technische Universität Darmstadt, 64289 Darmstadt, Germany
[c]Université Grenoble Alpes, Grenoble Institute of Engineering- PHELMA, 38000 Grenoble, France

ABSTRACT

Experimental investigations were carried out to study the effect of weld joint designs and post weld heat treatment (PWHT) on mechanical and corrosion properties of low carbon steel. Butt, bevel and half-lap joints were produced with a voltage of 20 V and current of 110 A with the use of 3.2 mm diameter electrode E6013. Full annealing was carried out on part of the welded samples in order to consider the possibility of post weld heat treatment for better performance. The mechanical properties (tensile, hardness, and impact toughness) were studied for both the as welded (AW) and PWHT samples as well as the corrosion performance in a natural sea water environment containing 3.5 wt.% NaCl using potentiodynamic polarization method. The microstructure of the AW and PWHT samples of the welded joints with the most promising mechanical and corrosion properties were then characterized by means of an optical microscopy. The results obtained reveals that the bevel joint followed by half lap joint and the butt joint of the as weld samples gave the best combination of the mechanical properties considered. On the other hand, the corrosion properties of the butt joint were superior to that of the bevel and half lap joint, respectively in the PWHT condition as compared to the AW samples. This implies that PWHT improves the corrosion resistance of the welded steel joints.

Key words: *low carbon steel; optimum welding parameters; weld joint design; post weld heat treatment.*

1. INTRODUCTION

Structural integrity is crucial in many industrial sectors where welding is the main technique for joining. In most structures, welds are identified as critical sections and are susceptible to mechanical failures [1]. The form of weld joint employed for any welding job may significantly affect the quality and strength of the weld, the labour cost and performance of the weld joint during service. Welding quality can be attained by meeting the essential requirements like bead geometry, porosity, inclusions and control by sensing either directly or indirectly the welding parameters involved in the arc welding process [2]. At present, welding is used in a wide range of applications and in many industries. The process of welding consists in forming a permanent joint of separate elements [3]. Choice of a correct weld joint design is critical to successful fabrication having mechanical characteristics that is at least as good as those of the base metal. Likewise, critical consideration should be given to the corrosion behavior of the joint [4]. Generally, poor joint design can negate even the most optimum welding conditions. Hence, a major consideration of weld joint design especially in arc welding is to provide enough accessibility and space for movement of the welding electrode or filler metal to achieve proper weld bead [5]. In half-lap joint, some material is removed from each of the members and the joint is the thickness of the thickest part which allows welding with less restrictive joint fit-up tolerances [6]. Conversely, welding process generally involves melting and subsequent cooling which results in the development of residual stress. This creates potential problems either immediately or during the life of the welded structure which can be removed through post weld heat treatment operation [7]. Likewise, corrosion

---

* *Corresponding author's.e-mail: iooladele@futa.edu.ng*

Received: 3 October 2019; Accepted: 24 November 2019

susceptibility of a weldment can be reduced by PWHT through reduction of residual stress gradients that stimulate stress-corrosion cracking (SCC) [8]. The treatment can also reduce micro-segregation and corresponding micro-galvanic cells.

Previous works have studied the effects of welding process parameters on mechanical properties using different weld joint designs. The effects of post weld heat treatment on the mechanical properties of tempered martensite and high strength steel welded joints has been studied [9]. The result obtained showed that hardness values in heat affected zones of tempered martensite steel were decreased with increasing post weld temperatures. Investigation was carried out to study the effect of repeated post-weld heat treatment on valves made of low-carbon steel, ASTM A216WCB [10]. The results of the study found that A216WCB's hardness, yield and tensile strength decreased by 6%, 2.98% and 6.9% respectively after 20 heat treatment cycles. This was attributed to recovery and some recrystallization due to the PWHT adopted. Momoh *et al.*, [11] carried out PWHT on 0.33% C low alloyed steel joined by Submerged Arc Welding (SAW) technique and investigated the resulting mechanical properties. Improved hardness and tensile properties were reported after heat treatment of the selected steel. Single V-groove butt joint of medium carbon steel were produced by arc welding, heat treated, and the resulting microstructure and mechanical properties evaluated by Dodo *et al* [12]. It was reported that full annealing modified the grain structure, improved ductility and toughness with appreciable reduction in strength and hardness of the weldment compared to the AS samples. The effects of fatigue strength between fillet lap joints and butt joints by the tensile load fatigue test was investigated [13]. The results obtained confirmed that the fatigue strength of butt joints increases two-fold more than that of fillet lap joints, while fillet lap joints and half penetration butt joint on which the root portion cracks generated remained impervious to the effects of high strength welding wire. The published papers have provided results on how PWHT influences mechanical properties. However, the effect on half lap joint on the mechanical and corrosion behavior have not been considered. Therefore, in this study, the effects of weld joints design and PWHT on mechanical and corrosion properties of low carbon steel using arc welding were examined. The weld joint designs considered were half-lap, bevel and butt joint. Subsequent to welding of the samples, full annealing was carried out on part of the welded samples before subjecting both the AW and PWHT samples to mechanical and corrosion tests.

2. MATERIALS AND METHOD

The materials used for this research were low carbon steel and mild steel electrode E6013 with chemical compositions as shown in Tables 1 and 2.

Table 1 - *Chemical composition of low carbon steel (%)*

Elements	Fe	C	Mn	Si	P	Ni
Compositions	98	0.157	0.279	1.28	0.0213	0.022

Table 2 - *Chemical composition of mild steel electrode E6013 (%)*

Elements	Fe	C	Mn	Si	P	Ni
Compositions	bal.	0.12	0.3	0.35	0.04	0.035

The low carbon steel was cut and machined into the required dimension and shape based on the intended joint designs as shown in Fig.1. The samples were joined together through butt, half-lap and bevel joint using MMAW machine techniques at a welding voltage 20 V and welding current of 110 A with the use of E6013 and 3.2 mm diameter as filler material. Subsequent to welding of the samples, part of the samples was subjected to full annealing at temperature of 850 °C for 1 hour. Tensile and hardness test were carried out on both the AW and PWHT samples. Corrosion analysis of the base metal (BM), weld metal (WM) and heat affected zone (HAZ) of both the AW and PWHT samples were also determined.

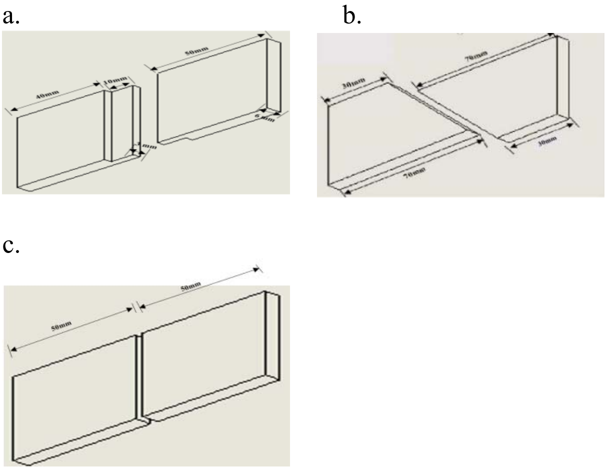


Fig. 1 *Half lap joint sample (a); bevel joint sample (b); butt joint sample (c)*

2.1 *Mechanical and corrosion tests*

Universal Testing Machine was used to carry out the tensile test on the samples. The ends of test samples were fixed into the grips connected to a straining device and to a load measuring device. Once the test sample fractured the result was generated by the computer software.

Izod impact test was carried out on the samples using Honfield Balance Impact Testing Machine according to ASTM E23. Before mounting on the machine, the test samples were notched to a depth of 2 mm with V-shaped hand file. The notched test samples were mounted on the impact testing machine, which was operated to apply a constant impact force on the test samples. The amount of impact energy the specimens absorbed before yielding were read off the calibrated scale on the impact testing machine.

The hardness of the BM, HAZ and WM across the welded joint of the samples was determined using a digital Vickers micro-hardness tester, Indentec Hardness Testing Machine according to ASTM E92-17 at an interval of 5 mm from the WM.

The welded samples with different weld joint designs of the low carbon steel were cut into equal sizes (10 x10 mm) of BM, WM and HAZ. The samples were mounted and polished before subjecting them to Tafel corrosion test using AUTOLAB potentiodynamic polarization test in natural sea water containing 3.5 wt.% NaCl solution.

2.2 *Microstructural analysis*

Weldment of both the AW and PWHT samples which comprises of the WM, HAZ and BM from the different weld joints were ground with different grades of emery papers and polished with selvyt cloth swamped with solution of 0.5 µm Silicon carbide until a mirror-like surface was attained. These samples were selected and viewed based on the optimum performance exhibited in both mechanical and corrosion tests. The mirror-like surface was etched in 2% NITAL (2% Nitric acid and 98% of Ethyl Alcohol) after which it was washed and dried. The microstructure of the weldment was viewed with an Accu-scope optical microscope.

3. RESULTS AND DISCUSSION

3.1 *Mechanical properties*

3.1.1 Tensile properties

The tensile properties which include stress-strain curve, tensile and yield strengths of the weld joints in the AW, PWHT and as received (AR) samples are presented in the Figs. 2 and 3.

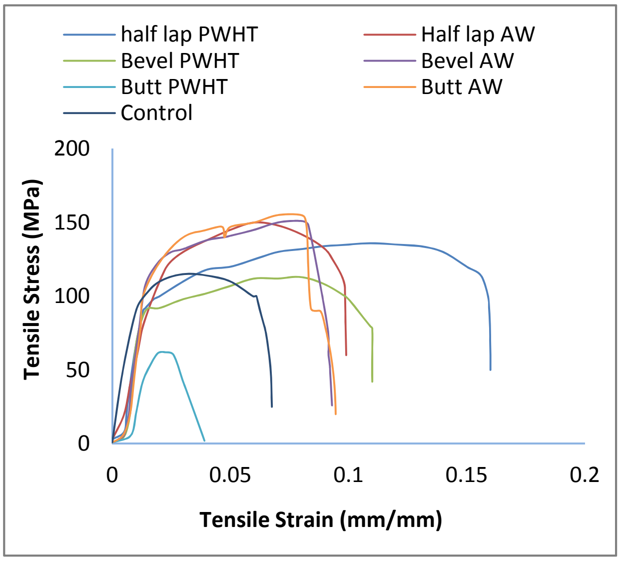


Fig. 2 *Tensile stress-strain curves for the AW and PWHT samples with different weld joints and control sample.*

The stress-strain curves of the AW and PWHT samples with different weld joints and the control sample that represent as received sample were shown in Fig 2. The response of the samples showed that AW samples from all the various weld joints possess high tensile strengths compared to the PWHT samples. Butt joint welded sample followed by bevel and half lap joints, respectively for the AW samples gave better tensile strengths compared to the PWHT and control samples. However, the reverse was the case after heat treatment as half lap followed by bevel and butt joints gave best results. After heat treatment, the tensile strengths of both half lap and bevel joints samples compete favorably but butt joint sample strength was drastically reduced. It was noticed that PWHT improved the elongation potentials of half lap and bevel joints welded samples compared to the AW samples and the control. These observations may be due to their joint designs which does not allow easy propagation of cracks coupled with the reduction in the induced internal stresses by annealing operation that was carried out on the samples which resulted to the reduction in the strength. Therefore, the welding operation and PWHT led to increment in the tensile properties of the bevel and half lap joints welded samples compared to the as-received sample.

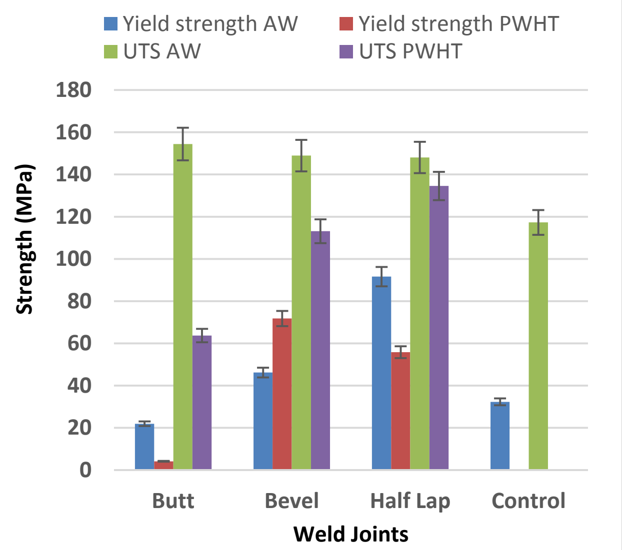


Fig. 3 *Tensile properties for the AW and PWHT samples with different weld joints and control sample.*

The charts for ultimate tensile strength (UTS) and yield strengths properties for the AW and PWHT samples with different weld joints as well as that of the control sample were as shown in Fig 3. It was revealed from the results that the ultimate tensile strengths of the AW samples were higher than that of the PWHT samples and the control. A trend was observed in the AW samples showing a decrease in UTS from butt joints to half lap while the yield strengths increased in a similar manner. Conversely after heat treatment, the trend changed as the ultimate tensile strengths increase from butt joint to half lap while the yield strengths displayed no special trend. From the results, AW butt joint has the highest ultimate tensile strength with value of 154.43 MPa followed by both the bevel and half-lap joint which has almost equal tensile strength with values of 148.95 and 148.06 MPa, respectively. This shows that the butt joint can withstand higher load before fracture than both the bevel and the half-lap joints. However, after subjecting the AW samples to post weld heat treatment, their tensile strength was reduced by 58.73, 24.05 and 9.12 % with values of 63.73, 113.13 and 134.56 MPa for butt, bevel and half-lap joints, respectively. From the results, only half lap joint has higher ultimate tensile strength than the control sample which has an ultimate tensile strength value of 117.30 MPa. This showed that the treatment employed did not have a significant effect on the tensile properties of half lap weld joint compared to bevel and butt joints. This could be that the influence of the annealing operation on the weld surfaces differs due to the differences in the weld geometry from the various welding joints thereby posing varying effects on the re-crystallization process of the welds [14].

In terms of yield strength, for the AW samples, half-lap joint has the highest with value of 91.62 MPa followed by the bevel joint with value of 46.19 MPa while the butt joint has the lowest yield strength with value of 4.15 MPa. This shows that the sample with half-lap joint will require higher stress to trigger plastic deformation than the bevel joint and control samples while the butt joint will require lower stress to activate plastic deformation. The ability of the half-lap joint to require high amount of stress to activate plastic deformation may be as a result of its joint design which adds to the performance efficiency of the weld [15]. On subjecting the AW samples to post weld heat treatment, it was observed that there was an increment in the yield strength of sample with bevel joint by 35.66 % with a value of 71.79 MPa while the yield strength was reduced by 81.08 and 39.06 % with values of 4.15 and 55.83 for butt and half-lap joints, respectively. This may be that the annealing process helped to relieve the residual stress induced in the weld joints during the welding process which in-turn eliminated pile up of dislocation thereby making the grains appear renewed and distortion free which leads to decrease in the yield strength of the samples [16].

3.1.2 Hardness

The hardness test result for the weldment of AW, PWHT and control samples were as shown in Fig.4. It was observed that the hardness of the AW samples was higher than that of the PWHT samples, which shows that the post weld heat treatment influences the AW samples. The average hardness values obtained across the weldment of bevel, butt and half-lap joints samples were 75.52, 72.97 and 69.26 HV respectively. After subjecting the AW samples to post weld heat treatment, the hardness values reduced by 2.94, 4.21 and 2.86 % with average hardness values of 73.30, 69.90 and 67.28 HV for bevel, butt and half-lap joint respectively. From the results, AW sample from bevel joint has higher hardness than the control sample with hardness value of 73.70 HV. The decrease in hardness value across the weldment after post weld heat treatment may be as a result of the annealing operation which served as a stress relieving process by reducing the residual stresses induced in the weld metal during welding [17,18]. The annealing operation could also allow uniform diffusion of carbon atom by reducing the concentration of carbide present in the AW samples.

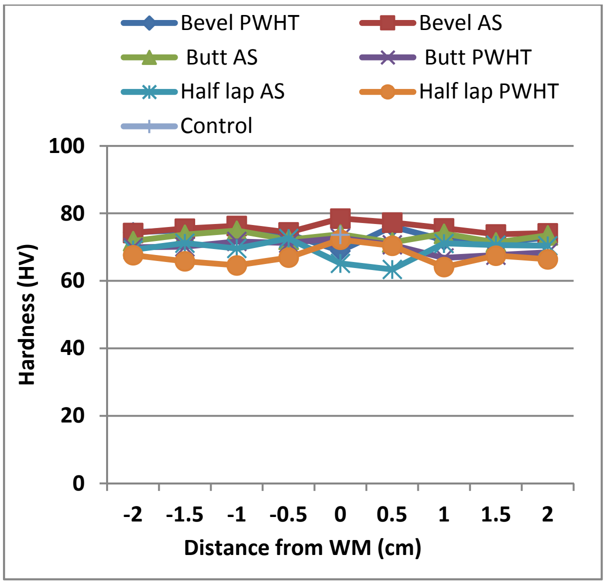


Fig. 4 *Variations in hardness value across the weldment of AW, PWHT and the control samples.*

3.1.3 Impact

From Fig.5, similar trend to the results of the ultimate tensile strength in Fig.3 was observed for both the AW and PWHT samples. The AW samples have higher impact energy than the PWHT samples for all the various weld joints design investigated. However, butt and bevel joints of the AW samples have the highest values of 62.97 and 62.15 J, respectively

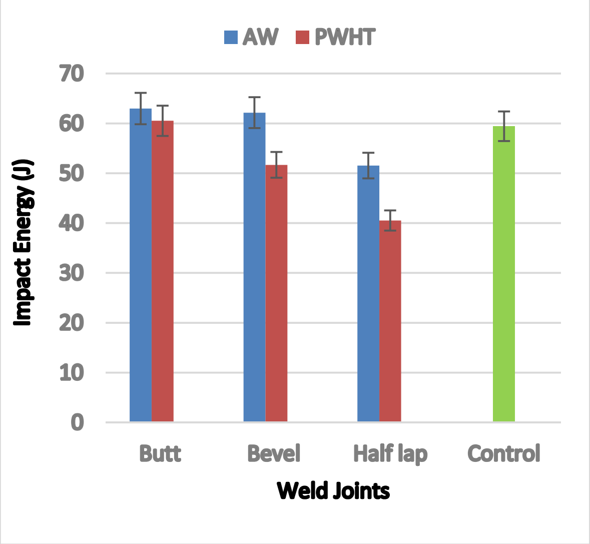


Fig. 5 *Impact energy for the AW, PWHT and control samples.*

After annealing, it was observed that the PWHT samples showed lower impact energy compared to their AW samples. The impact energies reduced by 3.89, 16.85 and 21.36 % for butt, bevel and half-lap joints, respectively. The reduction could be due to its joint design and re-crystallization process that could possibly be taking place during the annealing operation which relieved the internal stresses (residual stresses) and in-turn decreased the impact strength of the PWHT samples [19]. Therefore, butt joint has the highest impact energy for both AW and PWHT samples (62.97 and 60.52 J, respectively) and it was the only weld joint design that gave enhanced impact energy than the as received sample (59.43 J) that serves as control.

3.2 Corrosion properties

The graphs obtained from the experiments revealed that the polarization and passivity characteristics of the samples were analogous. Though, the corrosion current densities (Icorr) and corrosion potentials (Ecorr) show distinct corrosion behaviour between the AW and the PWHT samples. In most cases, it was also observed that the corrosion current densities were more intense for the AW samples in comparison with the PWHT samples. This indicates that the PWHT samples are more corrosion resistance than the AW sample in the environment. The plots in Fig.6, shows the corrosion performances of the weldment of the AW and PWHT samples with bevel joint. It was observed from the plot that corrosion susceptibility of the BM, HAZ and WM of the AW samples decreased after post weld heat treatment, which was in agreement with the Icorr value. The BM after PWHT had the least Icorr value showing that it is least susceptible to corrosion**.**

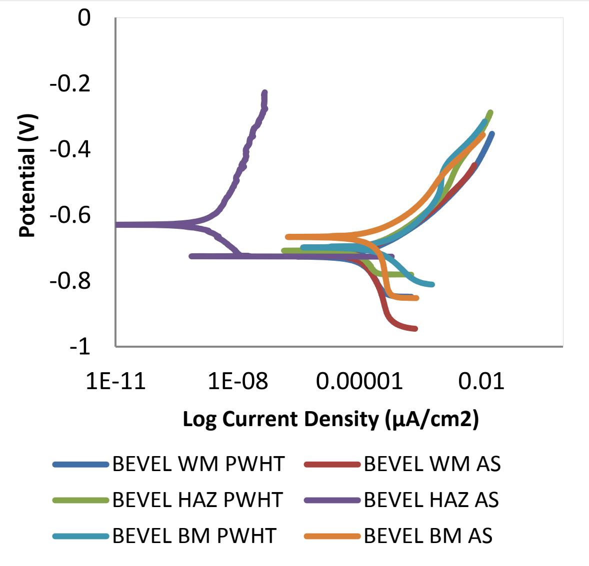


Fig. 6: *Potentiodynamic polarization curves of the AW and PWHT samples with bevel joint in natural sea water containing 3.5 wt% NaCl solution.*

From Fig.7, it was observed that the corrosion susceptibility of the weldment of the AW samples with butt joint was decreased after post weld heat treatment with the HAZ sample having the least corrosion susceptibility after PWHT. In addition, the WM of the butt joint showed better corrosion resistance compared to the bevel and half lap joint WM. It was observed from Fig.8 that the corrosion susceptibility of the half lap sample of HAZ decreased after PWHT. However, the Icorr values after PWHT increased in the WM and BM of the joint thereby reducing its corrosion resistance compared to the AW samples. Generally, the decrease in the values of the corrosion current densities (Icorr) of the weldment after post weld heat treatment decreased their susceptibility to corrosion and in all cases the PWHT employed proved to improve the corrosion resistance of the butt and bevel joint.

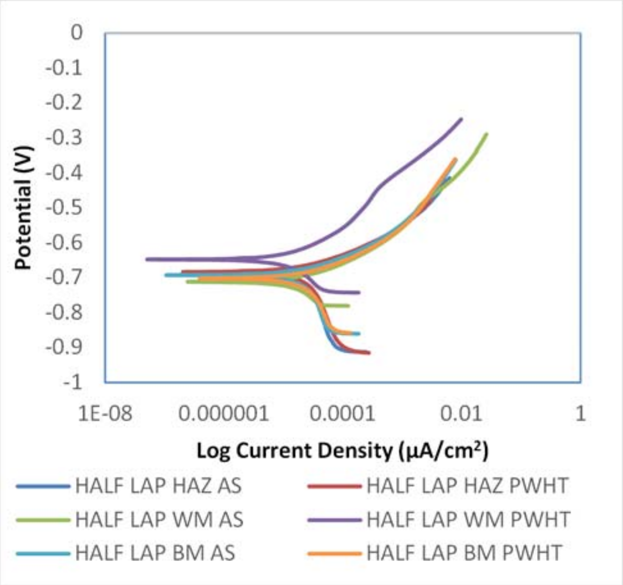


Fig. 7: *Potentiodynamic polarization curves of the AW and PWHT samples with butt joint in natural sea water containing 3.5 wt% NaCl solution.*

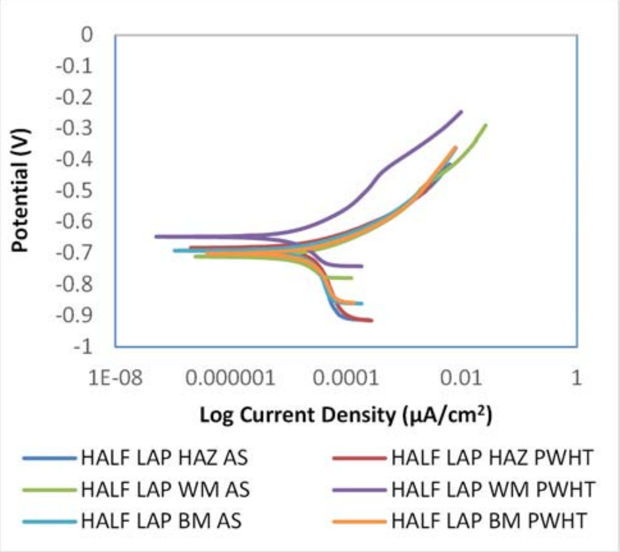
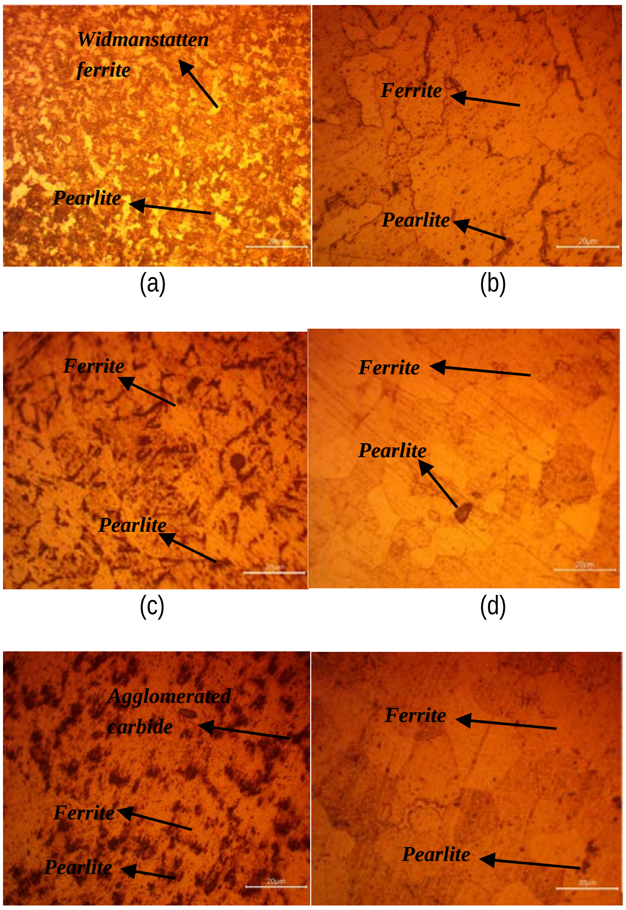


Fig. 8: *Potentiodynamic polarization curves of the AW and PWHT samples with half lap joint in natural sea water containing 3.5 wt% NaCl solution.*

3.3 Microstructure examination

The optical micrographs of the weld metal of the AW and PWHT samples with different weld joint were as shown in Fig.9. The micrograph in Fig.9(a) shows the microstructure of the WM of the AW sample with bevel joint. It was observed that it consists of the widmanstatten ferrite, ferritic and pearlitic phase which are randomly dispersed.

After the WM of the AW sample with bevel joint has been subjected to full annealing operation, micrograph in Fig.9(b) was obtained which is the microstructure of WM of the PWHT sample with bevel joint. It was observed that the Widmanstatten ferrite was eliminated while the amount of pearlite present reduced and finely dispersed randomly across the ferritic phase. This could occur as a result of excess carbon atoms ejected from the ferrite phase at higher temperature (850°C) above its lower critical temperature which the sample was subjected to.



(a) (b) (c) (d) (e) (f)

Figure 9. *Optical micrographs of weld metal of: (a) AW of Bevel joint; (b) PWHT of Bevel joint; (c) AW of Butt joint; (d) PWHT of Butt joint; (e) AW of Half lap; (f) PWHT of Half lap.*

The micrograph in Fig.9(c) shows the microstructure of the WM of AW sample with butt joint. From the microstructure, it was observed that coarse pearlites were randomly dispersed in the ferritic phase. This could be as result of heat of welding which does not allow uniform diffusion of the carbon atoms in the ferritic phase but rather short and random diffusion of carbon atoms which make them to agglomerate randomly forming pearlitic phase dispersed in the ferritic phase. After the WM of the AW sample with butt joint has been subjected to full annealing, micrograph in Fig.9(d) was obtained. The pearlitic phase dissolved thereby making the carbon atoms to diffuse uniformly in the ferritic phase forming coarse ferrite structure and some colonies of pearlite [20].

The micrograph in Fig.9(e) represents the microstructure of WM of the AW sample with half lap joint. From the microstructure, it was observed that after welding, there were formation of refined grains of polygonal pearlite structure and agglomerated carbide [21] which are randomly dispersed across the ferritic phase. After full annealing of the WM of the AW sample, micrograph in Fig.9(f) was obtained. From the microstructure obtained, it was observed that the annealing process allow diffusion and solubility of the agglomerated carbide into the ferritic phase with fine grains of pearlite randomly dispersed on it.

4. CONCLUSIONS

From the investigation of the effect of weld joints and post weld heat treatment on the mechanical and corrosion properties of low carbon steel, the following conclusion were drawn:

- Half-lap of the AW sample has the best combination of tensile properties with tensile and yield strength value of 148.06 and 91.62 MPa respectively. This shows that the weld joint design adds to the performance efficiency of the weld. While bevel joint followed by the butt joint of the as weld samples has the highest hardness values across the weldment. Impact toughness was best with the butt joint showing that it possesses a balance of strength and ductility both in as weld and post weld heated states. Favorable results for the as weld samples in the mechanical properties considered showed that the welding parameters put in place during welding are optimum for the process.
- Samples with butt joint followed by the bevel joint of the PWHT samples showed the least susceptibilities to corrosion. This implies that PWHT is necessary to improve the corrosion resistance of the welded joint.

REFERENCES

[1] Barsoum, Z., Khurshid, M., (2017). Ultimate Strength Capacity of Welded Joints in High Strength Steels. *Procedia Structural Integrity,* 5, 1401-1408.

[2] Won-Bin, O., Tae-Jong, Y., Bo-Ram, L., Chang-Gon, K., Zong-Liang, L., I11-Soo, K., (2019). A Study on Intelligent Algorithm to Control Welding Parameters for Lap-joint. *Procedia Manufacturing,* 30, 48-55.

[3] Rudawska, A., Niedziałkowski, P., Miturska, I., Szabelsk, J., Grzesiczak, D., (2018). Selected Strength Aspects of Adhesive Lap Joints and Butt-Welded Joints of Various Structural Materials. *Advances in Science and Technology Research Journal,* 12(1), 135-141.

[4] Oladele, I.O., Betiku, O.T., Okoro, A.M., Eghonghon, O., Saliu, L.O., (2018). Comparative Investigation of the Mechanical Properties and Corrosion Behavior of Dissimilar Metal Weld Fusion Zone, Heat Affected Zones and Base Metals. *Annals of faculty of Engineering Hunedoara-International Journal of Engineering,* 1(15), 187-192

[5] Anon, (2001). *WeldingHandbook-Welding Science and Technology* (9th ed.). American Welding Society, Miami.

[6] Sun, X. (2010). *Failure Mechanism of Advanced Welding Processes* (illustrated ed.). Woodhead Publishing, Washington.

[7 Research Education Technical Support and Information, (2003). *Post Weld Heat Treatment of Welded Structures.* Welding Technology Institute Australia, Silver water.

[8] Davis, J. R. (2006). *Corrosion of Weldments.* ASM International, Ohio.

[9] Umut, Y.U., Hamdullah, C., (2015). The Effects of Post Weld Heat Treatment on the Mechanical Properties of Tempered Martensite and High Strength Steel Welded Joints. *The 2015 World Congress on Advances in Structural Engineering and Mechanics,* 1-20.

[10] D'Archy, C., Ruddy, M., Haines, J., Gibbons, J. P., Stanton, K. T., (2015). The effect of repeated post-weld heat treatment on low-carbon steel ASTM A216WCB. *Materials: Design and Applications,* 229 (6), 522-525.

[11] Momoh, I.M., Akinribide, O.J., Ayanleke, J., Olowonubi, J., Olorunfemi, G.O., Oshodin, T., (2013). Investigating the Mechanical Properties of Post Weld Heat Treated 0.33%C Low Alloy Steel, *International Journal of Science and Technology,* 2 (6), 433-437.

[12] Dodo, M.R., Ause, T., Adamu, M.A., Ibrahim, Y.M., (2016). Effect of Post-Weld Heat Treatment on The Microstructure and Mechanical Properties of Arc Welded Medium Carbon Steel. *Nigerian Journal of Technology, 35 (2),* 337 – 343.

[13] Kodama, S., Matsuda, K., Ishida, Y., Ogawa, M., (2018). Improvement of Fatigue Strength of Arc Welded Joints Using High Strength Steel Sheets for Automobile Chassis Members. *Nippon Steel & Sumitomo Metal Technical Report,* Futtsu.

[14] Olawale, J.O., Ibitoye, S.A., Oluwasegun, K.M., Shittu, M.D., Ofoezie, R.C., (2012). Correlation between Process Variables in Shielded Metal-Arc Welding (SMAW) Process and Post Weld Heat Treatment (PWHT) on Some Mechanical Properties of Low Carbon Steel Welds. *Journal of Minerals and Materials Characterization and Engineering,* 11, 891-895.

[15] Liu, H., Nakata, K., Yamamoto, N., Liao, J., (2011). Mechanical and Strengthening Mechanism in Laser Beam Welds of Pure Titanium. *Science and Technology of Welding and Joining,* 16 (7), 581-585.

[16] Guo, Y., Hu, J., Li, J., Jiang, L., Liu, T., Wu, Y., (2014). Effects of Annealing Temperature on the Mechanical and Corrosion Behavior of a Newly Developed Novel Lean Duplex Stainless Steel. *Materials,* 7, 6604-6619.

[17] Masubuchi, K., Blodgett, O. W., Matsui, S., Ruud, C.O., Tsai, C. L., (2001). *Welding Handbook* (9th ed.). American Welding Society, Miami.

[18] Oladele, I.O., Betiku, O.T., Fakoya, B.M., (2017). Effect of post weld heat treatment on the mechanical and corrosion behaviour of welded Al-Fe-Si alloy joints, *Leonardo Electronic Journal of Practices and Technologies,* Issue 13, 75-86.

[19] Raji, A.N., Oluwole, O.O., (2012). Effect of Soaking Time on the Mechanical Properties of Annealed Cold-Drawn Low Carbon Steel. *Materials Sciences and Applications,* 3, 513-518.

[20] Oladele, I.O., Alonge, B. D., Betiku, T.O., Igbafen, E.O., Adewuyi, B.O., (2019). Performance Evaluation of the Effects of Post Weld Heat Treatment on the Microstructure, Mechanical and Corrosion Potentials of Low Carbon Steel. *Advanced Technologies and Materials,* 44 (2), 42-46.

[21] Datta, R., Veeraraghavan, R., Rohiraa, K.L., (2009). Weldability Characteristic of Torr and Corrosion-Resistant TMT Bar Using SMAW Process. *Journal of Material Engineering and Performance,* 11 (2), 369-375.