Corrosion Behavior of Welded Austenitic Stainless Steel in Different Environments

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Abstract

Corrosion behavior of welded austenitic stainless steel in 0.5 M hydrochloric acid and wet-steam corrosive media has been studied. The immersion time in the corrosive media was 30 days to simulate the effect on stainless steel structures/equipment in offshore and food processing applications. Annealing heat treatment was carried out on the samples. The gravimetric technique was used for the corrosion tests. Seawater sample has highest weight loss of 4.0 mg for the heat-treated samples and 4.5 mg for the unheat-treated samples. For the different media used, seawater sample has the highest corrosion rate of 0.64×10^{-6} mm/year for the heat treated samples and 0.72×10^{-6} mm/year for the unheat-treated samples. The post-welding heat treatment was found to increase the mechanical properties of the austenitic stainless steel especially tensile strength but it reduces the transformation and thermal stresses of the samples. These findings were corroborated by the microstructural examination of the stainless steel specimen.

Keywords: *Austenitic Stainless Steel, Corrosion, Seawater, Hydrochloric Acid, Steam*

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INTRODUCTION

Corrosion is chemically induced damage to a material that results in deterioration of the material and its properties. This may result in failure of the component. Several factors should be considered during a failure analysis to determine the effect corrosion plays in the failure [1]. Corrosion is the reaction of metallic material with its environment which gradually leads to deterioration or destruction of the materials. Corrosion is one of the factors that greatly influence fatigue [2]. It is the deterioration of material and loss of its properties as a result of reactions and interactions with its environment. Materials corrode at various rates and the extent of corrosion damage depends on interrelated variables involved [3]. Stainless steels are widely used by different industries such as the oil and gas (onshore and offshore), pulp and paper, marine, automobile, food processing industries and for construction of storage tanks (www.materialsengineer.com/DA Food Proces sing.htm). Stainless steels are iron alloys which depend upon a very thin transparent passive surface film of chromium oxide to resist corrosion [4].

Though austenitic stainless steel is said to be resistant to corrosion, this has however not been established in all environments and conditions. Despite the introduction of polymers and composites in recent years, metals remain important in structures because of their strength, stiffness, toughness and tolerance of high temperature. The noble metals, such as gold and platinum, are an exception to this, but they are too rare for common use. Although one of the main reasons why stainless steels are used is corrosion resistance, they do in fact suffer from certain types of corrosion in some environments and care must be taken to select a grade which will be suitable for the application. Corrosion can cause a variety of problems, depending on the application and the environment [5].

Many research works have been carried out on corrosion of stainless steel. Among such is the work done by Aruleba [6]. He studied the effect of isothermal tempering and time on stress corrosion failure of stainless steel rods in acidic and sea water environments. He discovered that the corrosion penetration rate

of stainless steel decreases with increasing temperature and time. Also, Loto and Ives [4] worked on the corrosion resistance of super austenitic stainless steel in seawater. They discovered that except the type 3161, all the alloys used in the research work had high resistance to corrosion in seawater. Oni [7] worked on the effect of tempering temperature and time on stress-induced failure of low-carbon steel in corrosive environments. He showed that resistance to stress corrosion failure increases with tempering temperature and time. Adeyemi [8] worked on the effect of heat treatment on the quality of the surface finish of turned steel rods. He observed that the surface finish/roughness numbers of the mild steel rods in annealed and normalized conditions under lubricated conditions were greatly dependent on the cutting speed. Hosary and Saleh [9] worked on the synergistic effect of halides and coal tar distillation of the corrosion of mild steel in sulfuric acid. They showed that halides and coal tar distillation products inhibit corrosion. Aiyelero [10] worked on the effect of welding and heat treatment on the mechanical properties of austenitic stainless steel. He observed that the microstructure of the as-received samples is more fine than the welded and heat treated samples. The as-received samples have higher values of impact energy. The objective of this work is to study the corrosion behavior of welded austenitic stainless steels in different corrosive media using gravimetric technique.

MATERIALS AND METHODS
Materials
The corrosive media used in this study includes:
0.5 M hydrochloric acid, seawater, wet steam
The etchants used are: 5 g $FeCl_2$, 50 ml HCl, 100 ml water (for the as-received samples) and 4 g $CUSO_4$, 20 ml HCl, 20 ml water (for the heat-treated).

Equipment
The equipment used in this study includes:
Spectrometer metal analyzer, lathe machine, gemco heat furnance, weighing balance, plastic bowls, austenitic stainless steel, metal inert gas welding machine, grinding, polishing and etching machines, photographic visual metallurgical microscope.

Methods
Preparation of Test Fluid
20.80 cm^3 of HCl from standard Winchester bottle was dissolved in 500 cm^3 of distilled water to obtain the desired concentration from Chemical Engineering Department of Ahmadu Bello University, Zaria, Nigeria and Seawater solution was obtained from Bar Beach in Lagos State, Nigeria (Table 1) while the specimens were subjected to steam at Sunseed Nig. Ltd, Jos road, Zaria, Nigeria. The seawater has the pH value of 8 and the salinity of 3.5% [7].

Preparation of Specimen
The work material (austenitic stainless steel rods) was purchased from the steel market in Zaria in the form of rods and the chemical composition was carried out at Universal Steel Ikeja, Lagos, using a spectrometer machine.

Metal Analyzing Procedure
This was done to determine the elements present and their percentages in the stainless steel. A 20×30 mm piece of standard pipe samples was made. The surface of the sample was ground on the grinding machine to obtain a smooth surface. The sample was placed in the orifice on the machine; a pin to pin spark was impressed on the sample using a solid technique optical emissions spectrograph with 0.0001% sensitivity. The reading was taken from a direct computerized spectrometer. The procedure was repeated two times and the mean value was obtained that reveal a type 316, straight grades austenitic stainless steel as shown in the Table 2. A straight grade austenitic stainless contain maximum of 0.08% C while type 316 contains 16 to 18% chromium and 11 to 14% Nickel. (http://www.spiusa.com/Ref001/austenitic.htm)

The austenitic stainless steel rods of 10 mm diameter were cut into equal length and machined on the lathe machine to ASTM standard with the ASTM code D3166-99 for corrosion test as shown in Figure 1. The machining was done at the production workshop of the Mechanical Engineering Department, Ahmadu Bello University, Zaria, Nigeria.

Each specimen was cut into two equal parts and then welded together using MIG (Metal Inert Gas welding) at Centre for Energy Research and Technology, Ahmadu Bello University, Zaria, Nigeria, as shown in Figure 2 (a and b).

Table 1: *The Chemical Composition of Seawater.*

Element	O	H	Cl	Na	Mg	S	Ca	K	Br	C
% by wt	85.84	10.82	1.94	1.08	0.13	0.091	0.04	0.04	0.0067	0.0028

Table 2: *The Chemical Composition of Austenitic Stainless Steel.*

Element	C	Si	Mn	Ni	Cr	Mo	V	Cu
% by wt	0.079	0.212	1.216	14.189	16.189	1.538	0.037	0.155

Element	W	As	Co	Al	Pb	Ca	Zn	Fe
% by wt	0.416	0.150	0.134	0.008	0.004	0.0001	0.019	64.215
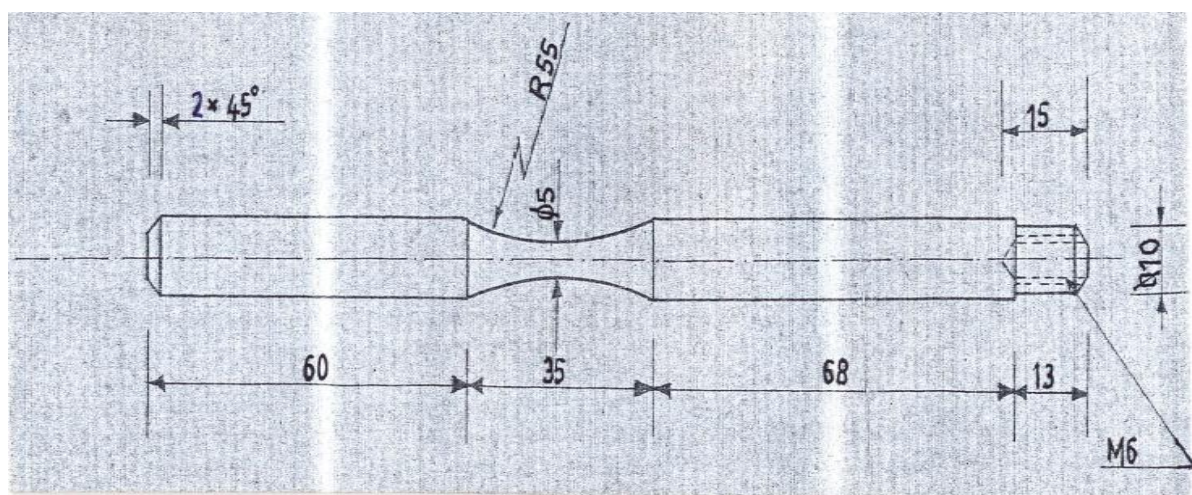
Fig. 1: *Fatigue Specimen (Schematic Diagram).*
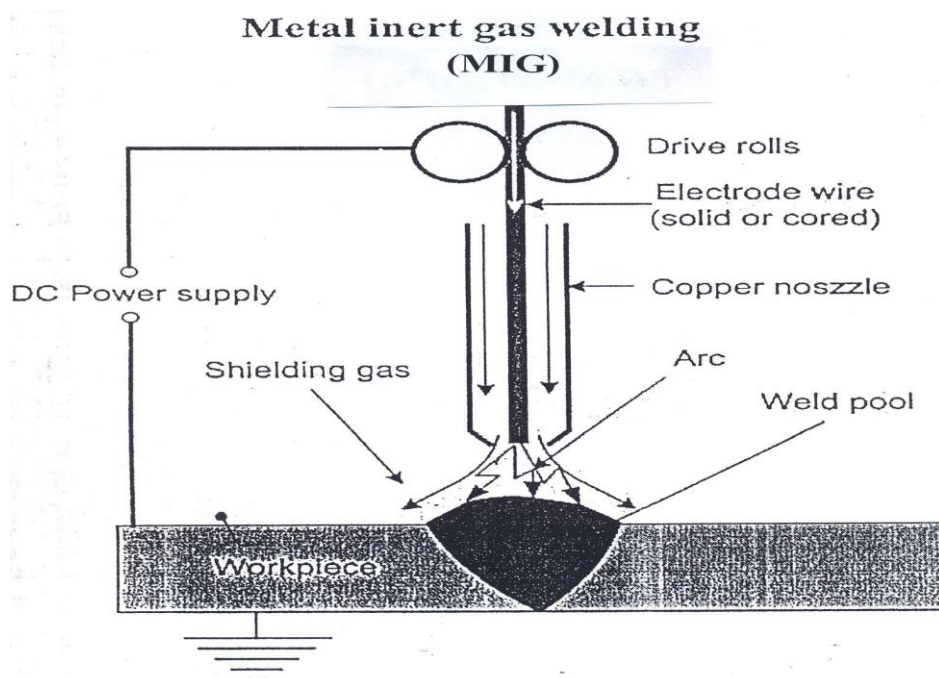

Fig. 2a: *Metal Inert Gas Welding (Center for Energy and Research Institute, Ahmadu Bello University, Zaria).*

***Fig. 2b:** Welded Corrosive Specimen.*

Some specimens were retained as-received conditions while the others were annealed at the Industrial Development Centre (IDC), Zaria, Nigeria. This is in order to relieve stresses, increase softness, ductility and toughness after welding.

Post-welding Heat Treatment
Annealing is a heat treatment that alters a material to increase its ductility and to make it more workable. It involves heating the material to above its critical temperature, maintaining that a suitable temperature, and then cooling, (www.heat.com.au/treatments-annealing).

***Fig. 3:** Gemco Furnace (Industrial Development Centre, Zaria).*

The samples were placed in the furnace as shown in Figure 3. The power was then switched on and the temperature was set at 930 °C. After attaining the set temperature, the samples were soaked for 2 h after which the furnace was switched off and the samples were left to cool to the room temperature in the furnace according to the method of Aiyelero [10]. The samples were then removed from the furnace. The respective annealed specimens were then immersed in seawater, 0.5 M hydrochloric acid and steam-corrosive media for thirty days.

Weight Loss Experiment
The weighed test specimens were weighed before immersed totally in each of the corrosive media in a plastic bowl and then covered for 30 days. The test specimens were taken out of the corrosive media (one each) after every 5 days, washed with distilled water and acetone, air dried and re-weighed according to the method of Yawas [11].

Plot of weight loss versus exposure time and corrosion rate versus exposure time are shown graphically in Figures 4 to 13. The results of

the tests are shown in Tables 3–5. All the experiments were performed at room temperature.

Metallography

Metallography was carried out on the as-received, annealed and corrosive specimen in the following sequence of operation: grinding, polishing, etching in order to know the effects of various tests on the microstructure. The photomicrography of the specimen at the point of fracture and the parent material was taken using a photographic visual metallurgical microscope at Metallurgical and Material Engineering Department of Ahmadu Bello University, Zaria, Nigeria.

The microstructural examinations are shown in Plates 1 to 5.

RESULTS AND DISCUSSION
Results

The results of corrosion tests and microstructural examination of the samples are shown in (Tables 3–5), (Figures 4–13) and Plates 1–5b.

Effects of Corrosive Media

The graphs of weight loss against the exposure time and corrosion rate against the exposure time for both the heat-treated and unheat-treated samples were plotted in the graphs below.

***Table 3:** Austenitic Stainless Steel in Seawater.*

Time of immersion (days)	Initial weight (g)	Final weight (g)		Weight loss (mg)		CPR (mm/year) $\times 10^{-6}$	
		Heat treated	Unheat treated	Heat treated	Unheat treated	Heat treated	Unheat treated
5	144.6515	144.6499	144.6496	1.6	1.9	1.54	1.83
10	145.3782	145.3760	145.3757	2.2	2.5	1.06	1.21
15	146.4812	146.4786	146.4784	2.6	2.8	0.84	0.89
20	144.0620	144.0590	144.0587	3.0	3.3	0.72	0.76
25	144.6620	144.6586	144.6583	3.4	3.7	0.66	0.71
30	144.6882	144.6842	144.6837	4.0	4.5	0.64	0.72

***Table 4:** Austenitic Stainless Steel in 0.5 M HCl.*

Time of immersion (days)	Initial weight (g)	Final weight (g)		Weight loss (mg)		CPR (mm/year) $\times 10^{-6}$	
		Heat treated	Unheat treated	Heat treated	Unheat treated	Heat treated	Unheat treated
5	144.4878	144.4865	144.4863	1.3	1.5	1.25	1.44
10	145.1132	145.1116	145.1113	1.6	1.9	0.77	0.92
15	144.9120	144.9099	144.9096	2.1	2.4	0.67	0.77
20	144.8972	144.8947	144.8943	2.5	2.9	0.60	0.69
25	144.3292	144.3262	144.3259	3.0	3.3	0.58	0.64
30	142.6882	144.6846	142.6843	3.5	3.9	0.56	0.63

***Table 5:** Austenitic Stainless Steel in Wet Steam.*

| Time of immersion (days)	Initial weight (g)	Final weight (g)		Weight loss (mg)		CPR (mm/year) $\times 10^{-6}$	
		Heat treated	Unheat treated	Heat treated	Unheat treated	Heat treated	Unheat treated
5	145.7825	145.7814	145.7813	1.1	1.2	1.06	1.16
10	146.6805	146.6791	146.6789	1.4	1.6	0.67	0.77
15	144.2469	144.2452	144.2450	1.7	1.9	0.55	0.61
20	142.8146	142.8125	142.8122	2.1	2.4	0.51	0.58
25	146.3098	146.3073	146.3070	2.5	2.8	0.46	0.54
30	143.9804	143.9775	143.9771	2.9	3.3	0.45	0.53
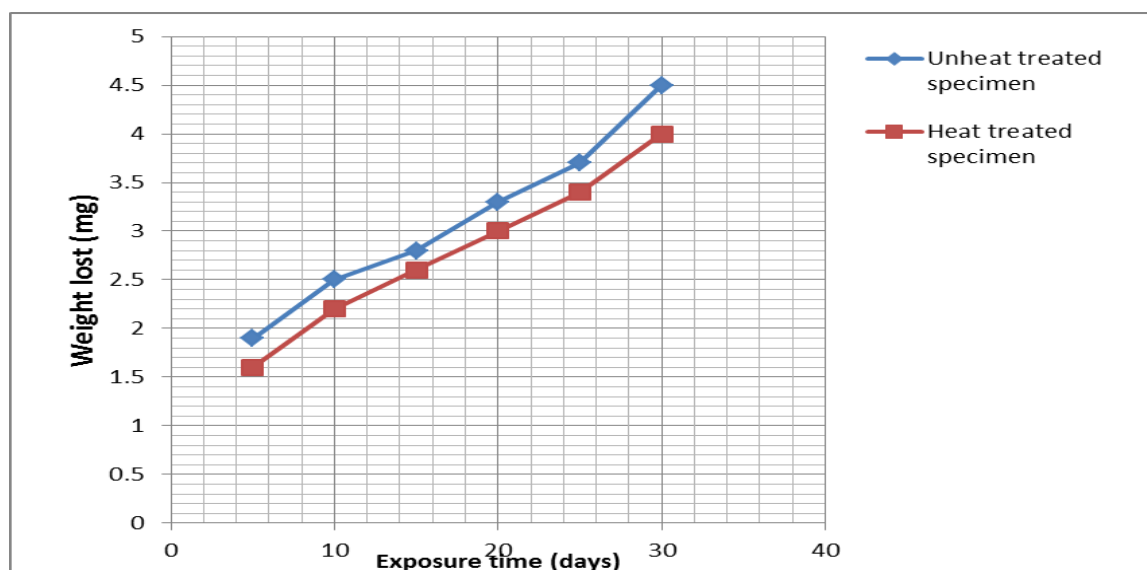
Fig. 4: *Variation of Weight Lost with Exposure Time of Austenitic Stainless Steel in Seawater.*
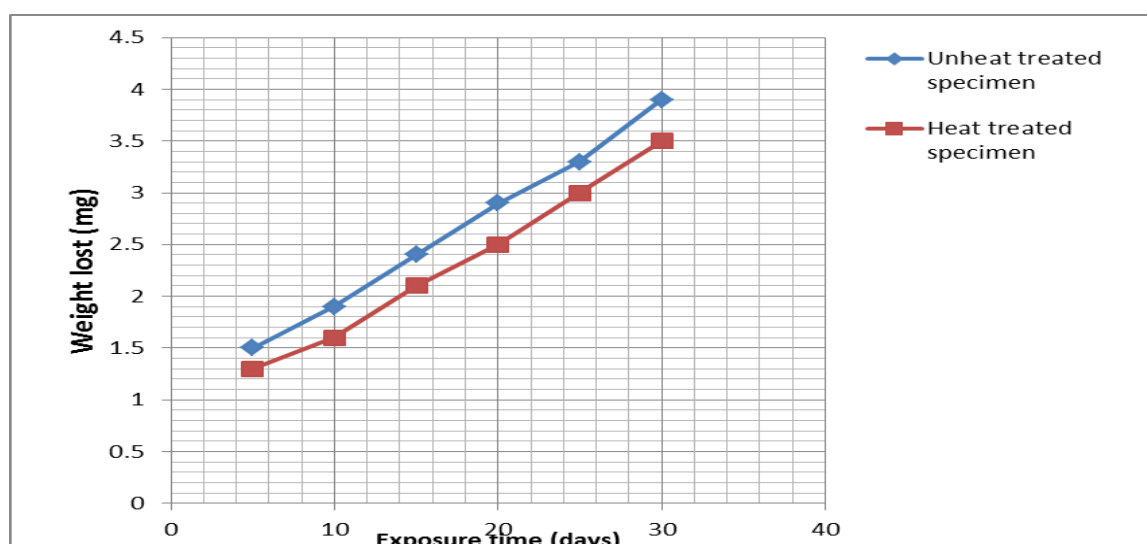

Fig. 5: *Variation of Weight Lost with Exposure Time of Austenitic Stainless Steel in 0.5 M HCl.*
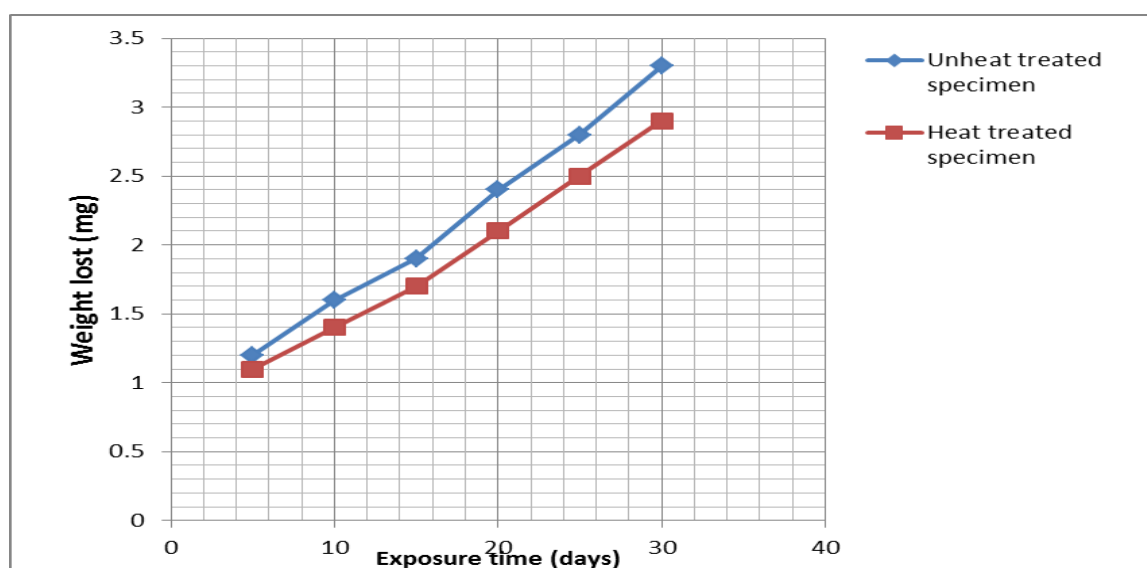

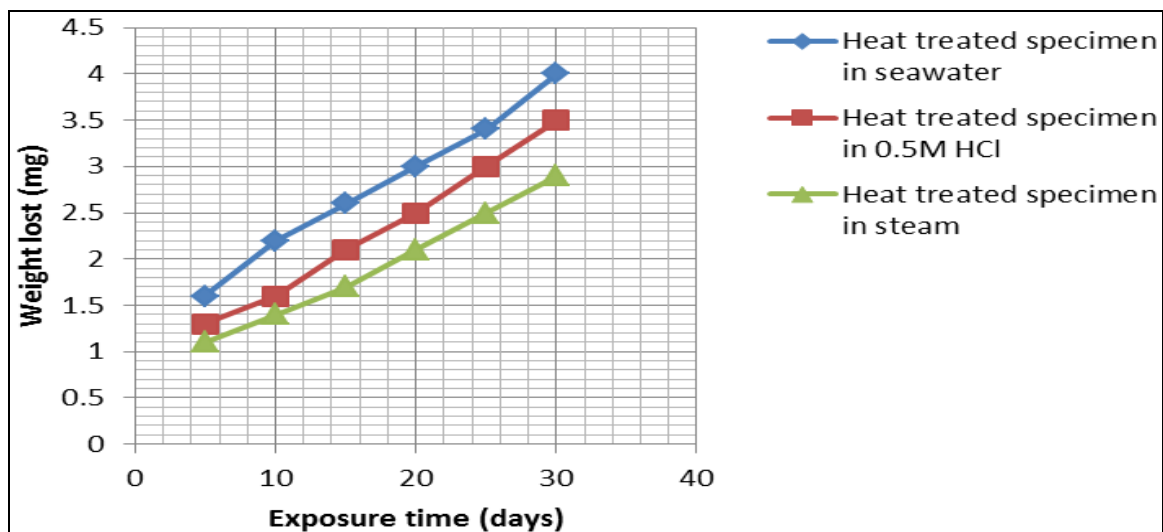***Fig. 6:*** *Variation of Weight Lost with Exposure Time of Austenitic Stainless Steel in Wet Steam.*

Fig. 7: *Variation of Weight Lost with Exposure Time of Heat-Treated Austenitic Stainless Steel in Seawater, 0.5 M HCl and Steam.*
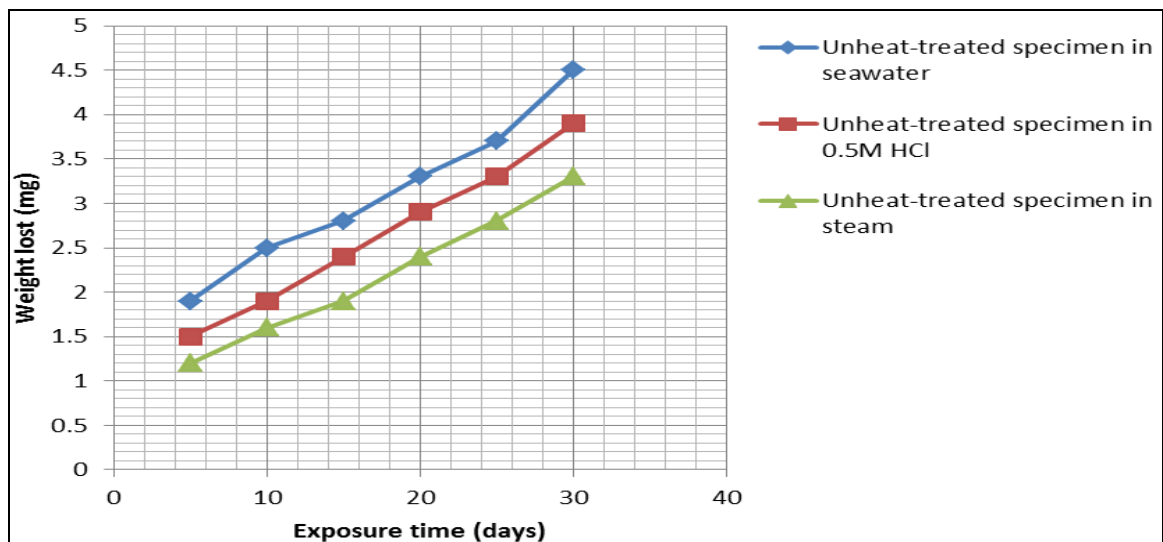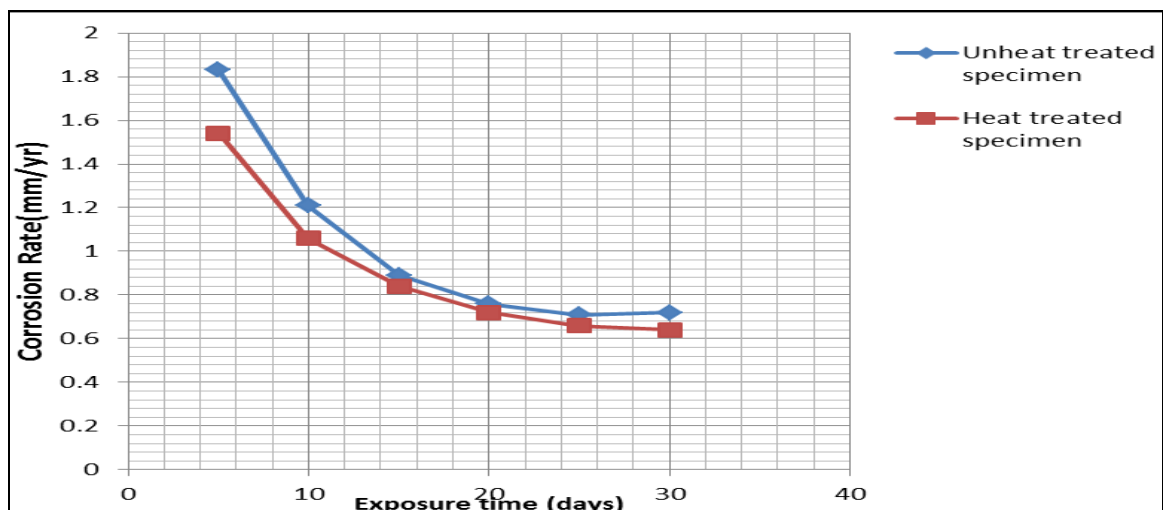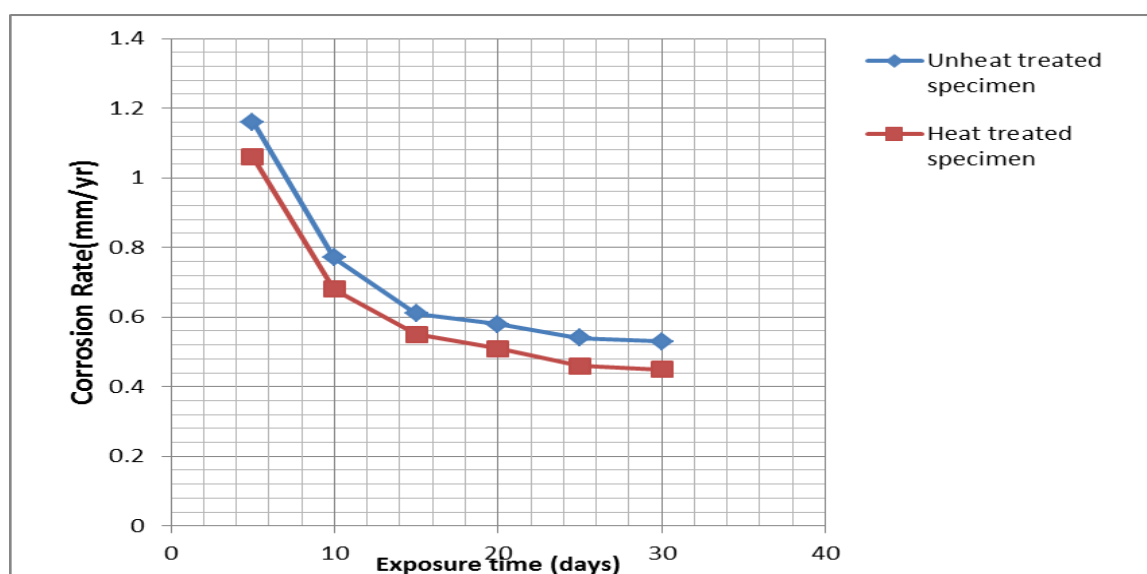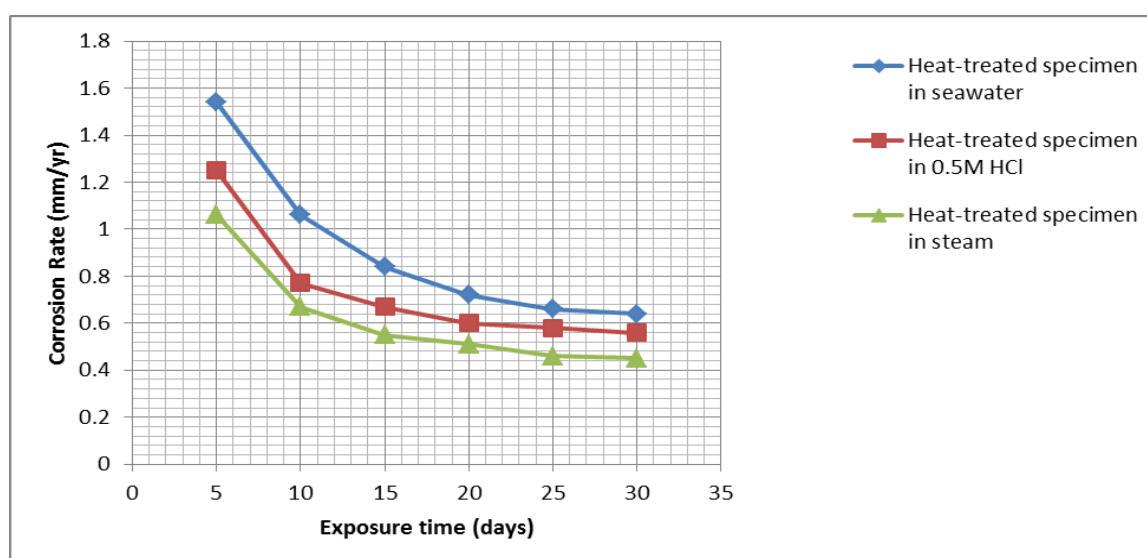

Fig. 8: *Variation of Weight Lost with Exposure Time of Unheat-Treated Austenitic Stainless Steel in Seawater, 0.5 M HCl and Wet Steam.*

Fig. 9: *Variation of Corrosion Rate with Exposure Time of AusteniticStainless Steel in Seawater.*
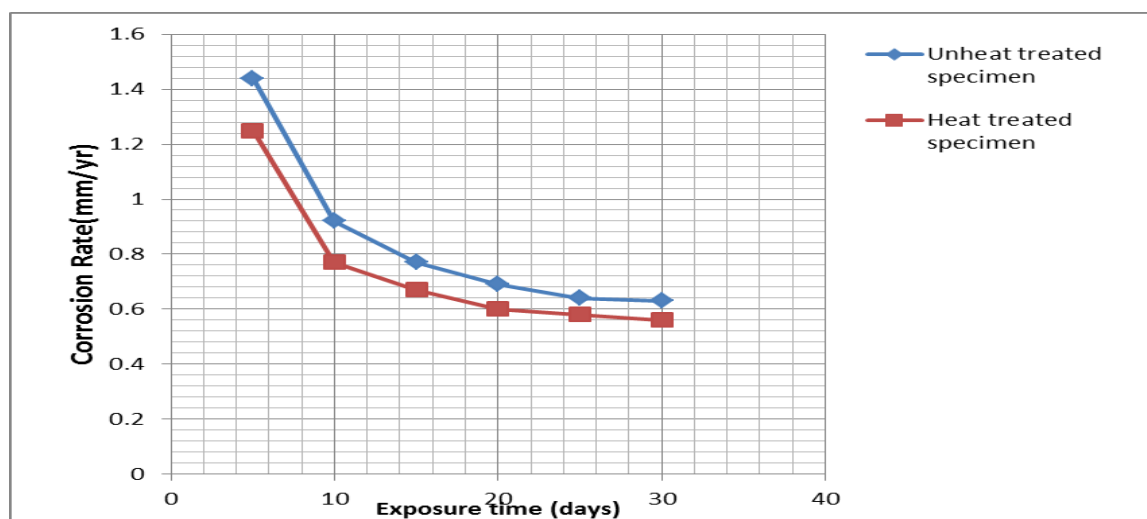
Fig. 10: *Variation of Corrosion Rate with Exposure Time of Austenitic Stainless Steel in 0.5 M HCl.*

Fig. 11: *Variation of Corrosion Rate with Exposure Time of Austenitic Stainless Steel in Wet Steam.*

Fig. 12: *Variation of Corrosion Rate with Exposure Time of Heat-Treated Austenitic Stainless Steel in Seawater, 0.5 M HCl and Wet Steam.*
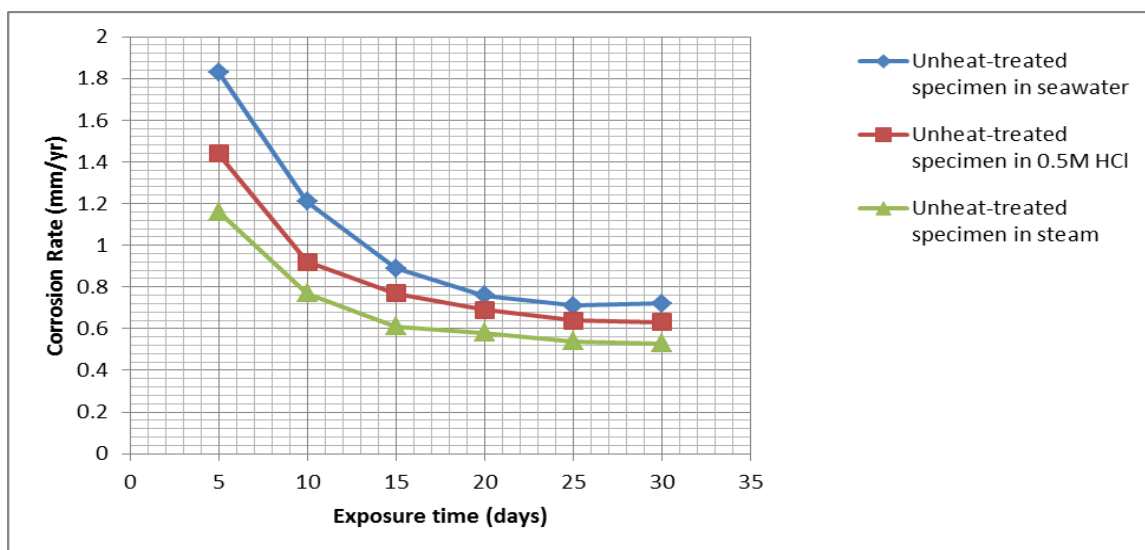
Fig. 13: *Variation of Corrosion Rate with Exposure Time of Unheat-Treated Austenitic Stainless Steel in Seawater, 0.5 M HCl and Wet Steam.*
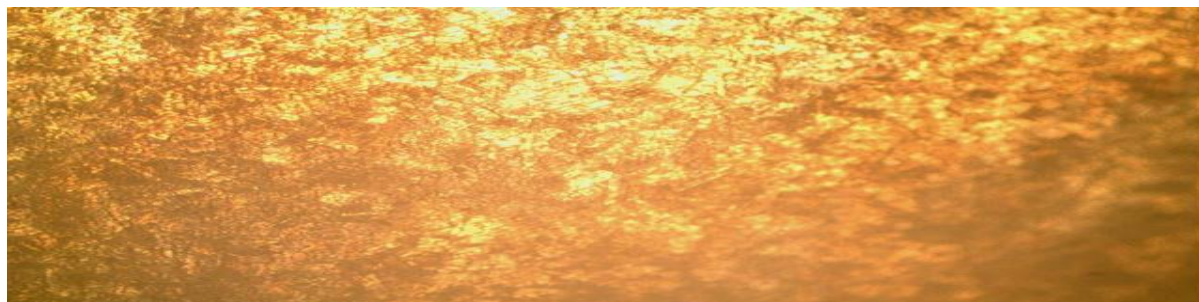

Plate 1a: *Micrograph of the Parent As-received Austenitic Steel Showing Some Non-metallic Inclusion (Black), Apha Ferrite (White) in Austenitic Matrix (White Background) × 100.*

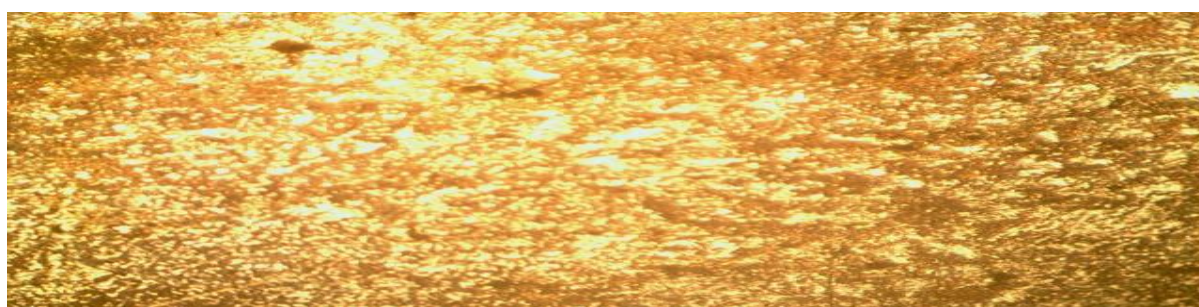***Plate 1b:*** *Micrograph of the Weldments of the As-received Austenitic Steel Showing Some Carbide Inclusion (Black), Delta Ferrite (Lacy-White) in Austenitic Matrix (White Background) × 100.*

Plate 2a: *Micrograph of Parent Annealed Austenitic Stainless Steel Showing Some Carbide Inclusion ($M_{23}Cr_6$) Precipitates (Black), Delta Ferrite (White) in Austenitic Matrix (White Background) × 100.*
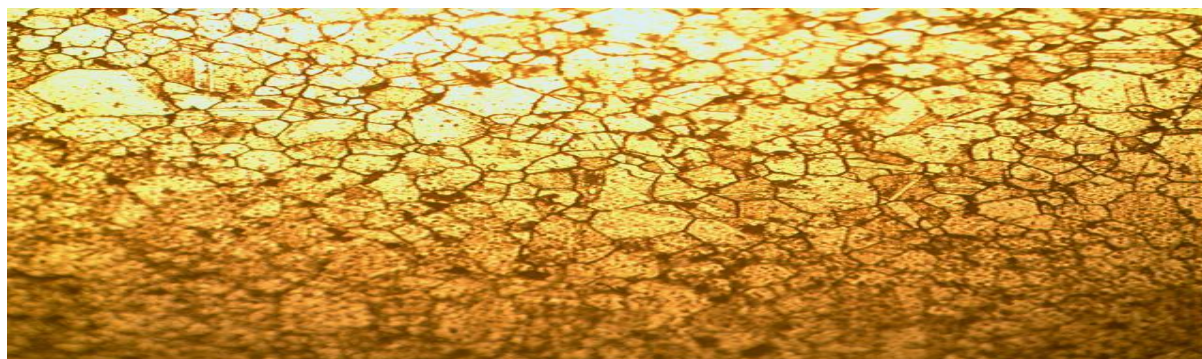
Plate 2b: *Micrograph of the Weldments of the Annealed Austenitic Stainless Steel Showing High Proportions of Carbide ($M_{23}Cr_6$) Precipitates along the Grain Boundaries(Black), Delta Ferrite (Acicular-White) in Austenitic Matrix (White Background) × 100.*
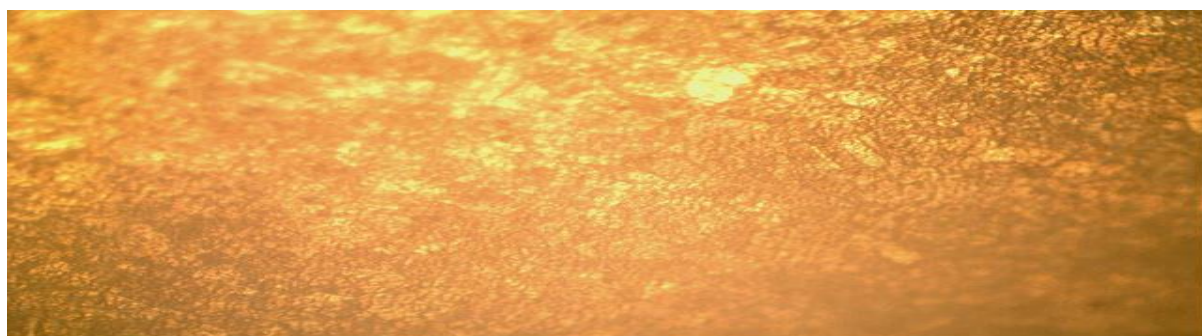

Plate 3a: *Micrograph of the Acidic Corroded Parent Austenitic Stainless Steel Showing Visible Corrosion on the Carbide ($M_{23}Cr_6$) Precipitates and Delta Ferrite (Acicular-White) but Less in the Austenitic Matrix (White Background) × 100.*
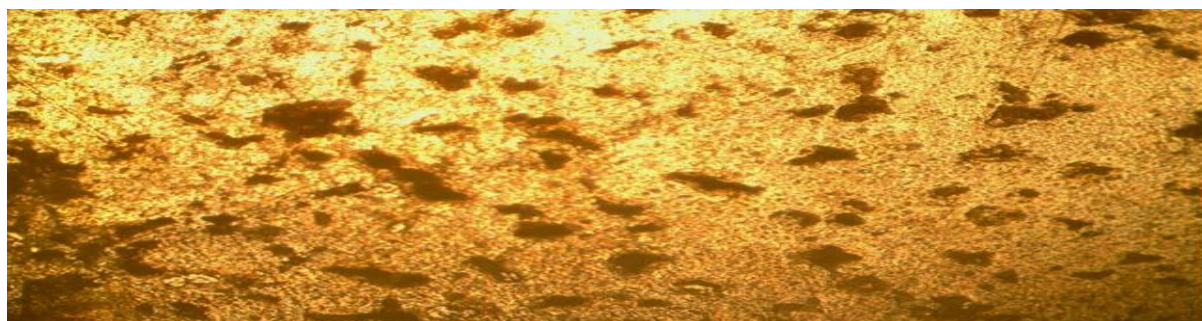

Plate 3b: *Micrograph of the Acidic Corroded Weldments of the Austenitic Stainless Steel Showing High Attack on the Carbide ($M_{23}Cr_6$) Sites (Black) and Sigma Phase (Black) but Relatively Less in the Austenitic Matrix (White Background) × 100.*
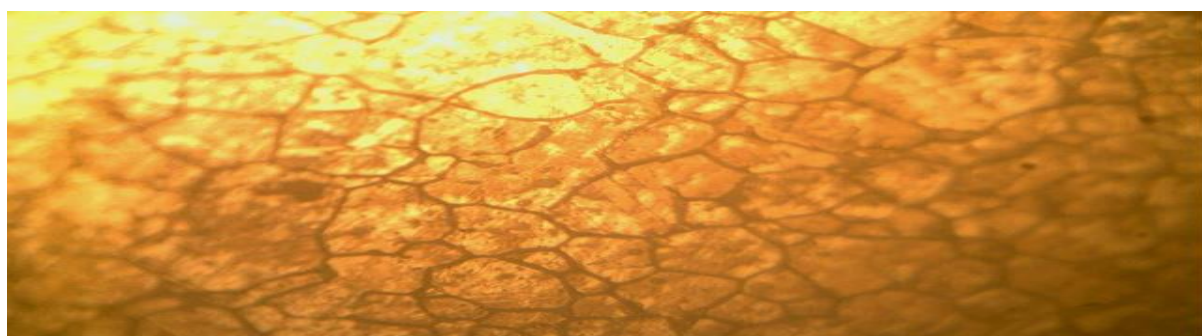

Plate 4a: *Micrograph of the Sea Water Corroded Parent Austenitic Stainless Steel Showing Significant Visible Rate of Attack on the Carbide ($M_{23}Cr_6$) Sites (Black) and Delta Ferrite (Lacy-White) but Probably no Attack on the Austenitic Matrix (White Background) × 100.*
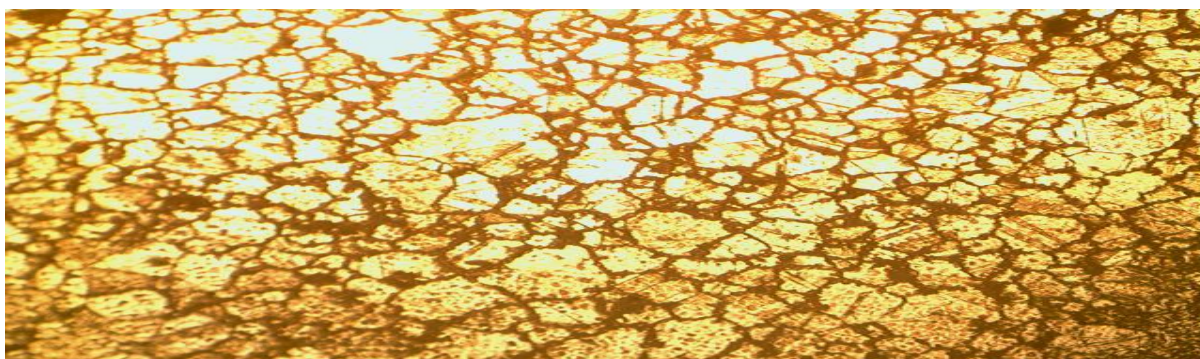
Plate 4b: *Micrograph of the Sea Water Corroded Weldments of the Austenitic Stainless Steel Showing Significant Attack on the Carbide ($M_{23}Cr_6$) Sites (Black) and Sigma Phase (Black) Distributed along the Austenitic Matrix (White Background) × 100.*
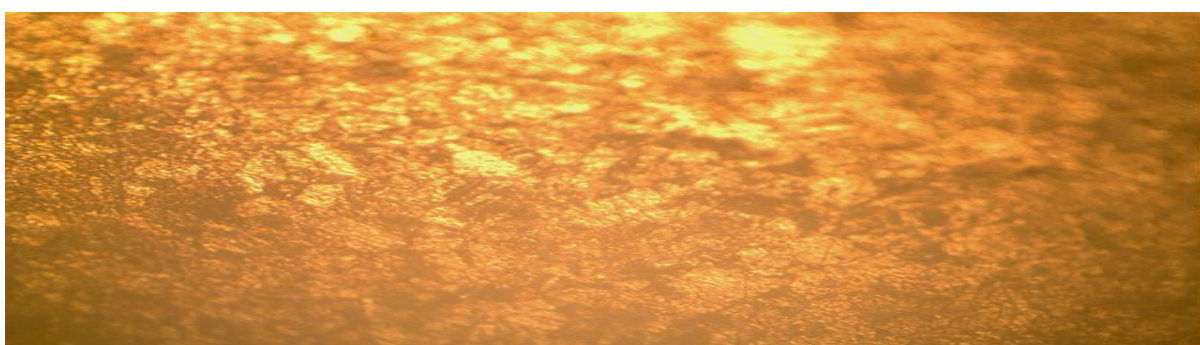

Plate 5a: *Micrograph of the Wet Steam Corroded Parent Austenitic Stainless Steel Showing Visible High Proportions of Corroded Carbide ($M_{23}Cr_6$) Sites (Black) and Sigma Phase (Black) Distributed along Grains Boundaries of the Austenitic Matrix (White Background) × 100.*
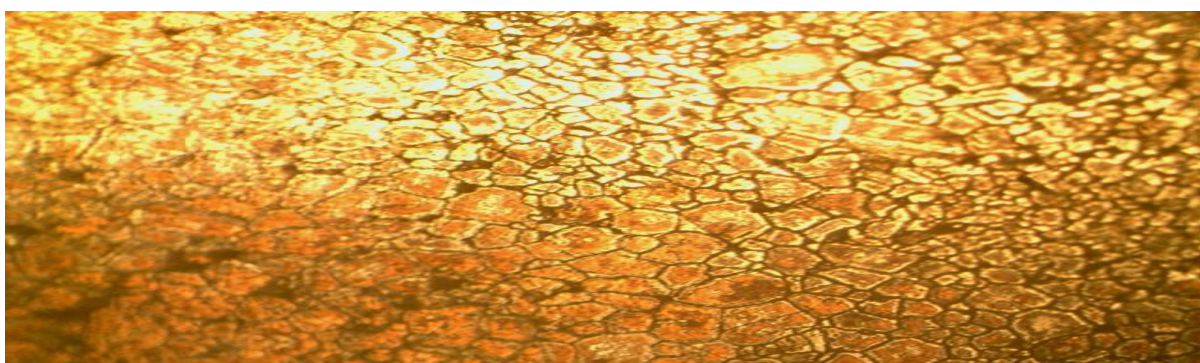

Plate 5b: *Micrograph of the Wet Steam Corroded Weldments of the Austenitic Stainless Steel Showing Visible High Proportions of Corroded Carbide ($M_{23}Cr_6$) Sites (Black) and Sigma Phase (Black) Distributed along the Austenitic Matrix (White Background) × 100.*

DISCUSSION

Weight Loss of Austenitic Stainless Steel

Figures 4–6 show variations of weight loss with exposure time of austenitic stainless steel in the different media used (seawater, 0.5 M hydrochloric acid and wet steam). The graph trends show that weight loss increases with increase in exposure time. The unheat-treated samples have higher weight loss than the heat-treated specimen for all the media. This is due to; more is the time duration of samples in the corrosive media, the more they are corroded due to the formation of chromium carbide precipitates. Also, the weight loss in seawater-corroded specimen is the highest followed by acidic-corroded specimen and steam-corroded specimen; this is due to the presence of chloride ions in seawater. This invariably reveals that stainless steel suffers greater corrosion in seawater due to the attack of

chloride ions. This is in agreement with the findings of Aruleba [6], Omotade [12] and Afolabi [13].

Corrosion Rate of Austenitic Stainless Steel
Figures 7, 8 and 9 show the corrosion rate with exposure time of austenitic stainless steel in the different media used. The graphs show that corrosion rate of austenitic stainless steel decreases with increasing exposure time. Also, the unheat-treated specimen have higher corrosion rate than the heat treated specimen in all the media. This is because as the iron in the surface corrodes, it leaves a chromium enriched surface behind; therefore, the corrosion rate then would decrease as the chromium enriched surface begins to impact more passivity. It is evident from the plots that the corrosion rate of seawater is greater than that of the other media used throughout the exposure period, this corroborates the findings of Afolabi [13] and Dillion [14].

Microstructure
Plates 1 to 5 show the microstructures of as-received specimen, heat-treated specimen, seawater-corroded specimen, acidic specimen and wet-steam-corroded specimen for both the base material and weldments of austenitic stainless steel. The microstructure of the parent as-received austenitic stainless steel reveals alpha ferrite (white) in austenitic matrix while the weldment reveal delta ferrite (lacy-white) in austenitic matrix. Also, the microstructure of the media used gives predominantly carbide (M_{23} Cr_6) precipitates in austenitic matrix while the weldment reveals high proportions of carbide precipitates along the grain boundaries, where M_{23} represents the carbide complexes that are formed. This research is in agreement with earlier researches by Rajasekhar *et al.* [15], Zhang *et al.* [1] and Lakshminarayanan *et al.* [16].

CONCLUSIONS
From the results and discussion in this work, the following conclusions can be drawn:
1. The weight loss of austenitic stainless steel increases with increase in exposure time and seawater specimen has the highest weight loss owing to the presence of chloride ions.
2. The corrosion rate of austenitic stainless steel decreases with increase in the exposure time; and seawater specimen have the highest corrosion rate followed by acidic specimen and then wet-steam specimen.
3. The microstructure of the parent as-received austenitic stainless steel reveals alpha ferrite (white) in austenitic matrix while the weldment reveals delta ferrite (lacy-white) in austenitic matrix. Also, the microstructure of the media used gives predominantly carbide (M_{23} Cr_6) precipitates in austenitic matrix while the weldment reveals high proportions of carbide precipitates along the grain boundaries.
4. Finally, austenitic stainless steel, though possessing a high degree of resistance to corrosion, still suffers corrosion to some extent when used in corrosive environment and even suffers double when there is a tendency to fatigue in corrosive environment.

REFERENCES
1. Zhang YM, Pan C, Male AT. Welding of austenitic stainless steel using double sided arc welding process. *Journal of Materials Science and Technology*. 2001; 17: 1279–84p.
2. Fontana MG. *Corrosion Engineering*, 3rd Edn. McGraw Hill, Inc; 1998; 4–5, 153p.
3. Callister DW. *Materials Science and Engineering: An Introduction*, 7th Edn. John Wiley and Sons Incorporation, UK; 2007.
4. Loto CA, Ives MB. Corrosion resistance of super austenitic stainless steel in seawater. *NSE Technical Journal*. 1994; 29(1): 1–2p.
5. Iliyasu I. The susceptibility of austenitic stainless steel to stress corrosion cracking in some aggressive environments. *Unpublished M.Sc. Thesis*. Mechanical Engineering Department, ABU, Zaria.
6. Aruleba OG. Effect of isothermal tempering and time on stress–corrosion failure of stainless steel rods in acidic and seawater environments. *Unpublished B.Sc. Thesis*. Mechanical Engineering Department, UNAD, Ado-Ekiti.

7. Oni A. Effect of tempering temperature and time on stress-induced failure of low-carbon steel in corrosive environment. *Nigeria Journal of Technical Education*. 1998; 16(1): 42–9p.

8. Adeyemi M. Effect of Heat Treatment on the Quality of the Surface Finish of Turned Steel Rods. *Journal of Engineering Research*. 1998; 6(1): 27–35p.

9. Hosary AA, Saleh RM. Synergistic effect of halides and coal tar distillation of the corrosion of mild steel in sulphuric acid. *Symposium on Corrosion Inhibitors*. 1985; 373p.

10. Aiyelero MA. Effect of welding and heat treatment on the mechanical properties of austenitic stainless steel. *Unpublished B.Sc. Thesis*. Mechanical Engineering Department, ABU, Zaria. 2005.

11. Yawas DS. Suitability assessment of some plant extracts and fatty acid vegetable oils as corrosion inhibitors. Ph.D dissertation. 2005.

12. Omotade EA. Corrosion fatigue and microstructural behaviours of stainless steel rods under varied tempering temperature. *Unpublished B.Sc. Thesis.* Mechanical Engineering Department, UNAD, Ado-Ekiti. 2005.

13. Afolabi AS. Corrosion and stress corrosion behavior of low and medium carbon steel in agro-fluid media. *Leonardo Electronic Journal of Practices and Technologies*. 2007; 10: 55–66p. ISSN 1583–1078.

14. Dillion CP. *Forms of Corrosion*. MPE Engineers Inc. 2001.

15. Rajasekhar K. microstructural evolution during solidification of austenitic stainless steel weld metals: A color metallographic and electron microprobe analysis study. *Mater Charact*. 1997; 38(2): 53–65p.

16. Lakshminarayanan AK, Balasubramanian V, Shanmugam K. Effect of welding processes on tensile, impact, hardness and microstructure of joints made of aisi 409 fss base metal and 308l ass filler metals. *Iron Mak Steel Mak*. 75–80p.