Investigation into the Effects of Microstructure on the Corrosion Susceptibility of Medium Carbon Steel

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--**ABSTRACT**---
A study on the effects of microstructural changes on the Corrosion Susceptibility of Medium Carbon Steel in different corrosive media was carried out. This was done by austenitizing the coupons at 925 ^{o}C and quenching in a controlled manner into various quenchants to obtain normalized, annealed and martensitic microstructures. The coupons were later exposed to various environments and allowed to stay in the environment for 60 days. The weight loss measurements were taken at interval of 10 days. In this study, it can be concluded that microstructures obtained by different heat treatment processes are sensitive to the environment. The observable difference in corrosion rates could be attributed to precipitation of ferrite and carbide phases. These phases led to setting up of microgalvanic cells within the microstructure with the carbide phase becoming cathodic and the ferrite anodic. The result also tends to suggest that the more ferrite is precipitated (anodic area) in the normalized structure, the more corrosion rate increases. Furthermore, the combining effect of ferrite precipitation, transformation stress and carbide precipitation tends to cause higher corrosion rate in the martensitic structures. This could be attributed to high metastability (non-equilibrum position) of martensitic structure. In general, normalized structure showed the lowest susceptibility to corrosion attack while the martensitic structure showed the highest susceptibility to corrosion attack. More so, 0.5MH$_2$SO$_4$ was the most aggressive environment, followed by 0.5MHCL, Seawater and lastly Effluent water.

KEYWORDS: microstructure, ferrite, pearlite, martensitic, lattice distortions

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I. INTRODUCTION

In modern industrialization and technological advancement, metals account for over 90% of equipment composition used for construction. In the oil and gas industry, metals are used in pipelines, surface equipment and vessels, oil storage tanks, wellhead equipment, downhole equipment, drilling and production platforms, etc. In construction industry, they are mainly the structural elements of buildings. Metals are also used in automobile industry, food processing industry, chemical industry, and domestic wear industry.

In selecting materials for a specific applications, due considerations are paid to the availability of such materials, fabricability, maintainability and most importantly the cost of the material. For bulk constructions, long-distance, large-diameter pipelines, strength and economic considerations have shown that carbon steel is the most feasible alternative (Nyborg, 2003). But carbon steel is highly susceptible to corrosion attack. Hence, structures made of steel like buildings, bridges, industrial plant, ships, aircrafts, pipelines, drilling platforms, etc. are degraded in service by corrosion (Oltra, 2003).

Corrosion cells are created on the metal surfaces when it comes in contact with an electrolyte. These cells form due to energy differences between the metal and the electrolyte, and also different area on the metal surface could have different potentials with respect to the electrolyte. These variations could be due to metallurgical factors or environmental factors (Oltra, 2003). The corrosion rate of medium carbon steel varies depending on the materials microconstituents and the environment in which it is exposed (Ovri, 2008).

Most engineering metals are soft and very ductile in pure forms but their microstructure and composition can be altered by alloying with other elements, such as chromium, nickel, magnesium, manganese, silicon, etc. and/or through heat treatment to obtain a desired mechanical property for a particular application. This practice is employed also in the production of corrosion resistant steels. Hence, materials microstructure plays an important role in determining its strength and stability in a corrosive environment.

Corrosion testslay the foundation for obtaining adequate information on materials performance in the process environment, for ensuring resources are effectively used, and that materials choices are compatible with the long-term economic goals for the plant. They are important tool for evaluating the performance of materials used in scientific, industrial, engineering, consumer, and aesthetic applications. Corrosion tests are widely used

to evaluate the durability of materials of construction in reactive environments. It evaluates a range of materials degradation processes that affect the final performance of these materials and directly influence the materials chosen for these applications.

Hence, investigation into the Effects of Heat Treatment on Corrosion Susceptibility of Medium Carbon Steel exposed to various corrosive environments is the subject of this study

II. MATERIALS AND METHODS

Test Materials

The material used for this study was a medium carbon steel obtained from Delta Steel Company, Ovwian-Aladja, Delta State. It was in the form of ribbed bars of about 16 mm in diameter. The chemical composition as supplied by the manufacturer is given in Table 1.

The corrosive environments were Effluent water, Seawater (NaCl), $0.5MH_2SO_4$, and 0.5HCL. The effluent water was obtained from a line used by Mantrac (CAT) Nigeria Ltd, Ikeja Lagos in preparing metal surfaces for powder coating and the analysis is shown in Table 2.
The seawater was obtained from Bar Beach, Victoria Island, Lagos. The acids were prepared in the Chemistry Lab of Federal University of Technology, Owerri.

Preparation of Corrosion Coupons

The 16 mm diameter ribbed steel reinforcing bar was machined in a centre lathe to remove the ribbed surface in other to prevent crevice corrosion (Ovri, 2008). They were then cut into suitable lengths using a hacksaw. The coupons were subsequently subjected to slow and sequential material removal processes. The reason for material removal was to eliminate the gross scratches and deformities, introduced by the cutting tool, from the coupon surfaces (Colwell, 2005). After the grinding operations, the coupons were then heat treated.

Heat Treatment of Corrosion Coupons

The coupons were grouped into 5 sets, labelled AC, FC, WQ, BQ, and OQ. All the 5 sets of coupons were heated in a Gallenkamp Laboratory Furnace from ambient temperature to about 925 ^{o}C and were held for about one hour at this temperature.
The coupons were removed from the austenitic condition in the furnace and

i.   WQ-Set quenched in water,
ii.   BQ-Set quenched in brine, and
iii.   OQ-Set quenched in oil.The coupons were then allowed to cool down to room temperature and then removed.
iv.   AC-Set was allowed to cool in still air to room temperature, and
v.   The furnace was shut down to allow FC-set coupons to cool down in it to room temperature.

Test Procedure

The test techniques were total immersion method in accordance with standard prescription (Corbett, 2005) and weight loss measurement after scheduled intervals were used.The specimens were immersed in the corrosive medium under constant test conditions throughout the duration of the test programme. The weight losses of the coupons were determined at intervals of 10 days for a period of 60 days. Table 3 illustrates the

Table 1: Chemical Composition of the Medium Carbon steel in %wt

Element	C	Si	Mn	P	S	Cr	Cu	Ni	Mo	Sn	Fe
%wt Composition	0.457	0.145	0.58	0.020	0.053	0.184	0.319	0.115	0.015	0.011	Bal

Table 2: Effluent Water Chemical Analysis   pH 8.9

Analysis	Residual Chlorine	Iron	Total Alkalinity as CaCO3	Total Acidity as CaCO3	Total Hardness as CaCO3	Ca Hardness as CaCO3	Mg Hardness	Cl	Nitrite	Nitrate	Organic Matter KMnO4	Salinity	Total Dissolved Solid
Result (mg/l)	0.0	0.23	56	78	560	358	202	105	0.35	0.0	0.85	923.1	1200

lanned Interval Test Method adopted in this study. The data generated were used to calculate the corrosion rate. The variation in environment corrosiveness and metal corrodibility were also noted.

Table 3 - Planned Interval Test Scheme.

Specimen #	Duration (days)
	0 10 20 30 40 50 60
Set 1	
Set 2	
Set 3	
Set 4	
Set 5	
Set 6	
Set 7	

Medium Corrosive Strength Criteria	
- Unchanged if	1 = 7
- Decreased if	1 > 7
- Increased if	1 < 7

III.   RESULTS AND DISCUSSION

The *corrosion rate* measurement was carried out using the relationship (Davis, 2000):

Corrosion rate (mpy) = $\dfrac{534W}{DAT}$

Millimetres per year (mm/y) = 0.0254mpy
Where
mpy = mils/yr,
W = weight loss (mass loss) in mg;
D =Metal density, g/cm^3 (For this steel d = 7.98 g/cm^3);
A = Specimen area, in^2; and
T = Time of exposure (Duration), in hours.
Data to the fourth significant digit were used.
The corrosion rate generated using this equation is shown in Table 4. The Photomicrographs of Heat treated Coupons is shown in Plate 1.
The Relationship between grain size number and actual diameter of the grain is given in table 5. The Table was generated using the equation (Hosford, 2007);

$$n= 2^{N-1} \quad \text{or} \quad N = 1 + \frac{\ln n}{\ln 2}$$

Where
N = The ASTM grain size number
n = number of grains per square inch (or mm) as seen in a specimen viewed at a magnification of 100. Large values of N indicate a fine grain size.

Table 5: Relationships between grain size number and actual diameter of the grain

ASTM grain size number, N	Grain per inch square at 100 X	Actual grain diameter (inch)	(mm)
1	1	0.0100	0.25
2	2	0.0071	0.18
3	4	0.0050	0.125
4	8	0.0035	0.091
5	16	0.0025	0.062
6	32	0.0018	0.044
7	64	0.0012	0.032
8	128	0.0009	0.022
9	256	0.0006	0.016

Hosford, (2007)

From the ASTM No. given in Plate 1 and Table 5we obtain:
1.   Air Cooled (ASTM No. 5; [100X])
      Grain/in2 = 16, actual grain diameter 0.0025 in^2 (0.062 mm)
2.   Oil Quenched (ASTM No. 6; [100X])
      Grain/in2 = 32, actual grain diameter 0.0018 in^2 (0.044 mm)
3.   Furnace Cooled (ASTM No. 7; [100X]) - grain/in^2 = 64, actual grain diameter 0.0012 in^2 (0.032 mm)
      For the medium carbon Steel, Density: 7.98 g/cm^3, length 34 mm; diameter 11 mm.

Lateral surface area of a right circular cylinder = 2πrh

Exposed coupon area $= 2\pi r_1 (h + r_1) - \pi(r_2)^2$
$= 1352.46$ mm^2
$= 2.0963$ in^2

(a) As Received

(b) Air Cooled

(c) Oil Quenched

(d) Furnace Cooled

(e) Brine Quenched [100X] [800X]

(f) Water Quenched [100X] [800X]
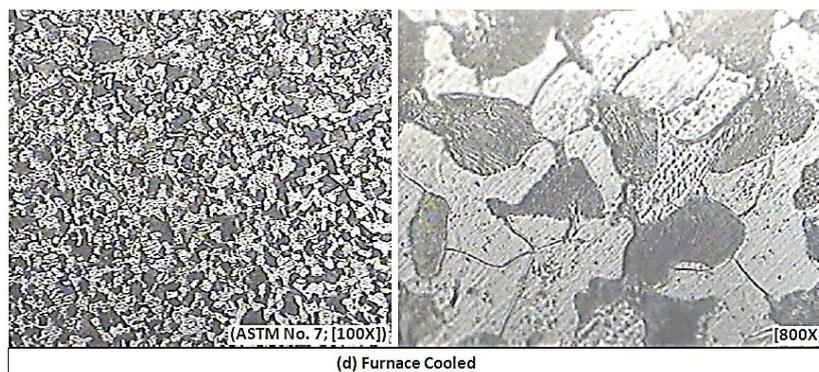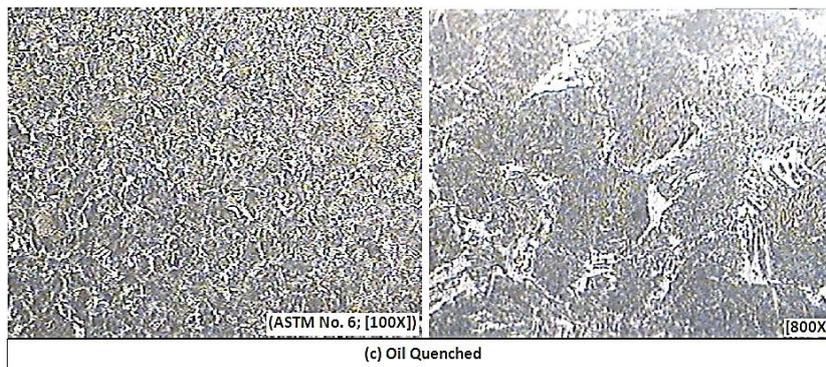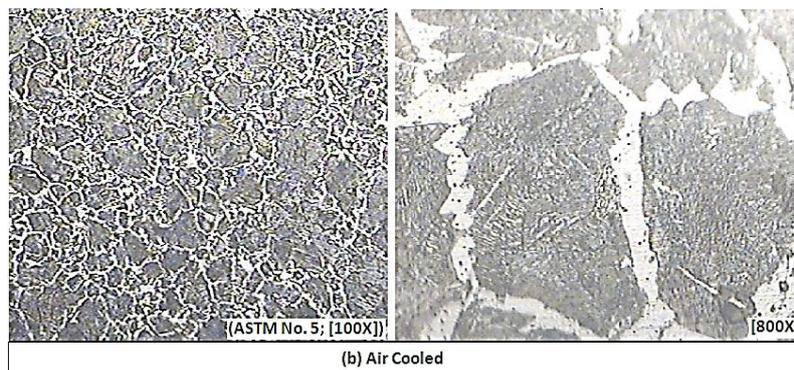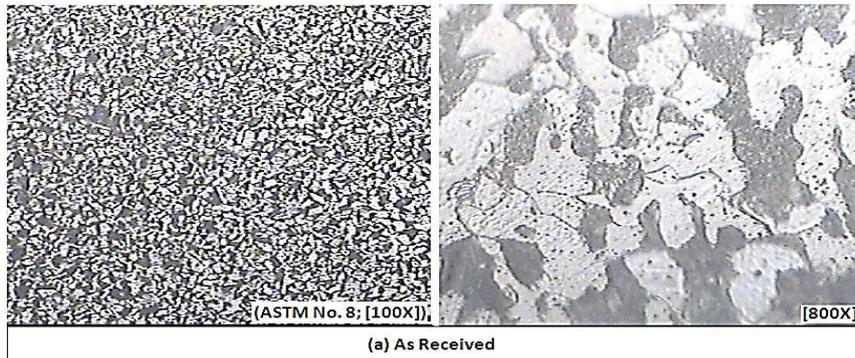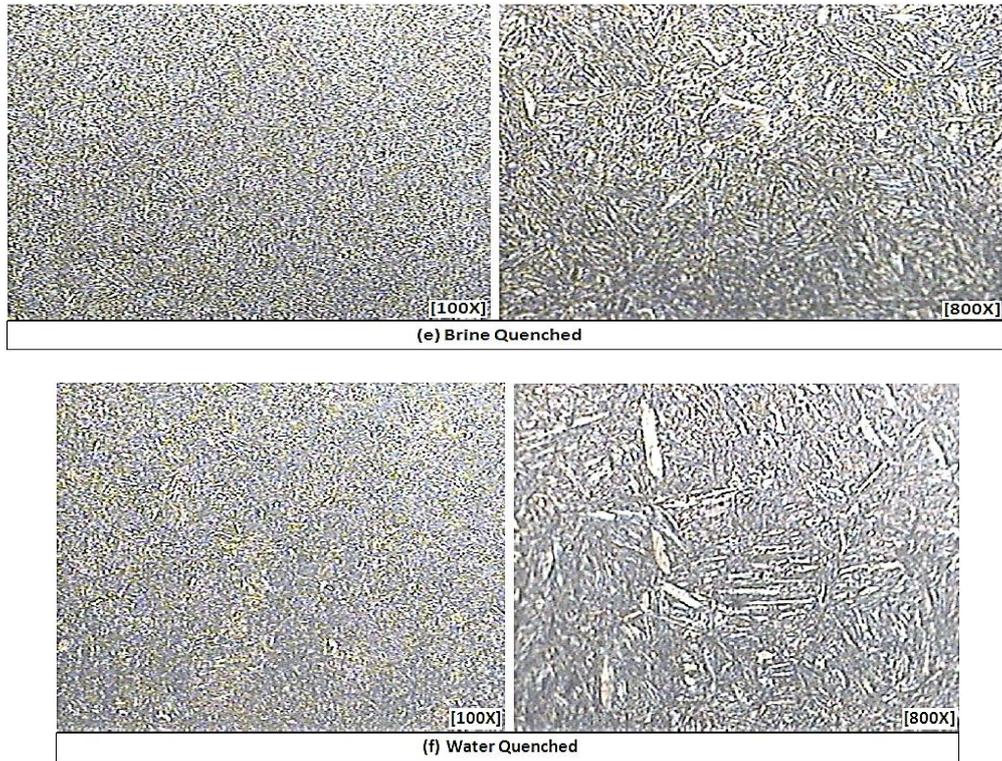
Plate 1 - Photomicrographs of the heat treated coupons in 100X and 800X magnifications: (a) As Received (AR), (b) Air Cooled (AC), (c) Oil Quenched (OQ), (d) Furnace Cooled (FC), (e) Brine Quenched (BQ), (f) Water Quenched (WQ).

Table 4 - Experimental reading for coupons in different environments.

1. **Air Cooled (AC)**

AC (Milieu: Effluent Water, EW)

Coupon #	Duration (days)	Duration (hours, *hr*)	Mass loss (W) (mg)	534W	dAT $16.7285 \times hr$	Corrosion (mpy) x 10^{-3}	Corrosion (mm/yr) x 10^{-5} 0.0254mpy
AC1	$0-10$	240	0.0005	0.267	4014.84	0.0067	0.0170
AC2	$0-20$	480	0.0008	0.427	8029.68	0.0532	0.1351
AC3	$0-30$	720	0.0008	0.427	12044.52	0.0355	0.0902
AC4	$0-40$	960	0.0009	0.481	16059.36	0.0300	0.0762
AC5	$0-50$	1200	0.0010	0.534	20074.20	0.0266	0.0676
AC6	$0-60$	1440	0.0010	0.534	24089.04	0.0222	0.0564
AC7	$50-60$	240	0.0001				
AC8	Calculated	AC6 - AC5	0.0000				

AC (Milieu: Seawater, SW)

Coupon #	Duration (days)	Duration (hours, *hr*)	Mass loss (W) (mg)	534W	dAT $16.7285 \times hr$	Corrosion (mpy) x 10^{-3}	Corrosion (mm/yr) x 10^{-3} 0.0254mpy
AC1	$0-10$	240	0.1160	61.944	4014.84	15.4287	0.3919
AC2	$0-20$	480	0.1520	81.168	8029.68	10.1085	0.2568
AC3	$0-30$	720	0.1290	68.886	12044.52	5.7193	0.1453
AC4	$0-40$	960	0.1218	65.059	16059.36	4.0512	0.1029
AC5	$0-50$	1200	0.1631	87.094	20074.20	4.3386	0.1102
AC6	$0-60$	1440	0.2350	125.472	24089.04	5.2087	0.1323
AC7	$50-60$	240	0.0340				
AC8	Calculated	AC6 - AC5	0.0719				

AC (Milieu: $0.5H_2SO_4$)

Coupon #	Duration (days)	Duration (hours, *hr*)	Mass loss (W) (mg)	534W	dAT $16.7285 \times hr$	Corrosion (mpy) x 10^{-3}	Corrosion (mm/yr) x 10^{-3} 0.0254mpy
AC1	0 – 10	240	0.1720	91.848	4014.84	22.8771	0.4019
AC2	0 – 20	480	0.2379	127.039	8029.68	15.8212	0.4019
AC3	0 – 30	720	0.4623	246.868	12044.52	20.4963	0.5206
AC4	0 – 40	960	0.5151	275.063	16059.36	17.1279	0.4351
AC5	0 – 50	1200	0.6681	356.765	20074.20	17.7723	0.4514
AC6	0 – 60	1440	0.6139	327.823	24089.04	13.6087	0.3457
AC7	50 – 60	240	0.1114				
AC8	Calculated AC6 - AC5		-0.0542				

AC (Milieu: 0.5HCL)

Coupon #	Duration (days)	Duration (hours, *hr*)	Mass loss (W) (mg)	534W	dAT $16.7285 \times hr$	Corrosion (mpy) x 10^{-3}	Corrosion (mm/yr) x 10^{-3} 0.0254mpy
AC1	0 – 10	240	0.0625	33.367	4014.84	8.3109	0.2111
AC2	0 – 20	480	0.1137	60.697	8029.68	7.5591	0.1920
AC3	0 – 30	720	0.1510	80.613	12044.52	6.6929	0.1700
AC4	0 – 40	960	0.1980	105.726	16059.36	6.5835	0.1672
AC5	0 – 50	1200	0.2398	128.032	20074.20	6.3780	0.1620
AC6	0 – 60	1440	0.2842	151.742	24089.04	6.2992	0.1600
AC7	50 – 60	240	0.0327				
AC8	Calculated AC6 - AC5		0.0444				

2. Furnace cooled (FC)

FC (Milieu: Effluent Water, EW)

Coupon #	Duration (days)	Duration (hours, *hr*)	Mass loss (W) (mg)	534W	dAT $16.7285 \times hr$	Corrosion (mpy) x 10^{-3}	Corrosion (mm/yr) x 10^{-5} 0.0254mpy
FC1	0 – 10	240	0.0020	1.068	4014.84	0.2660	0.6756
FC2	0 – 20	480	0.0020	1.068	8029.68	0.1330	0.3378
FC3	0 – 30	720	0.0023	1.228	12044.52	0.1020	0.2591
FC4	0 – 40	960	0.0030	1.602	16059.36	0.0998	0.2535
FC5	0 – 50	1200	0.0031	1.655	20074.20	0.0824	0.2093
FC6	0 – 60	1440	0.0027	1.442	24089.04	0.0599	0.1521
FC7	50 – 60	240	0.0000				
FC8	Calculated FC6 - FC5		-0.0004				

FC (Milieu Seawater, SW)

Coupon #	Duration (days)	Duration (hours, *hr*)	Mass loss (W) (mg)	534W	dAT $16.7285 \times hr$	Corrosion (mpy) x 10^{-3}	Corrosion (mm/yr) x 10^{-3} 0.0254mpy
FC1	0 – 10	240	0.1170	62.478	4014.84	15.5618	0.3953
FC2	0 – 20	480	0.1674	89.392	8029.68	11.1327	0.2828
FC3	0 – 30	720	0.1810	96.654	12044.52	8.0247	0.2038
FC4	0 – 40	960	0.1900	101.460	16059.36	6.3178	0.1605
FC5	0 – 50	1200	0.2267	121.058	20074.20	6.0305	0.1532
FC6	0 – 60	1440	0.2560	136.704	24089.04	5.6749	0.1441
FC7	50 – 60	240	0.0396				
FC8	Calculated FC6 - FC5		0.0440				

FC (Milieu: $0.5H_2SO_4$)

Coupon #	Duration (days)	Duration (hours, *hr*)	Mass loss (W) (mg)	534W	dAT 16.7285 x *hr*	Corrosion (mpy) x 10^{-3}	Corrosion (mm/yr) x 10^{-3} 0.0254mpy
FC1	0 – 10	240	0.2070	110.538	4014.84	27.5324	0.6993
FC2	0 – 20	480	0.2400	128.160	8029.68	15.9608	0.4054
FC3	0 – 30	720	0.2513	134.194	12044.52	11.1414	0.2830
FC4	0 – 40	960	0.3149	168.157	16059.36	10.4710	0.2660
FC5	0 – 50	1200	0.4465	238.431	20074.20	11.8775	0.3017
FC6	0 – 60	1440	0.5439	290.443	24089.04	12.0570	0.3062
FC7	50 – 60	240	0.1110				
FC8	Calculated FC6 - FC5		0.0008				

FC (Milieu: 0.5HCL)

Coupon #	Duration (days)	Duration (hours, *hr*)	Mass loss (W) (mg)	534W	dAT 16.7285 x *hr*	Corrosion (mpy) x 10^{-3}	Corrosion (mm/yr) x 10^{-3} 0.0254mpy
FC1	0 – 10	240	0.1927	102.902	4014.84	25.6303	0.6510
FC2	0 – 20	480	0.3025	161.542	8029.68	20.1181	0.5110
FC3	0 – 30	720	0.3738	199.636	12044.52	16.5748	0.4210
FC4	0 – 40	960	0.4145	221.354	16059.36	13.7835	0.3501
FC5	0 – 50	1200	0.4440	237.097	20074.20	11.8110	0.3000
FC6	0 – 60	1440	0.5345	285.495	24089.04	11.8504	0.3010
FC7	50 – 60	240	0.0612				
FC8	Calculated FC6 - FC5		0.0905				

3. **Water Quenched (WQ)**

WQ (Milieu: Effluent Water, EW)

Coupon #	Duration (days)	Duration (hours, *hr*)	Mass loss (W) (mg)	534W	dAT 16.7285 x *hr*	Corrosion (mpy) x 10^{-3}	Corrosion (mm/yr) x 10^{-5} 0.0254mpy
WQ1	0 – 10	240	0.0009	0.481	4014.84	0.1198	0.3043
WQ2	0 – 20	480	0.0050	2.670	8029.68	0.3325	0.8446
WQ3	0 – 30	720	0.0063	3.364	12044.52	0.2793	0.7094
WQ4	0 – 40	960	0.0063	3.364	16059.36	0.2095	0.5321
WQ5	0 – 50	1200	0.0071	3.791	20074.20	0.1888	0.4796
WQ6	0 – 60	1440	0.0071	3.791	24089.04	0.1574	0.3998
WQ7	50 – 60	240	0.0000				
WQ8	Calculated WQ6 - WQ5		0.0000				

WQ (Milieu: Seawater, SW)

Coupon #	Duration (days)	Duration (hours, *hr*)	Mass loss (W) (mg)	534W	dAT 16.7285 x *hr*	Corrosion (mpy) x 10^{-3}	Corrosion (mm/yr) x 10^{-3} 0.0254mpy
WQ1	0 – 10	240	0.1190	63.546	4014.84	15.8278	0.4020
WQ2	0 – 20	480	0.1350	72.090	8029.68	8.9779	0.2280
WQ3	0 – 30	720	0.1510	80.634	12044.52	6.6946	0.1700
WQ4	0 – 40	960	0.1750	93.450	16059.36	5.8190	0.1478
WQ5	0 – 50	1200	0.2210	118.014	20074.20	5.8789	0.1493
WQ6	0 – 60	1440	0.2577	137.612	24089.04	5.7126	0.1451
WQ7	50 – 60	240	0.0290				
WQ8	Calculated WQ6 - WQ5		0.0291				

WQ (Milieu: 0.5H$_2$SO$_4$)

Coupon #	Duration (days)	Duration (hours, *hr*)	Mass loss (W) (mg)	534W	d.A.T 16.7285 x *hr*	Corrosion (mpy) x 10^{-3}	Corrosion (mm/yr) x 10^{-3} 0.0254mpy
WQ1	0 – 10	240	0.4030	215.202	4014.84	53.6016	1.3615
WQ2	0 – 20	480	0.9379	500.839	8029.68	62.3735	1.5843
WQ3	0 – 30	720	1.0339	552.103	12044.52	45.8385	1.1643
WQ4	0 – 40	960	1.1321	604.541	16059.36	37.6442	0.9562
WQ5	0 – 50	1200	1.1494	613.780	20074.20	30.5756	0.7766
WQ6	0 – 60	1440	1.5098	806.224	24089.04	33.4685	0.8501
WQ7	50 – 60	240	0.1011				
WQ8	Calculated WQ6 - WQ5		0.3604				

WQ (Milieu: 0.5HCL)

Coupon #	Duration (days)	Duration (hours, *hr*)	Mass loss (W) (mg)	534W	d.A.T 16.7285 x *hr*	Corrosion (mpy) x 10^{-3}	Corrosion (mm/yr) x 10^{-3} 0.0254mpy
WQ1	0 – 10	240	0.1217	64.965	4014.84	16.1812	0.4110
WQ2	0 – 20	480	0.2309	123.322	8029.68	15.3583	0.3901
WQ3	0 – 30	720	0.2850	152.216	12044.52	12.6377	0.3210
WQ4	0 – 40	960	0.3457	184.620	16059.36	11.4961	0.2920
WQ5	0 – 50	1200	0.4219	225.321	20074.20	11.2244	0.2851
WQ6	0 – 60	1440	0.4973	265.549	24089.04	11.0236	0.2800
WQ7	50 – 60	240	0.0510				
WQ8	Calculated WQ6 - WQ5		0.0754				

4. Brine Quenched (BQ)

BQ (Milieu: Effluent Water, EW)

Coupon #	Duration (days)	Duration (hours, *hr*)	Mass loss (W) (mg)	534W	d.A.T 16.7285 x *hr*	Corrosion (mpy) x 10^{-3}	Corrosion (mm/yr) x 10^{-5} 0.0254mpy
BQ1	0 – 10	240	0.0018	0.961	4014.84	0.2394	0.6081
BQ2	0 – 20	480	0.0059	3.151	8029.68	0.3924	0.9967
BQ3	0 – 30	720	0.0083	4.432	12044.52	0.3680	0.9347
BQ4	0 – 40	960	0.0073	3.898	16059.36	0.2427	0.6165
BQ5	0 – 50	1200	0.0088	4.699	20074.20	0.2341	0.5946
BQ6	0 – 60	1440	0.0084	4.486	24089.04	0.1862	0.4729
BQ7	50 – 60	240	0.0000				
BQ8	Calculated BQ6 - BQ5		-0.0004				

BQ (Milieu: Seawater, SW)

Coupon #	Duration (days)	Duration (hours, *hr*)	Mass loss (W) (mg)	534W	d.A.T 16.7285 x *hr*	Corrosion (mpy) x 10^{-3}	Corrosion (mm/yr) x 10^{-5} 0.0254mpy
BQ1	0 – 10	240	0.1100	58.740	4014.84	14.6307	0.3716
BQ2	0 – 20	480	0.1270	67.818	8029.68	8.4459	0.2145
BQ3	0 – 30	720	0.1430	76.362	12044.52	6.3399	0.1610
BQ4	0 – 40	960	0.1709	91.261	16059.36	5.6827	0.1443
BQ5	0 – 50	1200	0.1990	106.266	20074.20	5.2936	0.1345
BQ6	0 – 60	1440	0.2640	140.976	24089.04	5.8523	0.1486
BQ7	50 – 60	240	0.0431				
BQ8	Calculated BQ6 - BQ5		0.0650				

BQ (Milieu: 0.5H₂SO₄)

Coupon #	Duration (days)	Duration (hours, *hr*)	Mass loss (W) (mg)	534W	dAT *16.7285 x hr*	Corrosion (mpy) x 10⁻³	Corrosion (mm/yr) x 10⁻³ *0.0254*mpy
BQ1	0 – 10	240	0.5735	306.297	4014.84	76.2913	1.9378
BQ2	0 – 20	480	0.8340	445.356	8029.68	55.4640	1.4088
BQ3	0 – 30	720	0.9717	518.888	12044.52	43.0810	1.0943
BQ4	0 – 40	960	1.1853	632.950	16059.36	39.4132	1.0012
BQ5	0 – 50	1200	1.1106	593.060	20074.20	29.5434	0.7504
BQ6	0 – 60	1440	1.2157	649.184	24089.04	26.9494	0.6845
BQ7	50 – 60	240	0.1001				
BQ8	Calculated BQ6 - BQ5		0.1050				

BQ (Milieu: 0.5HCL)

Coupon #	Duration (days)	Duration (hours, *hr*)	Mass loss (W) (mg)	534W	dAT *16.7285 x hr*	Corrosion (mpy) x 10⁻³	Corrosion (mm/yr) x 10⁻³ *0.0254*mpy
BQ1	0 – 10	240	0.1190	63.546	4014.84	15.8278	0.4020
BQ2	0 – 20	480	0.2150	114.810	8029.68	14.2982	0.3632
BQ3	0 – 30	720	0.2686	143.443	12044.52	11.9094	0.3025
BQ4	0 – 40	960	0.3552	189.677	16059.36	11.8110	0.3000
BQ5	0 – 50	1200	0.4013	214.272	20074.20	10.6740	0.2711
BQ6	0 – 60	1440	0.4795	256.065	24089.04	10.6299	0.2700
BQ7	50 – 60	240	0.0537				
BQ8	Calculated BQ6 - BQ5		0.0782				

5. Oil Quenched (OQ)

OQ (Milieu: Effluent Water, EW)

Coupon #	Duration (days)	Duration (hours, *hr*)	Mass loss (W) (mg)	534W	dAT *16.7285 x hr*	Corrosion (mpy) x 10⁻³	Corrosion (mm/yr) x 10⁻⁵ *0.0254*mpy
OQ1	0 – 10	240	0.0020	1.068	4014.84	0.2660	0.6756
OQ2	0 – 20	480	0.0021	1.121	8029.68	0.1396	0.3531
OQ3	0 – 30	720	0.0021	1.121	12044.52	0.0931	0.2365
OQ4	0 – 40	960	0.0023	1.228	16059.36	0.0765	0.1943
OQ5	0 – 50	1200	0.0023	1.228	20074.20	0.0612	0.1554
OQ6	0 – 60	1440	0.0021	1.121	24089.04	0.0465	0.1181
OQ7	50 – 60	240	0.0000				
OQ8	Calculated OQ6 - OQ5		0.0000				

OQ (Milieu: Seawater, SW)

Coupon #	Duration (days)	Duration (hours, *hr*)	Mass loss (W) (mg)	534W	dAT *16.7285 x hr*	Corrosion (mpy) x 10⁻³	Corrosion (mm/yr) x 10⁻³ *0.0254*mpy
OQ1	0 – 10	240	0.1070	57.138	4014.84	14.2317	0.3615
OQ2	0 – 20	480	0.1230	65.682	8029.68	8.1799	0.2078
OQ3	0 – 30	720	0.1310	69.954	12044.52	5.8080	0.1475
OQ4	0 – 40	960	0.1480	79.032	16059.36	4.9212	0.1250
OQ5	0 – 50	1200	0.1910	101.994	20074.20	5.0809	0.1291
OQ6	0 – 60	1440	0.2450	130.830	24089.04	5.4311	0.1380
OQ7	50 – 60	240	0.0368				
OQ8	Calculated OQ6 - OQ5		0.0540				

OQ (Milieu: 0.5H₂SO₄)

Coupon #	Duration (days)	Duration (hours, *hr*)	Mass loss (W) (mg)	534W	dAT 16.7285 x hr	Corrosion (mpy) x 10⁻³	Corrosion (mm/yr) x 10⁻³ 0.0254mpy
OQ1	0 – 10	240	0.2630	140.442	4014.84	34.9807	0.8885
OQ2	0 – 20	480	0.3838	204.949	8029.68	25.5239	0.6483
OQ3	0 – 30	720	0.6439	343.843	12044.52	28.5477	0.7251
OQ4	0 – 40	960	0.8260	441.084	16059.36	27.4658	0.6976
OQ5	0 – 50	1200	0.8408	448.987	20074.20	22.3664	0.5681
OQ6	0 – 60	1440	1.0429	556.909	24089.04	23.1187	0.5872
OQ7	50 – 60	240	0.1078				
OQ8	Calculated	OQ6 - OQ5	0.2021				

OQ (Milieu: 0.5HCL)

Coupon #	Duration (days)	Duration (hours, *hr*)	Mass loss (W) (mg)	534W	dAT 16.7285 x hr	Corrosion (mpy) x 10⁻³	Corrosion (mm/yr) x 10⁻³ 0.0254mpy
OQ1	0 – 10	240	0.1160	61.961	4014.84	15.4330	0.3920
OQ2	0 – 20	480	0.1924	102.774	8029.68	12.7993	0.3251
OQ3	0 – 30	720	0.2459	131.352	12044.52	10.9055	0.2770
OQ4	0 – 40	960	0.2643	141.120	16059.36	8.7874	0.2232
OQ5	0 – 50	1200	0.3006	160.515	20074.20	7.9961	0.2031
OQ6	0 – 60	1440	0.3554	189.772	24089.04	7.8780	0.2001
OQ7	50 – 60	240	0.0422				
OQ8	Calculated	OQ6 - OQ5	0.0548				

IV. GRAPH PLOTS

A. Corrosion rate Vs. Duration of coupons in different milieu
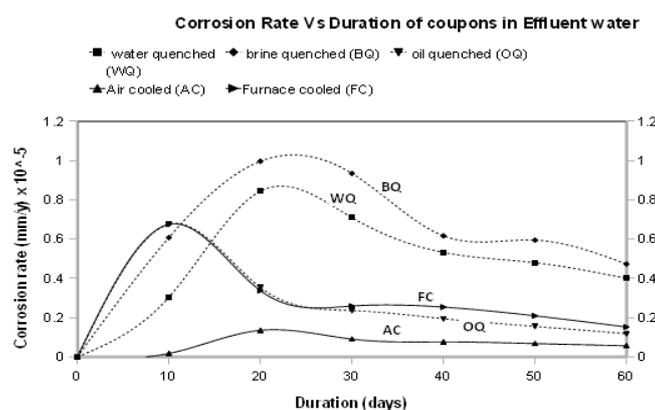
Fig. 1 - Corrosion Rate vs. Duration of coupons in Effluent water
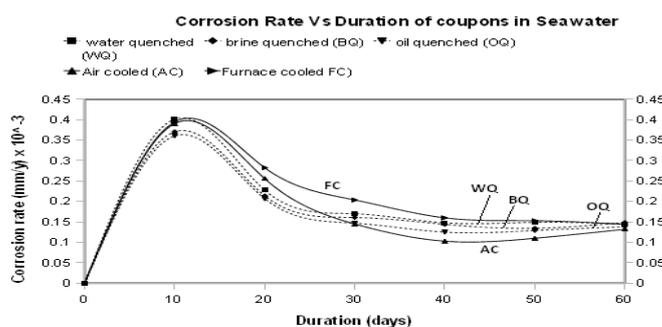
Fig. 2- Corrosion Rate vs. Duration of coupons in Seawater
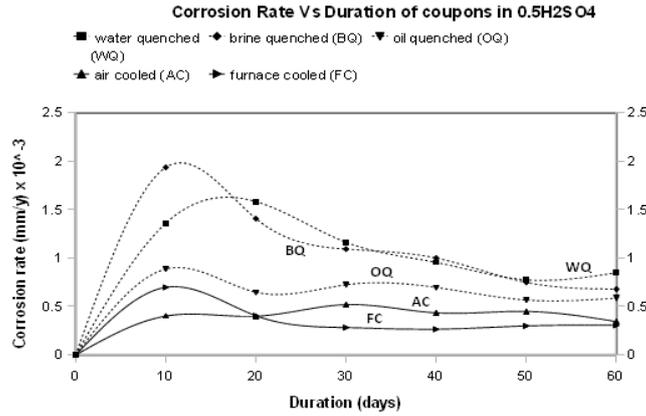
Fig. 3 - Corrosion Rate vs. Duration of coupons in 0.5MH$_2$SO$_4$
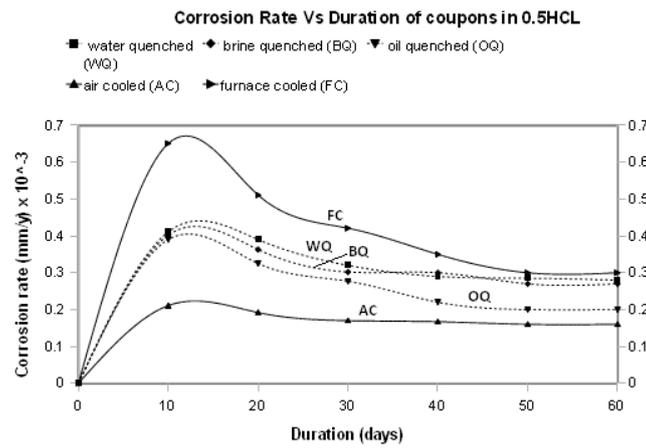
Fig. 4 - Corrosion Rate vs. Duration of coupons in 0.5MHCl

V. OBSERVATIONS AND DISCUSSION

Case 1
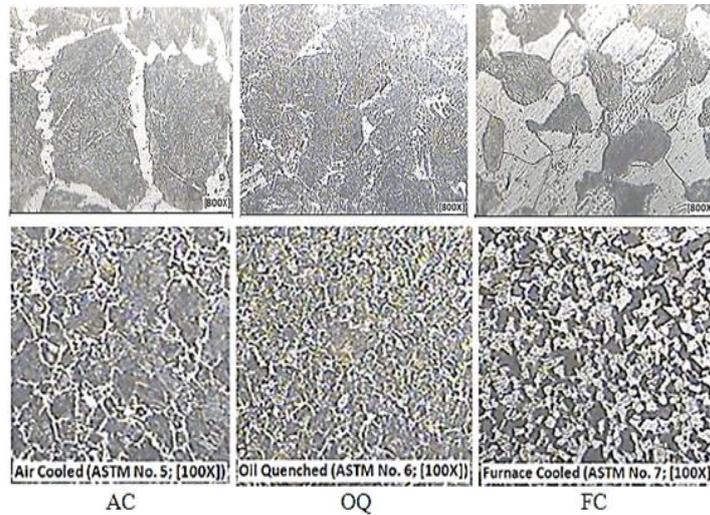
The photomicrograph of the air cooled coupon is AC above as extracted from Plate 1(b). This relatively rapid method of cooling, limited ferrite grain growth giving rise to precipitation of allotriomorphic ferrite or pro-eutectoid ferrite at prior austenite grain boundaries in a matrix of pearlite(α + Fe$_3$C). The white patches denote the ferrite while pearlite is dark.

The photomicrograph of the oil quenched coupon is OQ above as extracted from Plate 1(c). It showed ferrite in pearlitic matrix with grain size less than AC.

Plate 1(d) or FC above shows the photomicrograph of furnace cooled coupon. In this structure, the slow cooling condition in the furnace allowed extensive diffusion of carbon giving rise to considerable precipitation of ferrite. The resulted structure is equiaxed grains of ferrite and pearlite.

In all the media, the corrosion rates of AC, OQ, and FC microstructures decrease with time of exposure with FC generally higher than AC and OQ except in $0.5H_2SO_4$ medium. However, after about 40 days, the corrosion rates of AC, OQ, and FC structures tend to converge to 0.00014 mm/yr in seawater; AC and FC to 0.00025 mm/yr and OQ to 0.0006 mm/yr in $0.5H_2SO_4$. In 0.5HCL (Fig. 4), the corrosion rate of FC tends to 0.0003 mm/yr; OQ to 0.0002 mm/yr., while that of AC to 0.00016 mm/yr. This difference shows that the microstructural constituents in the coupons were environment sensitive. In the effluent water, the corrosion rates were practically small, of the order $x10^{-5}$ after 40 days.

This observable difference in corrosion rates could be attributed to precipitation of ferrite plates and carbide phase. The microstructural difference led to setting up of micro galvanic cells within the microstructure with the carbide phase becoming cathodic and the ferrite anodic. These micro galvanic cells add up to the natural corrosion process of medium carbon steel resulting from the energy difference between the metal and the electrolyte.

The corrosion rate was generally highest in annealed coupon (FC), followed by corrosion rate of oil quenched OQ and lastly the normalized coupon (AC) except in $0.5H_2SO_4$ medium were the OQ corrosion rate was higher than that of AC and FC. Comparatively, AC is relatively most corrosion resistant, followed by OQ and lastly FC. It then suggests that increase in the amount of ferrite precipitation (anodic area), resulting to differences in grain size, was the cause of change in rate of corrosion of normalized medium carbon steel.

Case 2

The photomicrograph of the WQ coupon is shown in Plate 1 (f) or as extracted in WQ below. This structure shows ferrite platelets separated by carbide distribution (cementite) in a martensite matrix.

WQ   BQ
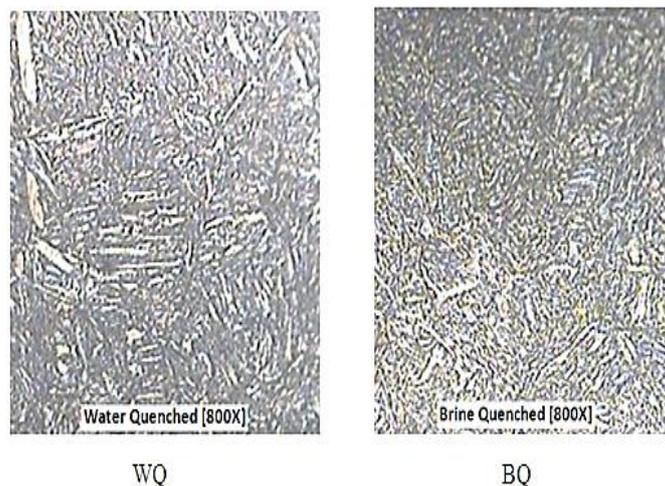
Plate 1(e) or BQ above shows the photomicrograph of brine quenched (BQ) coupon. It is similar to WQ. In this structure there is formation of smaller ferrite platelets with carbide dispersion (cementite) in a martensite matrix (see Bhadeshia, 2001 pg 16 -20 and Bhadeshia& Christian, 1990 pg 771 -772).

In all the media, the corrosion rates of the two microstructures decreased with time of exposure. WQ was slightly more susceptible to corrosion than BQ in seawater, 0.5H2SO4, and 0.5HCL. However, after about 40 days, (see graph plots of Fig. 2 to Fig. 4), the two structures tend to converge to 0.00015 mm/yr in seawater; WQ to 0.00028 mm/yr and BQ to 0.00027 in 0.5HCL. WQ tends to 0.0008 mm/yr while BQ tends to 0.0007 mm/yr in $0.5H_2SO_4$. Again in the effluent water, the corrosion rates were extremely small in comparison; WQ tending to 0.000004 mm/yr and BQ to 0.0000047 mm/yr after 50 days. There was close relationship between these graphs thus showing that the morphology of the microstructures were essentially the same.

BQ coupons were generally and slightly less corroded in the selected media. Since there structures contained essentially the same phases, the slight observable difference in corrosion rates could be due to variation in the amount of ferrite platelets and carbide precipitation present in the two structures. Also lattice distortion due to martensitic transformation seemed to be more in BQ, as suggested by smaller width of ferrite plates, than WQ. In general WQ was more susceptibility to corrosion than BQ.

Case 3

Air Cooled (ASTM No. 5; [100X]) Oil Quenched (ASTM No. 6; [100X]) Furnace Cooled (ASTM No. 7; [100X])
AC   OQ   FC

Water Quenched [800X]   Brine Quenched [800X]
WQ   BQ
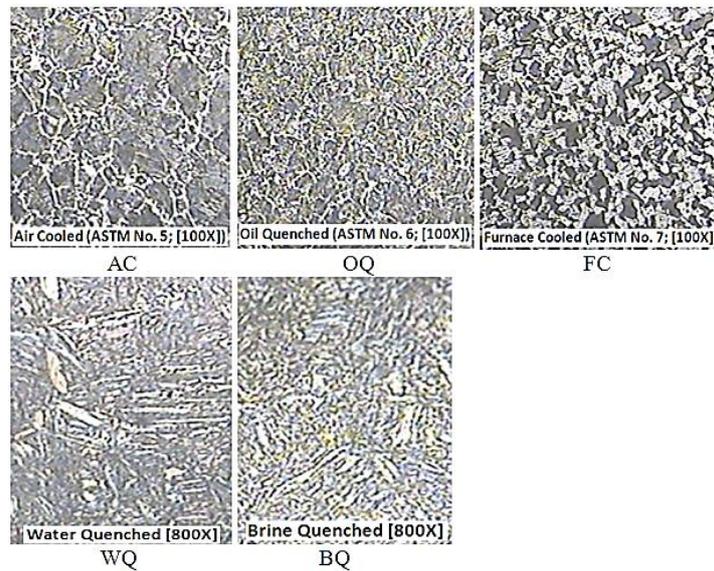
In comparing the five microstructures normalized microstructure (AC) had the lowest corrosion rate in seawater, 0.5HCL and Effluent water. FC had the lowest corrosion rate only in $0.5H_2SO_4$. AC was followed by OQ except in $0.5H_2SO_4$ medium where FC had the lowest value.

WQ offered the least resistance to corrosion in $0.5H_2SO_4$. BQ offered the least resistance in effluent water. FC offered least resistance to corrosion in seawater and 0.5HCL. From the graphs, martensite had the most environmental sensitive microstructure. The converging points of the corrosion rates are shown in Table 6 at 60th day.

Table 6: Corrosion Rate Converging Point at 60 days

Corrosion Rate Converging Point At 60 days				
Microstructure	Seawater	$0.5MH_2SO_4$	0.5MHCL	Effluent Water
AC	0.00014	0.00025	0.00016	0.0000005
OQ	0.00014	0.00060	0.00020	0.0000010
FC	0.00014	0.00025	0.00030	0.0000010
BQ	0.00015	0.00070	0.00027	0.0000047
WQ	0.00015	0.00080	0.00028	0.0000040

Table 6 shows that in general, corrosion rate is lowest in AC and increases thus: AC <OQ< FC <BQ<WQ. Also, on average, the corrosion rate of medium carbon steel tends to a common value after 50 days in seawater,Another observation was that there was decrease in corrosion rate of all the coupons with time which suggested the formation of a protective film on the coupon which decreases the metal corrodibility. This protective film was observed during the coupon test.

Finally, the weight loss of coupons in effluent water showed extremely small value. Since the coupons showed little or no protective film, it suggested that the effluent water had corrosion inhibition property.

B. Corrosion rate of each set of coupons in all the media
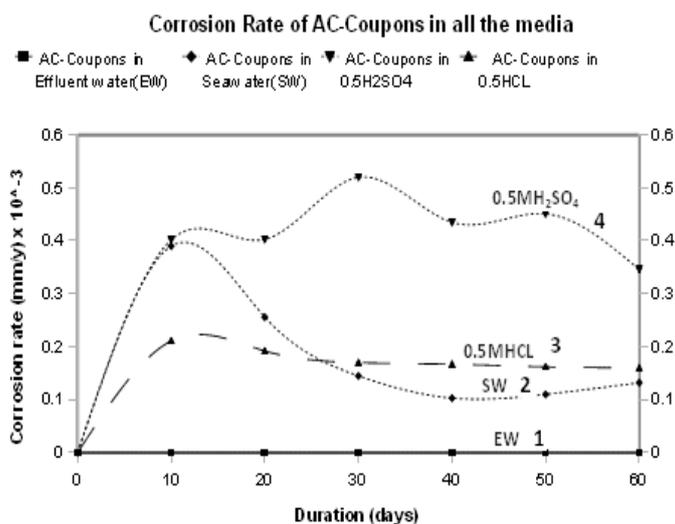
Fig. 5 – Corrosion rate of AC-Coupons in all the media
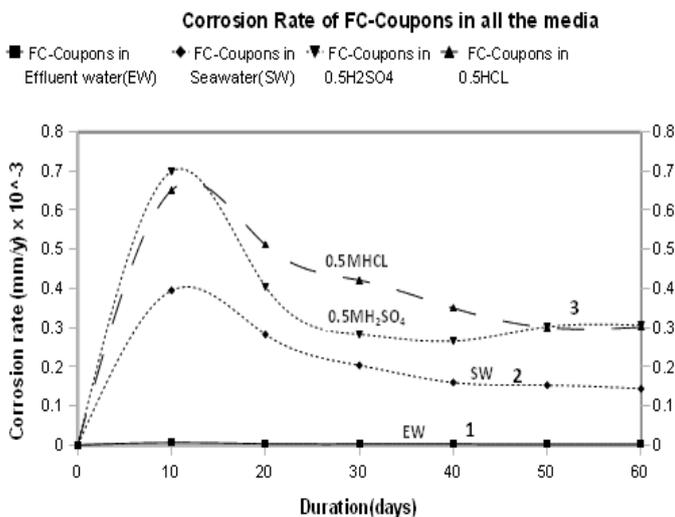
Fig. 6 – Corrosion rate of FC-Coupons in all the media
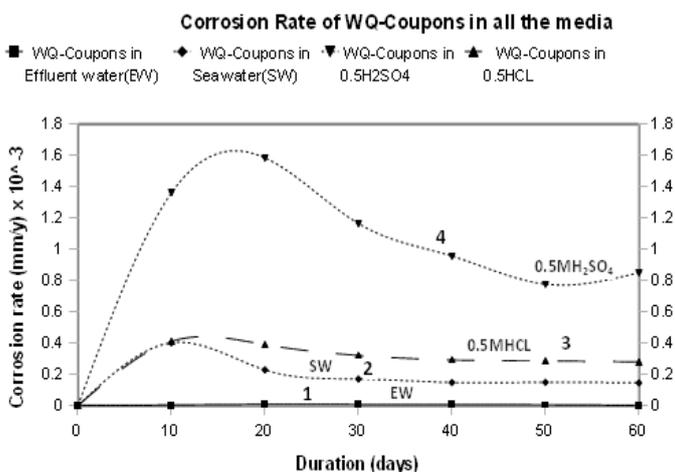
Fig. 7 – Corrosion rate of WQ-Coupons in all the media
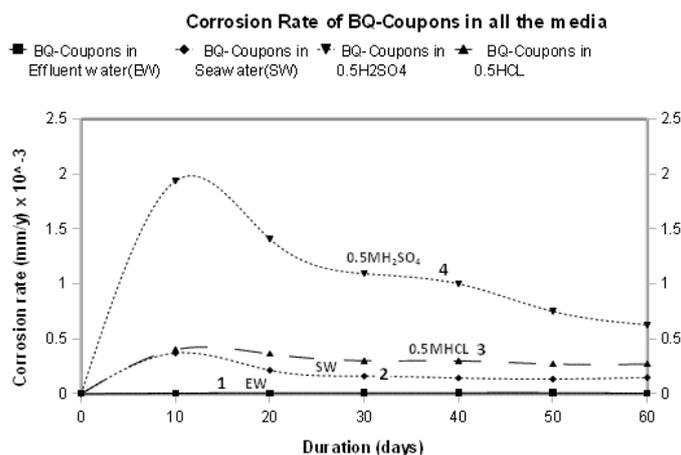
Fig. 8 – Corrosion rate of BQ-Coupons in all the media
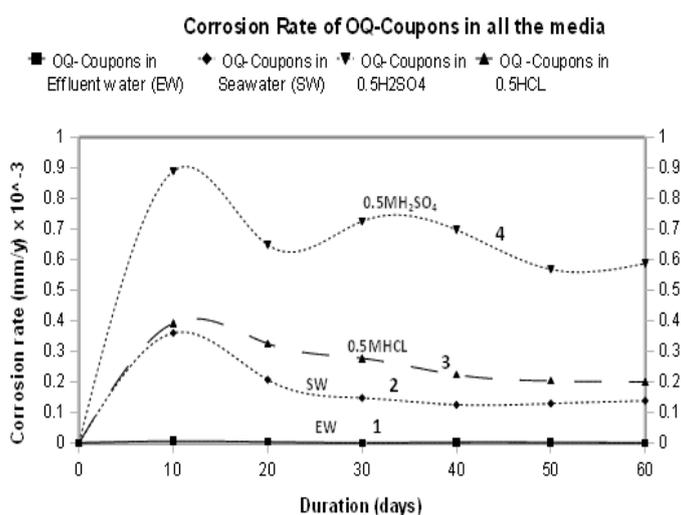
Fig. 9 – Corrosion rate of OQ-Coupons in all the media

Determination of Most Corrosive environment

If we assumed that corrosion process stabilized after 50 days and we assign medium corrosiveness value to the generated graphs as shown in Fig. 5 to Fig. 9, then a data would be generated as shown in Table 7.

Table7 - Most Corrosive environment measurement

Coupons	\multicolumn{4}{c}{Corrosive milieu}	Relative assumption
	EW	SW	$0.5H_2SO_4$	0.5HCL	
AC	1	2	4	3	4 = very high
FC	1	2	3	3	3 = high
WQ	1	2	4	3	2 = moderate
BQ	1	2	4	3	1 = low
OQ	1	2	4	3	
Total score	5	10	19	15	

From Fig. 5 to Fig. 9, all the coupon sets corroded far more in $0.5H_2SO_4$ except the FC coupons that corroded more in 0.5HCL but latter equalled almost that of $0.5H_2SO_4$ after 50 days. $0.5H_2SO_4$ was followed in corrosiveness by 0.5HCL, Seawater and lastly Effluent water. Using Table 7, general aggressiveness of the environment can be stated thus: $0.5H_2SO_4 > 0.5HCL >$ Seawater > Effluent water.

CONCLUSION

The aim of this study was to understand the effect of Heat Treatment on Corrosion Susceptibility of Medium Carbon Steel. In this study, it can be concluded that microstructure obtained by different heat treatment processes are sensitive to the environment. The observable difference in corrosion rates could be attributed to precipitation of ferrite and carbide phases. These phases led to setting up of microgalvanic cells within the microstructure with the carbide phase becoming cathodic and the ferrite anodic. Furthermore, the combining effect of ferrite precipitation, residual stress and carbide precipitation tends to cause higher corrosion rate in the hardened structures. More so, $0.5MH_2SO_4$ was the most aggressive environment, followed by 0.5MHCL, Seawater and lastly Effluent water. Observation noteworthy also is that the corrosion rate of effluent water was in the order of 10^{-5} mm/yr. This tends to show that Effluent water had corrosion inhibition properties.

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