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Effect of corrosion on the tensile strength of structural steel (UNS G10170) exposed to seawater

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ABSTRACT

Carbon steel is the most widely used engineering material and despite its relatively limited corrosion resistance, is used in large tonnages in marine applications, chemical processing, petroleum production and refining, pipelines, etc. The corrosion of carbon steels is a problem of enormous practical importance because the cost of metallic corrosion to the total economy of the world runs into hundreds of millions of dollars per year. This work was carried out to study the effect of corrosion on the mechanical properties of structural steel (UNS G10170) exposed to seawater. Steel samples were subjected to normalising heat treatment, before being immersed in seawater at 15 days intervals for duration of 90 days. The corrosion rates of the steel samples were determined by the weight loss method. The results showed a 9.00% decrease in hardness for the as received sample and 6.50% decrease for the normalised sample; 12.23% decrease in tensile strength for the as-received sample and 7.90% decrease for the normalised sample respectively at the end of the 90th day. It was found that ferrite was less noble than cementite, which caused it to sacrificially dissolve once the samples were polarized in the sweater environment thereby leading to loss of material (weight loss) and consequently reduction in mechanical properties.

1. Introduction

Steel is the basic material of construction in the offshore and onshore industries. Materials commonly used for marine structures comprise carbon and low alloyed steels. In a seawater environment, they are affected by general corrosion which is one of the most important factors influencing the structural capacity during its service life. The water properties such as salinity, temperature, oxygen content, P^H level and chemical composition may vary according to location and water depth [1]. In addition to environment, other factors have been found as important in affecting the corrosion rate of steel structures, for example, morphology, stress concentrations and steel surface preparation. [2,3]. Many corrosion resistant alloys have been developed; carbon steel, despite its relatively limited corrosion resistance, still remains the most versatile, least expensive and widely used engineering material which has found extensive application in various industries [3, 4, 5].

There is increasing attention being given to the deterioration of infrastructure exposed to actual hostile marine environments. As a result engineers are increasingly interested in the rate of loss of strength of steel and hence in the loss of material of the infrastructure system. Two main corrosion mechanisms are generally present in steel plates: general wastage that results in a generalised decrease of plate thickness and localised attack, which generally consists of local areas of extensive and deep damage that appears on the plate and depends critically on the environment [6,7].

Corrosion is one of the main reasons of structural failure of aged structures. The cost of metallic corrosion to the total economy must be measured in hundreds of millions of dollars per year, because carbon steel represents the largest single class of alloys in use, both in terms of tonnage and total cost [8, 9,10]. It is not only the high cost of corrosion, but also the health and environmental risks associated with potential failure of the oil and gas equipment that drive the developments of corrosion resistant materials and improved corrosion mitigation strategies worldwide. It is easy to understand that corrosion of carbon steel is a problem of enormous practical importance, thus necessitating constant research being carried out to determine the corrosion of carbon steel in various environmental conditions. Several studies for the corrosion of plain carbon steel under various environmental conditions including seawater conditions have been carried out [4, 6, 10, 11]. [10] reported that corrosion reduces the tensile strength of plain carbon steel in their investigation of the effect of corrosion on the tensile property of austenitised

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AISI 1040 steel exposed to stagnant seawater. For example, [3], discovered that the corrosion rate of medium carbon steel and carbon steel in seawater in general, decreases with time as protective barrier films may be a rust layer, calcareous deposits or bio-fouling.

In their purest form, most engineering materials are soft and ductile but their microstructure and composition can be altered by alloying with other elements such as nickel, silicon, chromium etc. and/or heat treatment to obtain desired mechanical property for particular application [6]. Also, this practice is utilised in the production of corrosion resistant steels. Thus, steel microstructure plays an important role in determining strength and stability in corrosive environment. Corrosion test results are the foundation for obtaining accurate information on materials performance in the process environment, and for ensuring that resources are effectively used and that materials used are compatible with long-term goals for the plant. They are important tools for evaluating the performance of materials used for scientific, industrial and engineering applications. Corrosion tests are widely used to evaluate the durability of construction materials in reactive environments and directly influence the material chosen for these applications [12,13,14]. Hence this work studies how corrosion affects the tensile strength of normalised structural steel and then exposed to seawater environment. The tensile strength of a material and in particular steel is often of primary concern and a major standards compliance requirement in the design and construction of platforms, pressure vessels, tanks, ships, engineering structures and pipelines in industrial and marine environments; hence this study seeks to investigate how seawater corrosion affects the tensile strength of structural steel exposed to seawater.

2.0 Materials and Methods

2.1 Test Materials

The material used for this study was 0.17%C steel obtained from Donasulu steel Company, Effurun, Delta State of Nigeria. The chemical composition as supplied by the manufacturer is shown in Table 1 [15]. The corrosive environment was natural sea water obtained from Escravos, Delta State, Nigeria which has its source from the Gulf of Guinea, Coast of the Atlantic Ocean. The composition of the seawater was analysed using mass spectrometer. The result of the analysis is shown in Table 2, [16].

Table 1: Chemical Composition of the Steel (Heat - No: 1155)

ELEMENT	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	Al	N	Fe
%Weight	0.17	0.31	0.78	0.03	0.03	0.51	0.09	0.05	0.008	0.047	0.007	balance

Source: [15]

Table 2: Composition of the Seawater used for the Experiment

S/No.	Parameters	Result
1	Dissolved oxygen (mg/l) at 27.5^{o}C	8.20
2	pH at 27.5^{o}C	7.45
3	Sodium (mg/l)	6.84
4	Salinity in form of chloride (mg/l)	7010.7
5	Sulphate (mg/l)	6.96

Source: [16]

2.2 Preparation of the Tensile Test Samples

The material used for this study was mild carbon steel (UNS G10170) with carbon content of 0.17% as determined by X-ray diffraction technique. The samples were then prepared for tensile test. Twenty-two mild steel cylindrical test samples, conforming to specifications outlined by American Society for Testing Materials [17], were machined. The test samples measured 172 mm in total length and the gauge section of the test samples measured 50 mm in length and 9.75 mm in diameter. To minimise the effects of surface irregularities, the gauge sections of the machined test samples were at first mechanically ground on progressively finer grades of silicon carbide (SiC) impregnated emery paper and then finish polished, to a mirror-like finish, using an alumina-based polishing compound. The purpose of polishing was to remove any and all of the circumferential scratches and surface machining marks. The key dimensions of the test samples are shown in Figure 1.

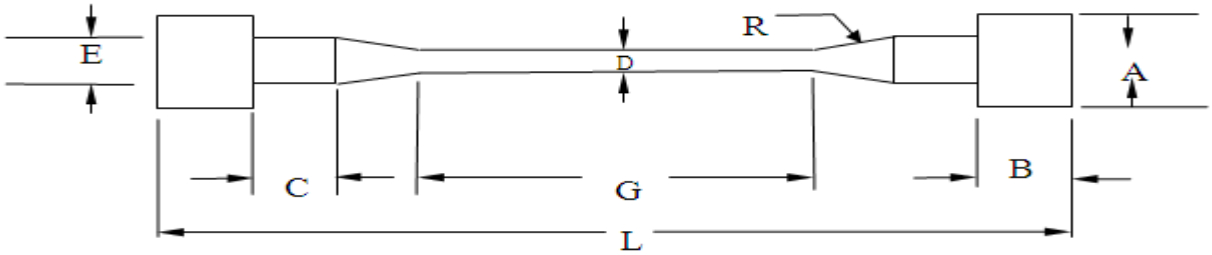


Figure 1: A schematic of the cylindrical test sample used for tensile testing.

A - Diameter of grip section	29.00 mm
B - Length of grip section	16.00 mm
C - Length of shoulder	12.50 mm
D - Gauge diameter	9.84 mm
E - Diameter of shoulder	17.78 mm
G - Gauge length	50.00 mm
L - Overall length	172.00 mm
R - Fillet radius	25.00 mm
ALL DIMENSIONS	± 0.50 mm

2.3 Heat Treatment of Samples

Standard heat treatment procedures were adopted to heat treat the mild carbon steel. 44 samples were used for this experiment. 22 samples were subjected to normalising heat treatment by heating them in a muffle furnace up to 910ºC and then soaked for 35 minutes before cooling in still air to ambient temperature. The remaining 22 samples were not heat treated.

2.4 Environment Preparation

The seawater obtained was placed in a single plastic container. Then both the heat treated and non-heat treated samples were fully immersed in the seawater inside the container.

2.5 Weight Loss Measurements

The samples were weighed accurately before the immersion tests to obtain the original weights W_o in order to conduct weight loss experiments. Corrosion rates were calculated on the basis of mass changes of the samples, these measurements were conducted on an analytical electron balance (0.0001 g in accuracy). Two samples each from the as-received and normalised sets respectively, were taken out at 15 days interval for a duration of 90 days and weighed after cleaning in order to obtain the final weight (W_f). Finally, the mass loss was graphed as a function of the number of cleaning cycles to get the mass of the corrosion products. The corrosion behaviour of samples was evaluated by measuring the mass loss as a function of the immersion time (at 15 days intervals for 90 days). After completion of exposure, corrosion products were removed using inhibited acid (15% HCl) by adopting a cleaning procedure based on ASTM G1 [18]. The samples were then rinsed in running water. Next the samples were then thoroughly dried in a dessicator at 50ºC. The cleaning procedure was repeated on samples, eight times to reach a steady state, with mass loss determined after each cleaning. Corrosion rates were calculated assuming uniform corrosion over the entire surface of the samples. The corrosion rate in mm per year (mm/y) was calculated from the weight loss using the formula [2].

$$CR = 87.6\, x\, \frac{\Delta W}{DAT} \qquad (1)$$

$where: \Delta W = W_o - W_f = weight\ loss\ in\ milligrams$
$D = metal\ density\ in\ gcm^{-3}\ (density\ for\ this\ steel\ sample = 7.86\ gcm^{-3})$
$A = area\ of\ sample\ in\ cm^2\ (total\ exposed\ surface\ area$
$= 85.00\ cm^2\ (tensile\ coupons)\ and\ 23.56\ cm^2\ (hardness\ coupons))$
$T = time\ of\ exposure\ of\ the\ metal\ sample\ in\ hours$

2.6 Determination of Mechanical Properties of the Steel Samples

Mechanical properties of the heat treated and non-heat treated samples were determined using standard methods. After the samples had been heat treated as appropriate and subjected to the corrosive environment for the stipulated periods respectively, the tensile and hardness tests were carried out on them to determine the mechanical properties of the steel and compare it with the non heat treated samples which were also subjected to the same tensile and hardness tests.

2.7 Hardness Test

For hardness testing, oxide layers formed during heat treatment were removed by stage-grinding and then polished. Average Brinell Hardness Number (BHN) readings were determined, according to ASTM standards [19] by taking two hardness readings at different positions, perpendicular to each other, on the samples, using a Brinell hardness tester applying a load of 1,500 kg. The samples were brought in contact with the indenter. The hardness of a sample is indicated by the penetration of the indenter on the said sample and displayed in dial of the machine.

2.8 Tensile Test

The samples for tensile test were tested with the universal testing machine according to ASTM standards [17]. The initial gauge length and diameter were measured before subjecting them to tension. The yield and maximum loads were recorded, the broken ends of each of the samples were fitted and final gauge length and also the smallest diameter of the sample's neck were measured. The steel sample was cut to length using a specially designed press cutter. The universal tensile testing machine in the quality-controlled laboratory was used for the tensile strength of the samples. Loading was applied in a progressive increasing tensile pull until it fractured. The samples were gripped and loaded till yield point was reached. The stress and corresponding strain at this point was recorded. The loading (tensile pull) continued till the maximum loading point was reached, again the

stress and the corresponding strain at this point recorded, and finally, with continued application of load, the material got to its break point. At this point, the stress and the corresponding strain was recorded including the gauge length (i.e., after the fracture). Results obtained for this testing are recorded as shown in Table 5. During the testing, the following mechanical properties were examined. The yield strength, tensile strength and ductility (% elongation and % reduction).

2.9 Metallography

An initial characterisation of the microstructure of the as-provided and normalised materials was done using a low magnification optical microscope according to ASTM standards [20]. Samples of desired sizes were cut from the as-received material i.e. steel, and were mounted in epoxy with the aid of a simplimet mounting press machine. The mounted samples were then ground using a series of silicon carbide impregnated emery paper (240 ,320 ,400 and 600 grit) on a No. 30-S143 abrasive paper roll Simplimet machine with water both as a lubricant and a coolant. Subsequently, the steel samples were mechanically polished using five-micron alumina solution and one-micron alumina solution. Fine polishing to a perfect mirror-like finish of the surface of all the steel samples was achieved using 0.1 micron alumina solution as the lubricant though the crystal structure was hidden. In order to reveal the crystal structure, the polished samples were subsequently etched using a reagent that is a solution mixture of 5-ml of nitric acid (HNO_3) and 90 ml of Ethanol and this reagent is called Nital. The etching reagent removes the amorphous layer of the steel. The polished and etched surface of the steel sample was observed in an optical microscope, magnified $\times 20$ and $\times 75$ respectively and photographed using standard bright field illumination technique as shown in figures 2 and 3 respectively. Precautions were taken during the metallographic process to avoid overheating of the sample during grinding because this may cause a tempering effect. Absolute cleanliness was ensured at every stage and light pressure was applied at all times during grinding and polishing.

2.10 Test Procedure

From the 44 samples used, 28 samples each of 172 mm length were machined into tensile test samples according to ASTM standards [17] and the other 14 samples each of diameter 30 mm and length 10 mm were machined into hardness samples according to ASTM standards [19], and the remaining 2 samples were prepared for metallographic control according to ASTM standards [20]. The head and shoulders of the tensile test samples were painted with lacquer to prevent corrosion and weighed before exposure to corrosion. 42 out of the 44 samples; (21 samples that were normalised including 21 samples which were not heat treated) were exposed to seawater. The test technique was total immersion method in accordance with standard procedures. The tensile tests were conducted at intervals of 15 days for a period of 90 days. At each monitoring day, (15-day interval) 6 samples; 3 normalised samples and 3 non-heat treated samples were removed from the seawater environment. They were washed in distilled water to remove corrosion products formed on them, dried and then tested. Tensile and hardness tests for the control samples were also carried out. Two different samples were prepared for each of the operation and the average values were calculated upon which the analyses were based. Equations (2-5) were used to obtain the tensile and hardness tests results tabulated in Table 4 and Table 3 respectively.

$$\sigma_y = \frac{yield\ load}{A_o} \quad (2)$$

$$UTS = \frac{maximum\ load}{A_o} \quad (3)$$

$$\%\ Elongation = \frac{\Delta L}{L_o}\ x\ 100 \quad (4)$$

$$\%\ Reduction\ in\ area = \frac{\Delta A}{A_o}\ x\ 100 \quad (5)$$

Nomenclature

A_o – *original cross sectional area*
ΔA – *change in cross sectional area*
L_o – *original length*
ΔL – *change in length*
UTS – *ultimate tensile strength*
σ_y – *yield point stress*
(UNS) – *unified numbering system for metals and alloys*

3.0 Results and Discussion

3.1 Microstructure Characterisation

The optical micrographs of the as-received and normalised UNS G10170 samples respectively are shown in Figure 2 and Figure 3. The micrographs are at two different magnifications and reveal the microstructure of the steel samples to be a combination of ferrite and pearlite. A lower carbon content in the steel resulted in a greater volume fraction of ferrite.

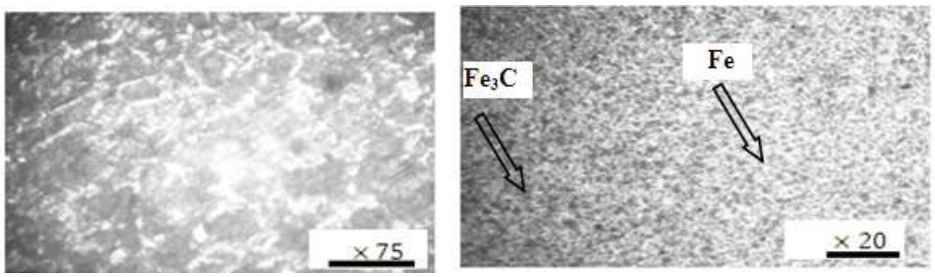


Figure 2: Optical micrographs showing the key micro-constituents of the as-received UNS G10170 steel samples at two different magnifications showing a larger volume fraction of ferrite. Iron carbide (dark areas) and ferrite (grey areas) as shown by the arrows.

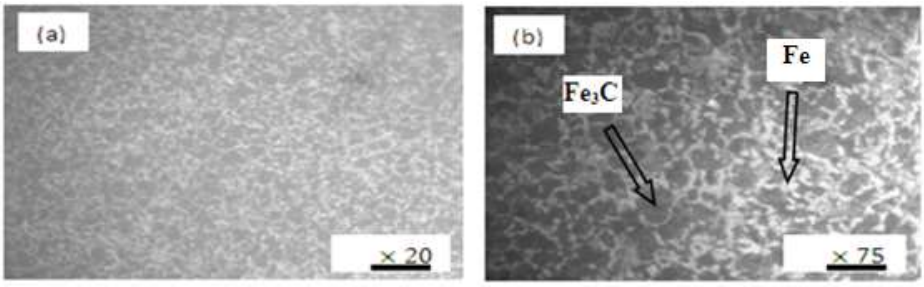


Figure 3: Optical micrographs showing the key micro-constituents of the normalised UNS G10170 of steel sample of fine ferrite-pearlite structure at two different magnifications. Iron carbide (dark areas) and ferrite (grey areas) as shown by the arrows.

Table 3: Tensile coupons corrosion test results

Immersion time (Days)	Immersion time (Hours)	Steel sample	Weight loss ΔW (mg)	CR (mm/y)
15	360	As-received	0.8686	0.000316
		Normalised	0.8362	0.000305
30	720	As-received	1.0683	0.000195
		Normalised	0.9735	0.000177
45	1080	As-received	1.1388	0.000138
		Normalised	1.0082	0.000122
60	1440	As-received	1.2814	0.000117
		Normalised	1.0736	0.000098
75	1800	As-received	1.4873	0.000108
		Normalised	1.1919	0.000087
90	2160	As-received	1.6468	0.000100
		Normalised	1.3604	0.000083

Table 4: Hardness sample corrosion test results

Immersion time (Days)	Immersion time (Hours)	Steel sample	Weight loss ΔW (mg)	CR (mm/y)
15	360	As-received	0.2405	0.000316
		Normalised	0.2307	0.000303
30	720	As-received	0.2962	0.000195
		Normalised	0.2701	0.000177
45	1080	As-received	0.3166	0.000139
		Normalised	0.2784	0.000122
60	1440	As-received	0.3552	0.000117
		Normalised	0.2976	0.000098
75	1800	As-received	0.4111	0.000108
		Normalised	0.3311	0.000087
90	2160	As-received	0.4565	0.000100
		Normalised	0.3771	0.000083

In figure 2, the micrographs show the microstructure of the as-received samples showing a greater volume fraction of ferrite than pearlite due to the low carbon content (0.17%) of the samples. The microstructure is made up of ferrite (grey areas) and

cementite (dark areas). In figure 3, the micrographs show the microstructure of the normalised steel samples showing a fine ferrite-pearlite structure. This is so because normalising heat treatment involves cooling in air to ambient temperature, which is a relatively fast cooling process that allows austenite decomposition to occur at relatively lower temperatures and thus less time for the formation of proeutectoid ferrite from austenite phase therefore resulting in better dispersion of ferrite-carbide aggregate and hence producing a fine ferrite-pearlite structure. This results in the formation of more pearlite and less pro-eutectoid ferrite is in the normalised samples than in the as-received samples.

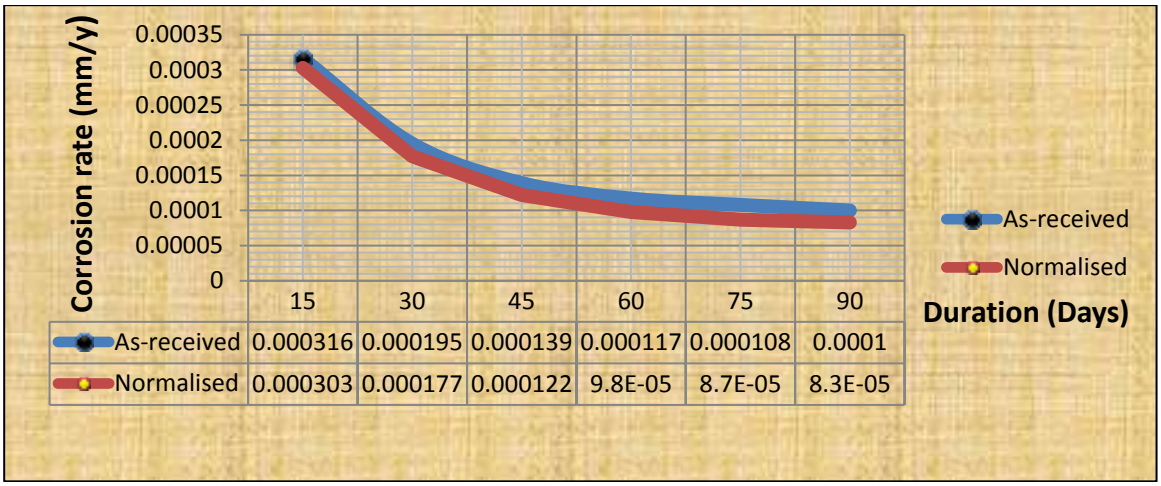


Figure 4: Graph of corrosion rate of tensile coupons vs duration in seawater

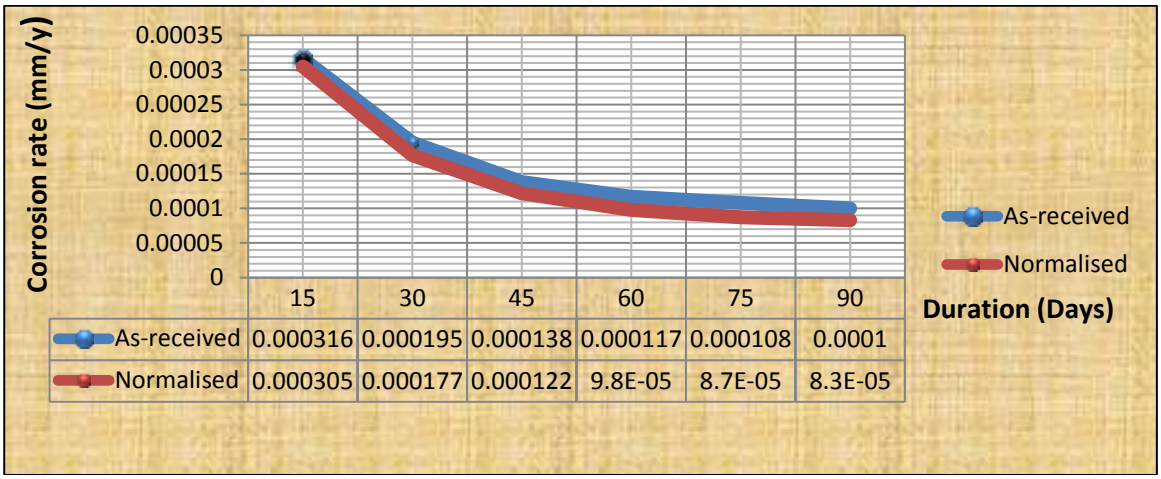


Figure 5: Graph of Corrosion rate of hardness coupons vs Duration in seawater

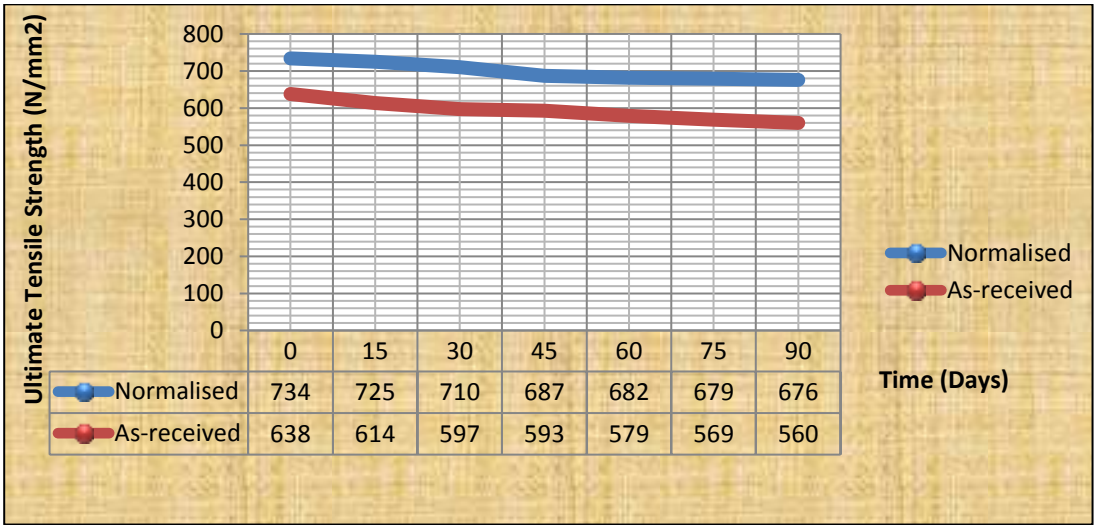


Figure 6: Graph depicting the variation of tensile strength with respect to exposure time for UNS G10170 steel samples.

Table 5 - Tensile Tests Results

Immersion Duration (Days)	Steel Samples	Yield Stress (N/mm^2)	Ultimate Tensile Strength (N/mm^2)	Fracture Strength (N/mm^2)	% Elongation	% Reduction in Cross-Sectional Area
0	As-Received	526	638	536	7.3	50.6
	Normalised	612	734	711	6.0	42.4
15	As-Received	472	614	507	6.6	49.9
	Normalised	604	725	703	5.6	37.6
30	As-Received	459	597	478	6.1	46.2
	Normalised	587	710	687	5.2	31.8
45	As-Received	451	593	470	5.7	43.2
	Normalised	575	687	658	4.9	29.7
60	As-Received	445	579	459	5.4	39.2
	Normalised	550	682	654	4.7	26.7
75	As-Received	438	569	450	5.2	34.8
	Normalised	536	679	640	4.6	24.9
90	As-Received	422	560	429	5.0	34.3
	Normalised	504	676	597	4.5	24.0

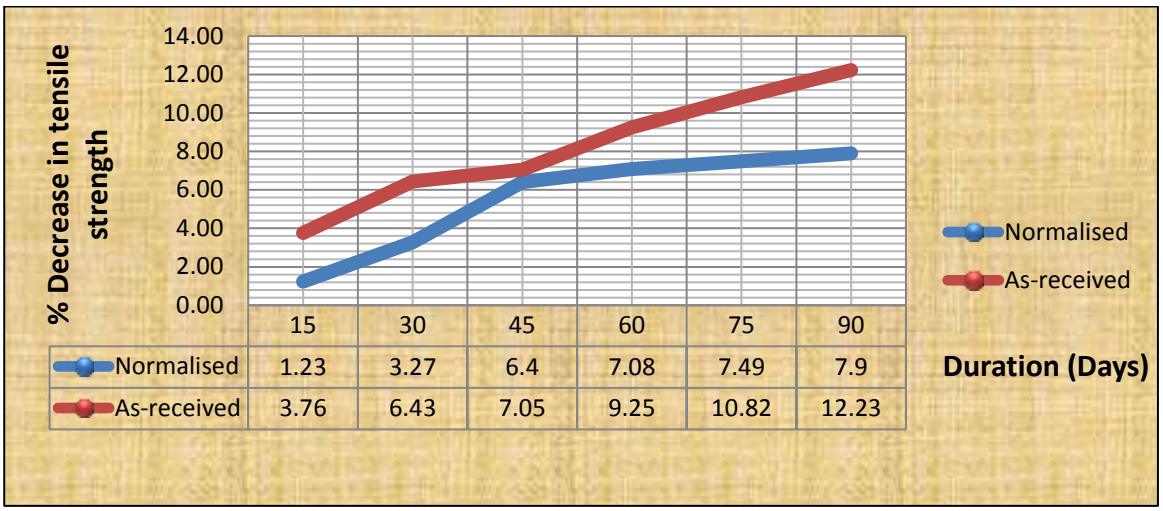
3.1 Tensile Properties

The tensile properties of the steel samples, at the ambient temperature (28°C) are summarised in Table 5. Results reported are the average values based on duplicate tests. The results showed that yield strength, ultimate tensile strength and fracture strength were all greater for the normalised steel samples than for the as-received samples. This could be attributed to the fine grained microstructure of the normalised steel samples. The relatively fast cooling rate in the heat treatment of the steel samples resulted in a finer microstructure than the as-received samples, thus resulting in higher yield strength, ultimate tensile strength and fracture strength for the normalised steel samples respectively. The strength of a material is its resistance against deformation especially plastic deformation or yielding. Yielding occurs due to movement of dislocations in metallic crystals. Movement of dislocation is stopped if some barrier or discontinuity comes in the path of dislocations. To make dislocations move and thereby cause plastic dislocation much more stress has to be applied over the material. Hence, the finer the grains, the more the grain boundaries and therefore more resistance to the movement of dislocations and thus an increase in strength. [21]. This is supported by the Hall-Petch equation [22] which showed that yield strength increases as the grain diameter decreases. Hence any process (as in this case of normalisation heat treatment) which tends to make the grains smaller (i.e causes grain refinement) will increase the strength of the material.

It was also observed from Table 5, that, ductility (percentage elongation and percentage reduction in cross sectional area) was higher in the as-received samples than in the normalised samples. This could likely be attributed to the finer ferrite-pearlite microstructure of the normalised steel samples. Fine grains result in more grain boundaries which retard the movement of dislocations. This results in higher strength and a reduction in ductility in terms of percentage elongation or percentage reduction in area. Also the higher volume fraction of ferrite in the as-received samples than the normalised could likely also account for the higher ductility of the as-received samples than the normalised samples, the reason being that ferrite is very soft and ductile whereas iron carbide is very hard and brittle. [21]. The line graph in figure 4 of corrosion rate of tensile coupons versus duration in seawater showed an initial decrease for the 45 days period followed by a fairly constant tensile strength values for the remaining 45 days period, The line graphs in figure 6 and 7 showed that there was a slight but steady decrease of tensile strength for both normalised and as-received samples showing that the longer the duration of exposure the more the corrosion leading to loss of tensile strength.

3.3 Hardness (Macro-hardness measurement)

The macrohardness values (Table 6) were summarised on the Brinell Hardness scale. Results reported were the average values based on duplicate tests. The results in Figures 5 and 7 showed that there was a steady decrease in the hardness of the steel against exposure time to seawater. The as-received samples showed a 9.0% decrease in hardness and 6.5% decrease for the normalised samples at the end of the 90^{th} day test period. The results in Table 6 showed that the normalised samples have higher hardness values than the as- received samples which could be attributed to the microstructure of the normalised samples having finer grains of pearlite-ferrite structure than the as-received samples having soft ferritic matrix. This agreed with [9], who studied the analysis of mechanical properties of mild steel applying various heat treatment. The higher volume fraction of ferrite which was very soft in the as-received samples than the normalised samples, which had a better dispersion of iron carbide which was very hard could likely account for the higher hardness in the normalised samples compared to the as-received samples.



	15	30	45	60	75	90
Normalised	1.23	3.27	6.4	7.08	7.49	7.9
As-received	3.76	6.43	7.05	9.25	10.82	12.23

Figure 7: Graph showing % decrease in Tensile strength with respect to exposure time for the normalised and as-received samples.

3.4 Corrosion Behaviour of Structural Steel in Seawater

Oxygen gas from the air entered the solution surface of carbon steel, and the corrosion occurred because of the highly exposed carbon steel substrate. Electrons flowed from the carbon steel, which served as the anode, to the oxygen-rich region on the surface, which served as the cathode. The cathodic reaction of the mild carbon steel was dominated by the reduction of oxygen. The anodic process which was more complicated, involves the dissolution of steel and the formation of iron compounds and eventually $Fe(OH)_3$ the main constituent of rust. Under the condition of a high amount of Cl^-, the existence of Cl^- was conducive to the formation of $Fe(OH)_3$. However, unlike the stable passive film that was usually compacted and tightly bonded to the steel, the iron oxide on the steel surface was a deposited layer. The effect of the iron oxide deposit layer on steel corrosion was mainly through a physical blocking effect which impeded the access of corrosion species to the steel surface, resulting in a low corrosion rate. Therefore, the compactness of the deposit layer was a main factor that affected the protectiveness of steel. However, the results tend to suggest a less porous and loose deposit layer formed on the normalised steel samples could be the reason for an improvement of the corrosion resistance than for the as-received steel samples. Therefore, the different corrosion rates are attributed to the compactness and completeness of the corrosion product layer formed on the steel surface. This explained the results reported in Tables 3 and 4.which accounted for reduction in corrosion rates for both the normalised and as-received steel samples as duration of exposure to seawater increases.

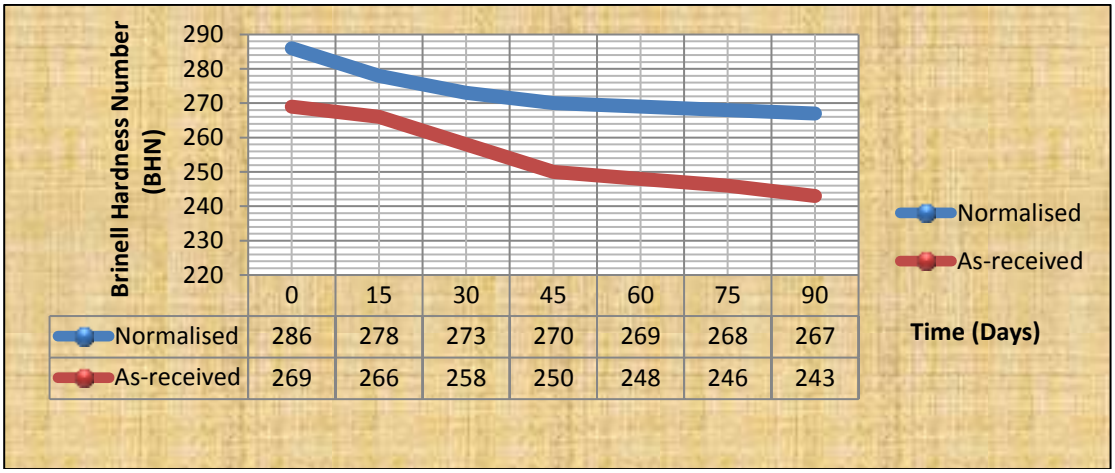
Table 6 - Macro-hardness Measurements (Brinell Hardness) made on the UNS G10170 steel samples.

Time (Days)	As- received Samples (BHN)	Normalised Samples (BHN)
0	269	286
15	266	278
30	258	273
45	250	270
60	248	269
75	246	268
90	243	267

3.5 Influence of Microstructure on the Steel Corrosion

The difference in corrosion rates of the steel samples could be attributed to the different microstructures of the as-received steel samples and the normalised samples. The difference in microstructure could likely be the reason why there was more corrosion in the as-received samples, thus resulting in higher decrease in the mechanical properties of the as-received samples than in the normalised samples. it had been proposed that the corrosion stability of the various microstructures might arose from

variations in the distribution of carbon bearing phases within the steel. Thus the reason for the observable difference in corrosion rates could be attributed to a segregated distribution of a iron carbide phase, cementite (Fe_3C). This two phase structure of α-iron and cementite set up micro galvanic sites that accelerated the corrosion reaction, in which the cementite acted as the cathode and the ferrite acted as the anode. This had also been reported before [2,10], when the ferrite was coupled to cementite. Also the results tend to suggest the more the volume fraction of ferrite (anodic area) as in the case of the as-received samples the more the corrosion rate increases. However [12] proposed that although the anodic dissolution rate will be high in the ferrite alone for low ferrite fractions, the corrosion rate for the overall sample will show a peak for intermediate ferrite fractions, suggesting a limiting value of increase in the amount of ferrite fraction. If the ferrite fraction becomes too high, the cathode area fraction is too low. This means that the supply of oxygen toward the cathode was too low to consume all the electrons that were produced at the anode.



	0	15	30	45	60	75	90
Normalised	286	278	273	270	269	268	267
As-received	269	266	258	250	248	246	243

Figure 8: Graph of variation of hardness with respect to time for UNS G10170 steel samples.

4.0 Conclusion and Recommendations

4.1 Conclusion

This work was carried out to study the effect of corrosion on the strength of structural steel (UNS G10170) exposed to natural seawater. Samples of the steel were subjected to machining processes, normalising heat treatment and exposure to seawater. Then the steel samples were further subjected to metallographic test, Brinell hardness test and tensile strength test respectively. At the end of the study, the results showed a 9.00% decrease in hardness for the as received sample and 6.50% decrease for the normalised sample; 31.5% decrease in percentage elongation for the as-received sample and 25.00% decrease for the normalised sample; 12.23% decrease in tensile strength for the as-received sample and 7.90% decrease for the normalised sample respectively at the end of the 90^{th} day. This study showed that corrosion affects the mechanical properties of structural steel exposed to seawater but corrosion rates were marginally reduced by heat treatment (normalisation) which induced a change in the microstructures of steel suggesting that the microstructure of steel affect the corrosion resistance of the steel. This was supported by [2,3,10]. The following conclusions were reached from the results of this work on UNS G10170 steel samples:

(i) Normalisation heat treatment increases tensile strength, yield strength, fracture strength and hardness with a corresponding decrease in ductility (% elongation and % reduction in area).

(ii) The mechanical properties (yield strength, tensile strength, fracture strength, % elongation, % reduction in cross-sectional area and hardness) decrease as the duration of exposure to sea water increases.

(iii) The corrosion rate based on weight loss for the normalised samples is marginally lower than for the as-received samples in seawater.

4.2 Recommendations

For a fuller understanding of the effect of corrosion on the strength of structural steel exposed to seawater, the following recommendations are made:

(i) Further study should be carried out with the steel samples exposed to the natural body mass of seawater to properly account for effect of flow, micrcobial activity, changes in seawater concentration etc

(ii) Much longer study period should be investigated to take into account the effect of bio-fouling etc.

References

[1] Saad-eldeen S, Garbatov Y, Guedes SC. Effect of corrosion degradation on the ultimate strength of steel box girders. Corrosion Engineering, Science and Technology, 2012; 47: 272-283.

[2] Igwenmezie VC, Ovri, JEO. Investigation into the effects of microstructure on the corrosion susceptibility of medium carbon steel. International Journal of Engineering and Science. 2013; 2(6):11-26

[3] Al-rubaeiy SI, Emman AA. The influence of microstructure on the corrosion rate of carbon steels. Engineering and Technology Journal, 2013; 31(10):1825-1836.

[4] Jenifer A, Daniel F, Belén C, Joaquín S, Iván D, Manuel M. Marine atmospheric corrosion of carbon steel: a review. Material Journal. 2017; 10: 406

[5] Lokendra KO, · Burak T, · Jeetendra B. Experimental and theoretical study of effect of Allium sativum extracts as Corrosion Inhibitor on mild steel in 1 M HCl medium. Journal of Bio- and Tribo-Corrosion 2020 Feb; 6:39

[6] Amjad HJ. Corrosion resistance of normalising heat treatment of carbon steel ck45 in seawater at different velocities. Journal of Engineering and Development, 2013; (17)4:144-15

[7] Yu-bing G, Chong L, Yong-chang L, Li-ming Y, Zong- qing M, Chen-xi L, Hui-jun L. Effect of Microstructure Variation on the corrosion Behaviour of High-Strength-Low- Alloy Steel in 3.5wt% NaCl Solution. International Journal of Minerals, Metallurgy and Materials, 2015; (22)6:604-612

[8] Sergio SMT, Gabriel FF, Humberto, FF, Maria JRS, Isnadi R. Influence of microstructure on the corrosion resistance of AISI 317L. Material Research. 2017 Mar.

[9] Nazma S, Ferdaus H, Mehedi I. Analysis of mechanical properties of mild steel applying various heat treatment. International Conference on Mechanical, Industrial and Energy Engineering. Held 2014 Dec 25-26, at Khulna, Bangladesh, (Pp. 1-4)

[10] Unueroh UG, Onyekpe B. The effect of corrosion on the tensile property of austenitised 1040 steel exposed to stagnant seawater. International Journal of Engineering Research in Africa. 2014; (12):35-41

[11] Chinwko EC, Odio BO, Chukwuneke JL, Sinebe JE. Investigation of the effect of corrosion on mild steel on five different environments. International Journal of Scientific and Technology Research, 2014; (3)7:306-30

[12] Thomas R. The influence of microstructure on the corrosion behavior of ferritic-martensitic steel. Masters Thesis: Delft University of Technology. 2015.

[13] Ayodele CO, Nenuwa OB. Investigation of the effects of heat treatment on the corrosion behaviour of welded low carbon steel in different environments. International Journal of Science and Technology. 2013; (3):8,

[14] Jinsun L, Keiji K, Masahiko Y, Yoichi M, Michiaki I. Effect of ozone on corrosion behavior of mild steel in seawater. Corrosion Science 2012; (55):205–212

[15] Donasulu Steel Company Limited, Effurun, Nigeria. 2018

[16] Chemical Laboratory, Petroleum Training Institute (PTI), Effurun, Delta State Nigeria. 2018.

[17] ASTM E8, Standard test method for tension testing of metallic materials. American Society of Testing and Materials.2016

[18] ASTM G1-03, Standard practice for preparing, cleaning, and evaluating corrosion test specimens. American Society of Testing and Materials.2017

[19] ASTM E10-18, Standard test method for brinell hardness of metallic materials. American Society of Testing and Materials.2017

[20] ASTM E3-11, Standard guide for preparation of metallographic specimens American Society of Testing and Materials. 2017

[21] Rajput ERK. A Textbook of Material Science and Engineering; Revised ed., S.K. Kataria & Sons Press, New Delhi, India. 2014

[22] Zachary CC, Braden EK, Christopher AS. Six decades of the Hall-Petch effect – a survey of grain size strengthening studies on pure metals. International Materials Reviews 2016; 61(8): 495-512