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Corrosion Susceptibility and Microstructural Evolution of Austempered AISI 1030 Steel in Sea Water Environment

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ABSTRACT

The aim of this study is to investigate the corrosion susceptibility and microstructural evolution of austempered AISI 1030 steel in seawater environment. The steel samples were austempered at varied temperatures of 300˚C, 320˚C and 340˚C respectively. The corrosion behaviour was determined by means of optical metallography microscopy (OMM) and weight loss measurement (WLM) at an interval of 15 days for the period of 75 days. Results indicated that, the specimens' austempered at 320°C offered fine microstructure due to the presence of acicular bainite and also some martensite in the microstructure. Austempering at 300˚C and 320˚C yielded a carbide-free bainite microstructure. Therefore, on the corrosion rate, the results indicated that the sample austempered at 320˚C was relatively the most corrosion resistant, followed by sample austempered 300˚C and lastly sample austempered at 340˚C.

1. Introduction

Carbon steel is essentially a metal alloy with a combination of two elements, iron and carbon. It is categorized into three main subcategories such as low carbon steel, medium carbon steel, and high carbon steel [1]. Medium carbon steels has a carbon composition ranging from 0.25 to 0.5%C and the high carbon content of these steels, along with manganese greater than 1% makes these steels hardenable and weldable [2]. The mechanical properties of this steel are improved via heat treatment. Heat treatment can only be performed on very thin sections, however, additional alloying elements, such as chromium, molybdenum and nickel, can be added to improve the steels ability to be heat treated and, thus, hardened [3]. Heat treatment is the process of enhancing the microstructures, physical and mechanical properties and corrosion resistances of metals for various desired engineering applications through controlled heating and cooling without changing the material shape [4]. Austempering (isothermal quenching) process involves heating a steel to austenite state and then quenching it in a bath held at a temperature above. The steel then remain at that temperature until the austenite is completely transformed to bainite, after which it is allowed to cool [5]. Corrosion is a natural process that reduces the binding energy in metals with the end result involving a metal being oxidized, as a bulk metal loses one or more electrons [6]. The lost electrons are conducted through the bulk metal to another site where they are reduced. In corrosion, the site where the metal atom loses electron is called the anode and the reducing species is the cathode [7]. Also, corrosion can be said to be the degradation of metallic materials properties due to interactions with its environment [8]. Corrosion of most metals is inevitable and all material types are susceptible to degradation. Most metals in contact with water (and moisture in air), acids, bases salts, oil, oppressive metal polishes and other solids and liquid chemicals corrode as well when exposed to gaseous materials like acid vapors, ammonia gas and sulphur containing gases [9]. Corrosion in sea water depends on numerous interdependent parameters and combines chemical, biological and mechanical factors which are particularly insidious degradation phenomenon and thus a hazard for metal structures integrity [10]. Sea water is extremely complex, heterogenous solution. It contains a large amount and diversity of dissolved solid material, dissolve gases and various species of biological matter [11]. Seawater is an electrolyte. The presence of a large number of dissolved salts, sodium chloride (NaCl), that are ionized makes it an excellent conductor and it influences the corrosion rates of metals in seawater [12]. The chloride ion is also particularly aggressive as most chloride compounds are highly soluble which limits the formation of polarizing anodic film. Medium carbon steel has wide application in sea water environment due to low cost, availability and versatility. However, due to the corrosiveness of the sea water environment and the susceptibility of medium carbon steel to corrosion, there is therefore the need to investigate the effect of austempering on the corrosion behaviour of AISI 1030 steel in sea water environment.

2. Material and methods

2.1. Material

The material used in this investigation is a medium carbon steel substrate of 16 millimeter diameter. The chemical composition of this material was analysed by using a mass spectrometer analyzer.

Table 1: Chemical composition of the medium carbon steel substrate

Elements	Compositions (wt %)
C	0.322
Si	0.2895
Mn	0.9095
S	0.1130
P	0.0470
Cr	0.1570
Ni	0.1070
Cu	0.3150
Nb	0.0001
Al	0.0085
B	0.0020
W	0.0001
Mo	0.0001
V	0.0001
Ti	0.0075
Fe	97.6285

2.2. Methods

2.2.1. Preparation of samples

The specimens totaling 40 were machined from the as-received medium steel bars with a gauge length of 20 mm and gauge diameter of 6 mm, as per ASTM-E8M standards. Out of the 40 pieces, 10 served as controls, 10 each were austempered at 300˚C, 320˚C and 340˚C respectively and were exposed to sea water.

2.2.2 The Heat Treatment

The specimens were first austenitized at 900˚C for 90 minutes in a high temperature muffle furnace, followed by isothermal treatment carried out in a resistance heated salt bath furnace. The salt blend comprises of 55% KNO_3 and 45% $NaNO_3$ by weight. This composition has a wide working temperature range varying from 222˚C to 540˚C. Accordingly austempering temperatures of 300˚C, 320˚C and 340˚C were selected and heat treatment was carried out for a fixed duration of 2 hours and quenched. The specimen's temperature after quenching above the transformation range were brought down to the upper limit of martensite formation and held at this temperature till the austenite was transformed completely to the intermediate structure. Then the samples were quenched into the furnace maintained at 300˚C. Thereafter, the temperature was increased from 300˚C to 320˚C for one hour at the rate of 14˚C/hr. The process was repeated for second set at 320˚C to 340˚C and was allowed to soak in this heated salt bath before being cooled in air. The specimens were taken out and cooled at room temperature in air medium. The austempered specimens were air cooled and possible decarburized layers were removed. Thermocouples were placed in the salt bath very close to the samples for monitoring the temperatures. The temperature of the salt bath remains constant during quenching as the salt bath is very large compared to the size of the test samples.

2.2.3. Analysis of the Sea Water Environment

In order to be able to have a good assessment of the corrosion of the materials, the corrosion medium was analyzed to determine the constituents present in the environment.

Table 2: Chemical composition of the sea water environment

Elements	Na	Mg^{++}	Ca^{++}	K^{+}	Sr^{++}	Cl^{-}	So_4^{2-}	Br	N_3B^3	HCo^{3-}
Composition	10360	1294	0.41	0.39	0.008	19.4	2.71	0.008	0.001	0.142

2.2.4 Weight Loss Measurement and Determination of Corrosion Rate

The corrosion rate for all the samples was investigated by periodic weight loss measurement at an interval of 15 days. Specimens were retrieved, washed properly in water, dried and weighed on an gelectronic weighing balance to determine the weight loss during exposure to sea water. The experiment was monitored for 75 days. The Corrosion rate were evaluated by using the relation in Equation (1).

$$\text{Corrosion rate (mpy).} = \frac{534W}{\rho AT} \qquad (1)$$

Where: W = Weight loss in mg, ρ = Density in g/cm^3, A = Total surface area in cm^2,
T = Total exposure time in hours, mpy = Mill per year.
Weight Loss $W = W_0 - W_1$
Area $A = 2\pi r(h + r^2)$, Length L = 20 mm = 2.0cm
Diameter d = 6 mm, Radius r = 3mm = 0.3cm
Density of steel $\rho = 7.98 g/cm^3$
Total exposure time = 15 -75 days (360 - 1,800hrs)

2.2.5 Metallography

All the steel samples were prepared for optical microscopy using standard metallographic practice. The surface of the specimens was etched using 3% Nital to reveal the grain boundaries. The micrography was done with a magnification of x 200.

3. Results and Discussion

3.1 Results

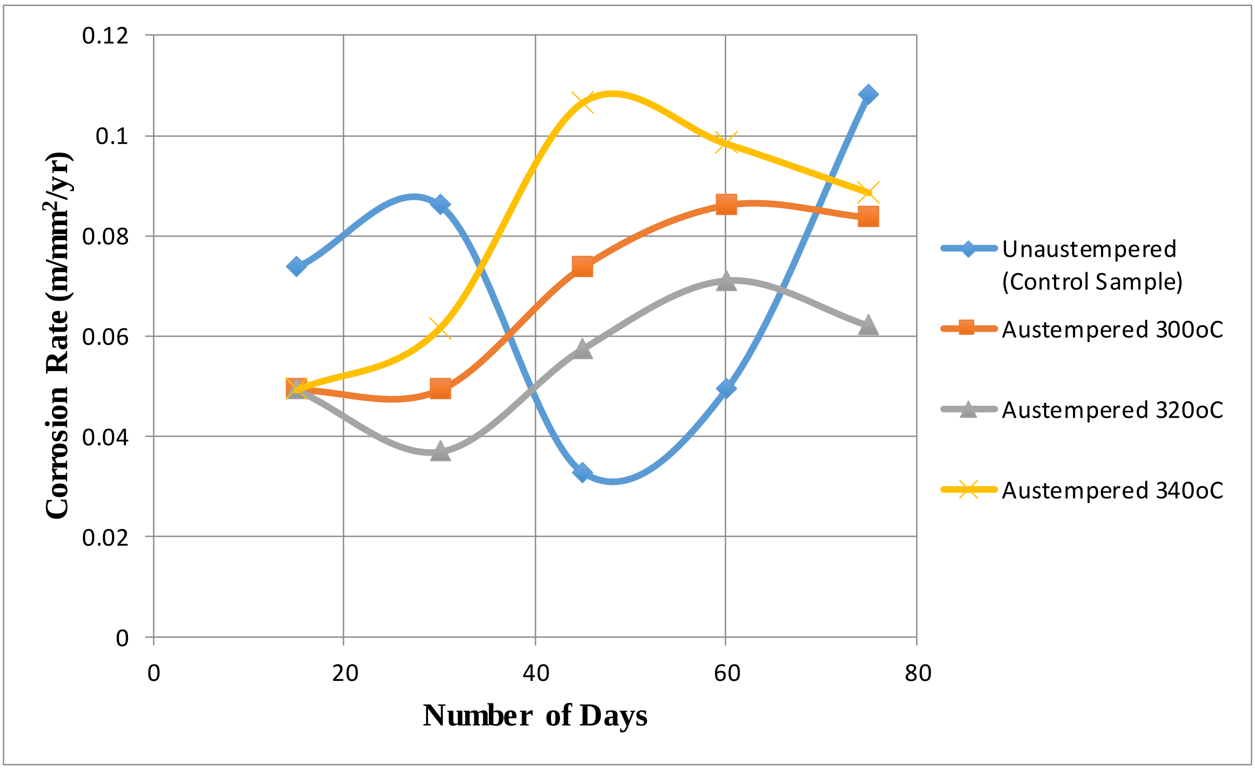


Figure 1: Plot of Corrosion Rates against Exposure time for the Austempered Steel Samples at 300 °C – 340 °C and Control Sample Immersed in Sea Water for 75 days

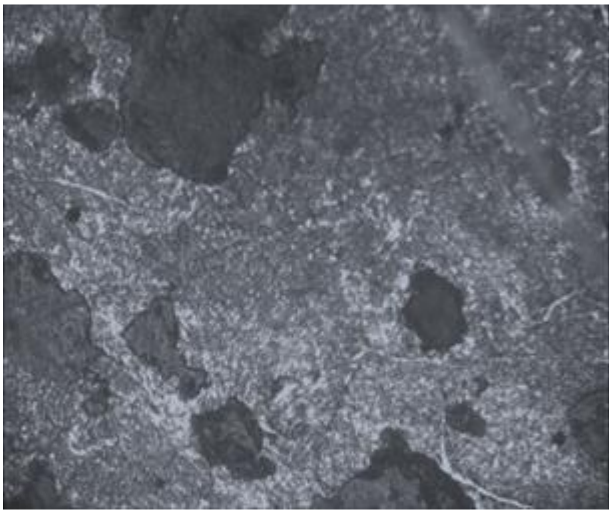


Plate 1a: Optical Micrograph of Control Sample of 0.3%C Steel Immersed in Sea Water For 15 Days - (200X)

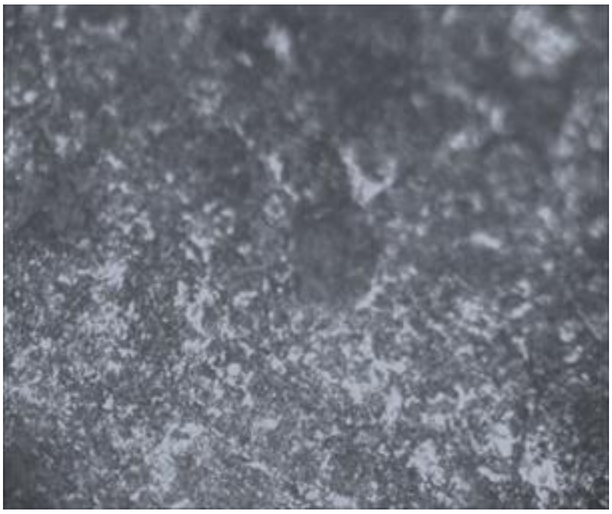


Plate 1b: Optical Micrograph of Austempered 0.3%C Steel at 300˚C Immersed in Sea Water for 15 Days -(200X)

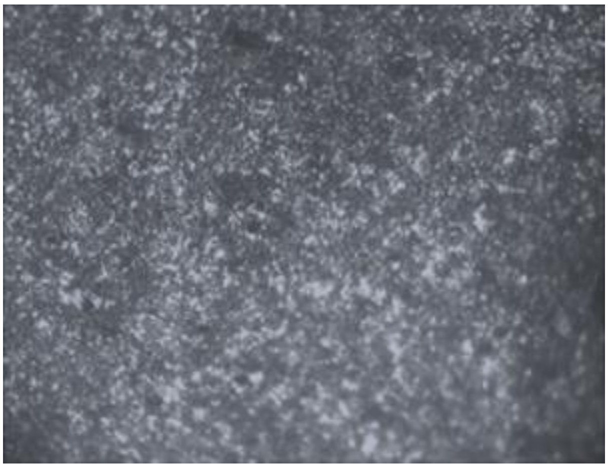


Plate 1c: Optical Micrograph of Austempered 0.3%C Steel at 320˚C Immersed in Sea Water for 15 Days - (200X)

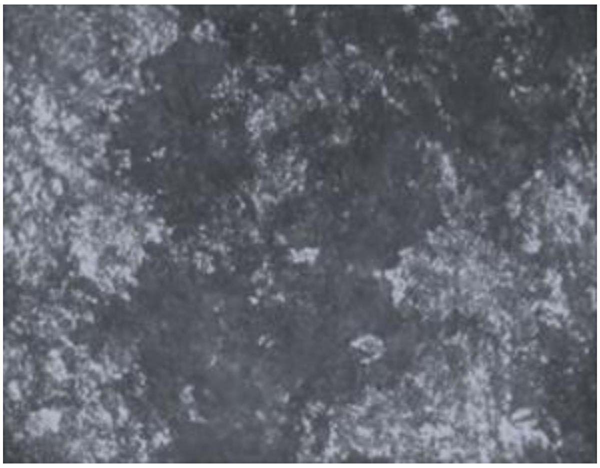
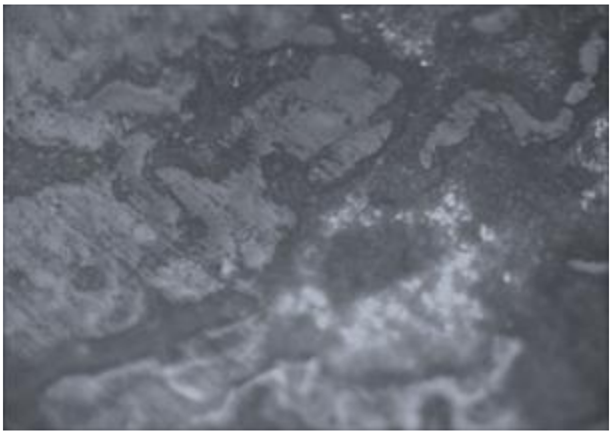


Plate 1d: Optical Micrograph of Austempered 0.3%C Steel at 340˚C Immersed in Sea Water for 15 Days - (200X**)**



Plat 2a: Optical Micrograph of Control Sample of 0.3%C Steel Immersed in Sea Water for 30 Days - (200X)

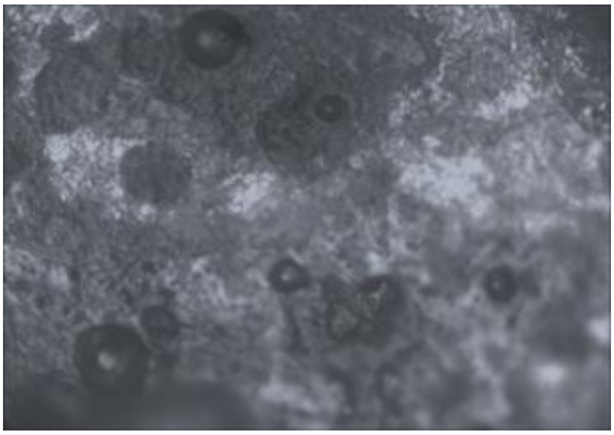


Plate 2b: Optical Micrograph of Austempered 0.3%C Steel at 300˚C Immersed in Sea Water 30 Days – (200X)

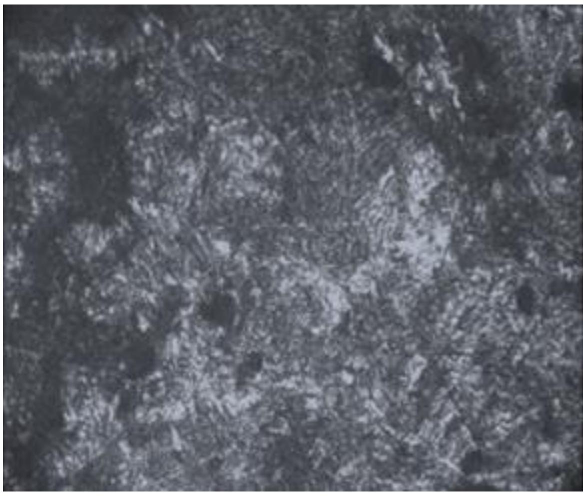


Plate 2c: Optical Micrograph of Austempered 0.3%C Steel at 320˚C Immersed in Sea Water for 30 Days - (200X)

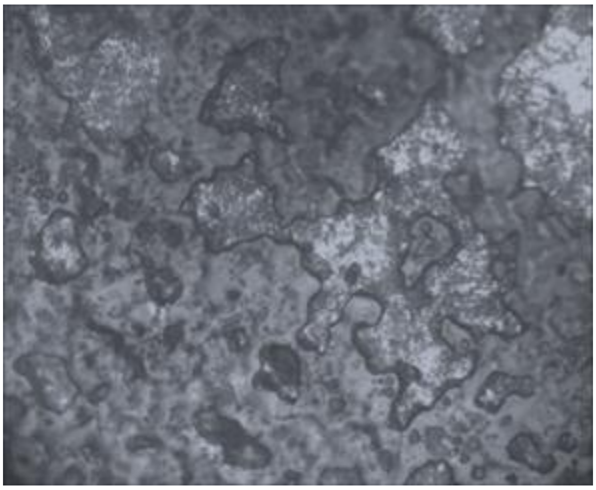
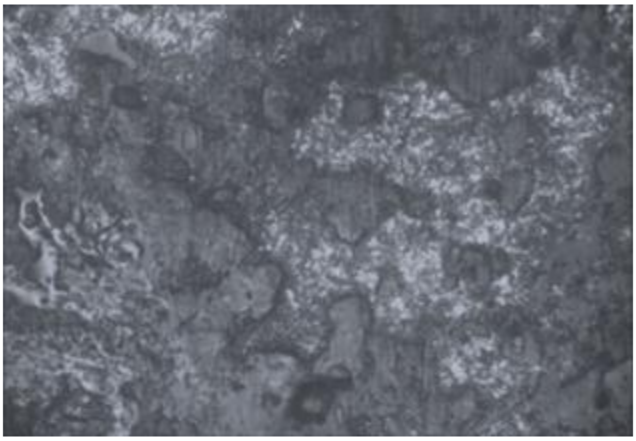


Plate 2d: Optical Micrograph of Austempered 0.3%C Steel at 340˚C Immersed in Sea Water for 30 Days - (200X)



Plat 3a: Optical Micrograph of Control Sample of 0.3%C Steel Immersed in Sea Water 45 Days - (200X)

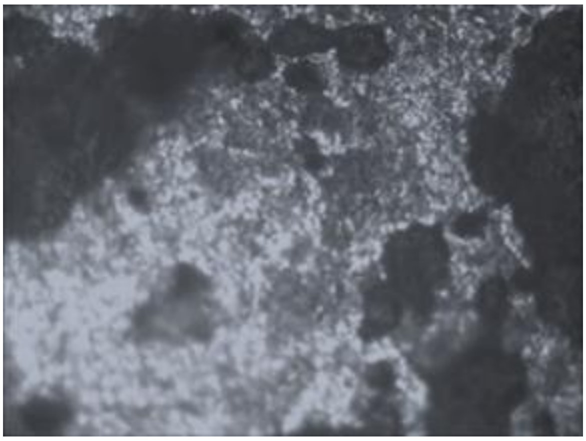


Plate 3b: Optical Micrograph of Austempered 0.3%C Steel at 300˚C Immersed in Sea Water 45 Days – (200X**)**

Plate 3c: Optical Micrograph of Austempered 0.3%C Steel at 320˚C Immersed in Sea Water 45 Days - (200X)

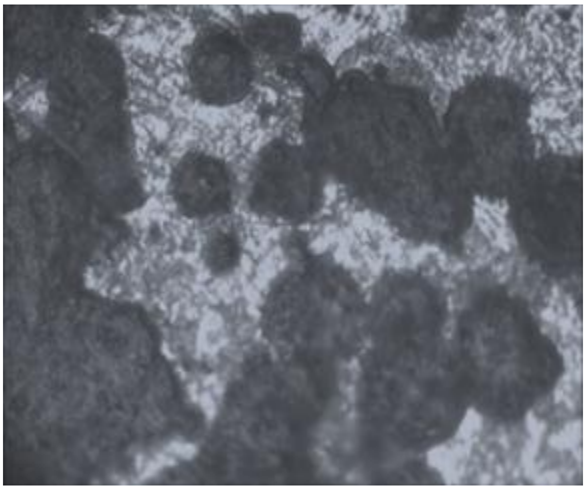
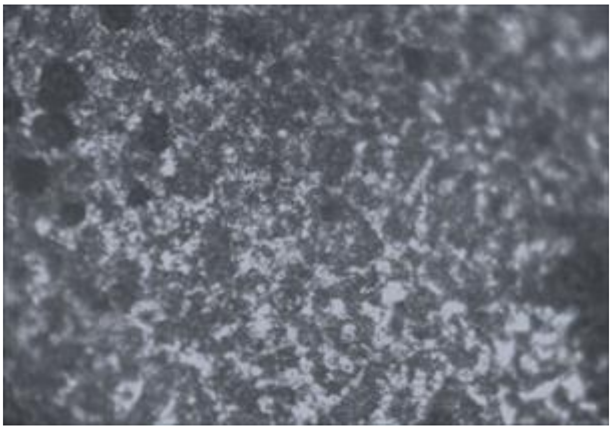


Plate 3d: Optical Micrograph of Austempered 0.3%C Steel at 340˚C Immersed in Sea Water 45 Days - (200X)



Plat 4a: Optical Micrograph of Control Sample of 0.3%C Steel Immersed in Sea Water for 60 Days - (200X)

Plate 4b: Optical Micrograph of Austempered 0.3%C Steel at 300˚C Immersed in Sea Water for 60 Days - (200X)

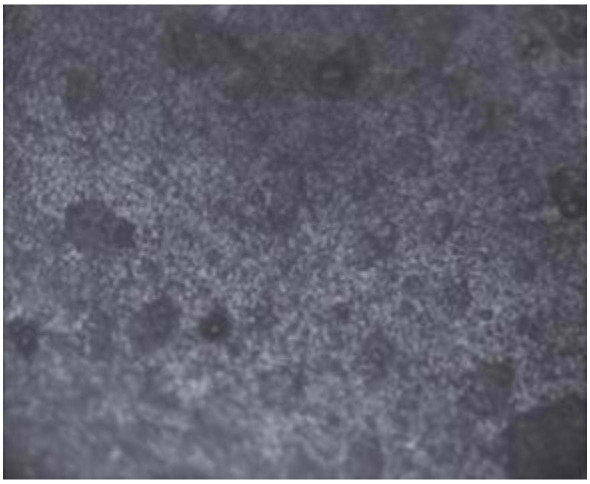


Plate 4c: Optical Micrograph of Austempered 0.3%C Steel at 320˚C Immersed in Sea Water 60 Days - (200X)

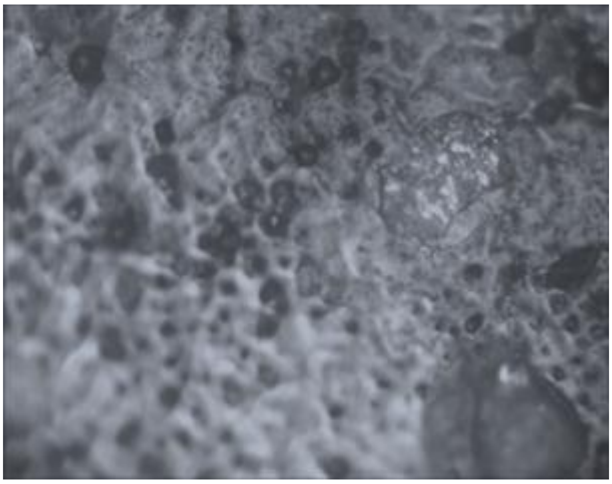
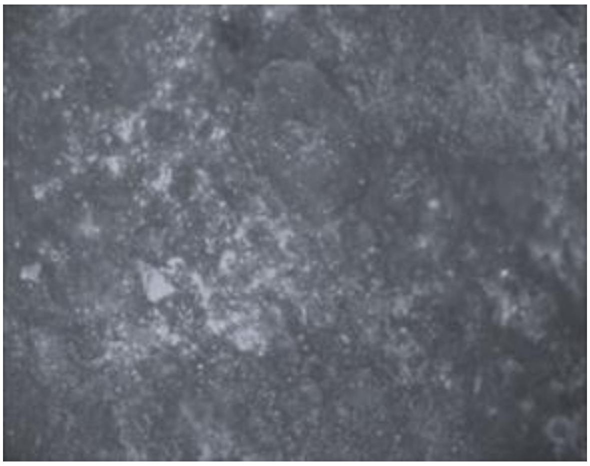


Plate 4d: Optical Micrograph of Austempered 0.3%C Steel at 340˚C Immersed in Sea Water 60 Days - (200X)



Plat 5a: Optical Micrograph of Control Sample of 0.3%C Steel Immersed in Sea Water 75 Days - (200X)

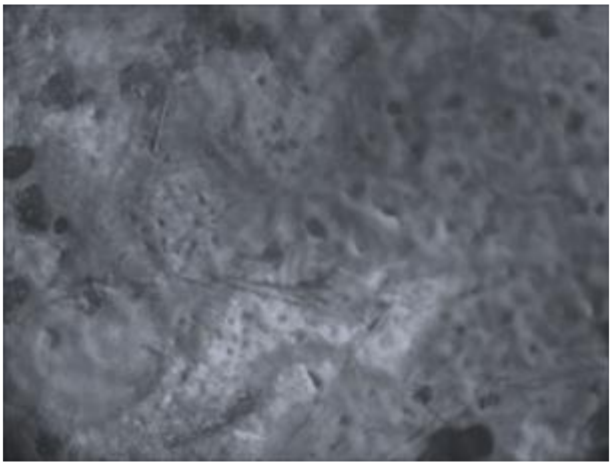


Plate 5b: Optical Micrograph of Austempered 0.3%C Steel at 300˚C Immersed in Sea Water 75 Days - (200X)

Plate 5c: Optical Micrograph of Austempered 0.3%C Steel at 320˚C Immersed in Sea Water 75 Days - (200X)

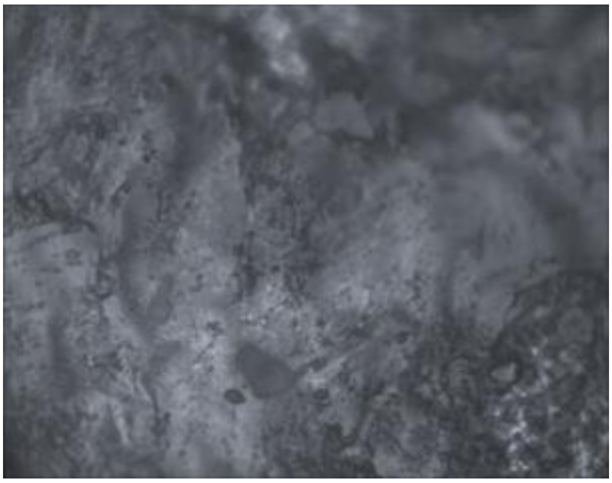


Plate 5d: Optical Micrograph of Austempered 0.3%C Steel at 340˚C Immersed in Sea Water 75 Days - (200X**)**

3.2 Discussion

3.2.1 Effect of Austempering Temperature and Time on the Corrosion Behavior of 0.3%C in Sea Water

The effect of austempering temperature and time on corrosion behavior of 0.3%C Steel in sea water medium as shown in **Figure 1**. The results presented indicate that in every corrosion test carried out the corrosion rate decreased gradually with exposure time. Also, all the austempered samples showed similar corrosion behaviour in this medium at the early stage, the unaustempered samples showed increased corrosion rate at the early stage followed by gradual decreased in the corrosion rate. The corrosion attack was found to be more severe from 30 - 60 days of immersion in this media. However, the corrosion rate decreases gradually after 60 days of exposure except unaustempered sample which shows exponential increase in corrosion. This indicates that austempering temperature and time as observed in this investigation have significant influence on the corrosion behavior of the 0.3%C steel in this medium.

The levels of the graphite phase affecting the corrosion of 0.3%C steel depends on both the time duration of heat treatment and the matrix structures developed [1]. Molybdenum is the most effective element, and results in the formation of carbides that are stable at high temperatures. The behavior of medium carbon steel is affected greatly by the combined effect of Ni and Mo. For this combination, it can be observed that for shorter austempering time the resistance to corrosion is quite high. Evidently, the presence of Ni and Mo can cause an increase in the bainitic content, which confirmed the hypothesis that Mo acts as a carbide stabilizer [13]. For determination of best austempering temperature of the steel samples investigated, the plot of corrosion rate in **Figure 1**, shows that samples austempered at 320˚C has lower corrosion rates during the entire period of exposure, then followed by 300˚C and lastly 340˚C. Therefore, the study concluded that sample austempered at 320˚C offers a better corrosion resistance in this medium which is attributed to the temperature which austenite is completely transformed into bainite. [14]. The two main phase that were formed during austempering are bainite and pearlite structures and it is believed that the matrix of bainite exhibits a lower corrosion rate than pearlite. It was observed that at austempering temperature, carbides were formed in the bainitic structure because of the presence of Mo in the composition of this material. The level of the carbide formation is expected to increase with increase in austempering time. The cementite structure shows a higher resistance to corrosion in this medium as the exposure time increases, thus enabled the stability of the material after a specific period of exposure time [15]. It was evident, therefore, that the corrosion behavior of this material is dependent on the concentration and type of its alloying elements, just as it is dependent upon the prior heat treatment.

3.2.2 Influence of Microstructure on Corrosion Performance in Sea Water

Austempering temperature and time have a significant influence on the microstructural constituents of the steel. An increase in the cooling rate is known to result in a martensite structure, while a decrease in the cooling rate (known as equilibrium cooling) results in ferritic and pearlitic structures. It should be noted that austenitizing medium carbon steel at 900˚C brings about homogeneity in the composition of the samples [16]. Therefore, it is expected that the nodules that have grown in the solid state will not be attached to the shell of the matrix. This was due to the fact that the eutectic cementite transformed during austempering into austenite initially contained no silicon. In view of the above, it could be concluded that austempering makes the structure bainitic and homogeneous. **Plates 1a – 5d,** show a micrograph of 0.3%C Steel. It is evident that this image contains some spherically shaped carbide nodules that are almost uniformly distributed within the structure of the metal. The micrograph of the medium carbon steel austenitized at 900˚C, austempered at varied temperatures of 300˚C, 320˚C and 340˚C for 2 hours and immersed in sea water, revealed that the grain boundaries of this material were greatly attacked by this environment. It can be observed that the grain boundaries of this material were greatly attacked by this environment. The corrosion product at these grain boundaries were suspected to be precipitates of metallic inclusions. These components may have been somewhat unstable at the austenitic temperature under investigation; hence they precipitated out into the grain boundaries and were therefore susceptible to attack in the sea water medium [17]. Results also indicated that, the specimens austempered at lower temperature i.e. at 300°C, offered fine microstructure due to the presence of acicular bainite i.e. lower bainite and also some martensite in the microstructure [15]. At lower austempering temperatures, there is greater supercooling and, consequently, ferrite nucleation is promoted. This results in higher ferrite contents as the austempering is done at lower temperatures. Austempering at 300˚C and 320˚C has yielded a carbide-free bainitic microstructure.

4. Conclusion

From the results of the investigation carried out, it was found out that, all samples were susceptible to corrosion in the sea water environment. Austempering temperatures and time had considerable influence on the corrosion behavior of the steel samples in the sea water environment. Increase in the austempering temperature caused a corresponding increase in ferrite and cementite in the microstructure of the samples. Samples austempered at 320˚C showed better corrosion resistance than the ones austempered at 300˚C and 340˚C respectively.

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