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REVIEW

A Review Study on Corrosion Fatigue and its Related Testing Methodologies

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ABSTRACT

Corrosion Fatigue is the mechanical degradation of a material under the joint action of damage mechanisms corrosion and fatigue. Corrosive nature of the seawater puts severe durability requirements on materials of which are often exposed to corrosion fatigue and abrasive conditions simultaneously. Therefore, identification of the combined effects of both corrosion and fatigue damage mechanisms is necessary to improve predictive models for the corrosion fatigue phenomenon. Present article is the result of a desktop study (scientific literature and standards) with the aim of study the feasibility of designing and manufacturing of a corrosion fatigue testing set-up that would allow the designer to compare the performance of different materials exposed to corrosion fatigue, permitting also the comparison with results from dry fatigue testing. The corrosion fatigue mechanism is described in more detail and a short presentation of some typical lab-scale corrosion fatigue test setups is given. This is followed by illustration of international standards and guidelines which will be used to design a new corrosion fatigue test set-up for evaluating the fatigue behavior of material in seawater environment. Finally the experimental techniques for corrosion fatigue crack detection and propagation along with the fundamental basic of corrosion fatigue modeling are illustrated.

1. Introduction

Corrosion fatigue is a common failure mechanism in rock drilling components and many other mechanical parts subjected to cyclic loads in corrosive environments. This phenomenon occurs in several engineering alloys in presence of different environments, and it is the cause of failure of several engineering structures, such as ships or offshore platforms, boilers, superheater tubes, turbine and pump components and pipes carrying corrosive liquids [1]. A crucial part in the design of such components resides in the selection of the right materials for the application, which ideally involves testing and comparison of their performance under working conditions [2]. It is usual to separate the corrosion fatigue life into two separate stages: crack initiation and crack growth. For many structures, such as additive manufactured material including Metals, Thermoplastics, Glass, Medical & Biochemical, crack initiation, during which micro-cracks form, grow and coalesce to become a macro-crack, is less important because fabrication imperfections (flaws, porosity, slag inclusion, etc.) are always present. Therefore,

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the majority of the fatigue life is spent in the crack growth stage.

Inclusions are extremely harmful for a metal exposed to corrosion fatigue conditions, and its impact is higher in corrosive environments than in inert conditions [3]. Most of the literature mentions MnS inclusions as the most hazardous for steels under corrosion fatigue situations. Areas with MnS inclusions create localized anodic regions, which will easily form corrosion pits [4]. A detrimental effect of the presence of these inclusions must be expected on both crack initiation and crack propagation, as explained hereby. One of the biggest problems with MnS inclusions is that they easily dissolve in the presence of water. When a MnS inclusion is present on the surface of a steel part subjected to corrosion fatigue, it will dissolve, forming a tiny pit on the metal surface. This pit will potentially form a crack since it will act as a stress concentrator.

Many factors such as Concentration of the Corrosion Species, Temperature, percentage of NaCl, range of pH, Surface Finish, Stress Ratio, Load Frequency, Stress Intensity, Hardness Gradients, Metallurgical Variables (grain size and microstructure), Inclusions, Porosity, Surface Residual Stresses, Crack Closure Effects, etc., can influence corrosion fatigue phenomenon.

Corrosion fatigue is one of the most important research areas nowadays because there are many applications necessitate alloys operating in harsh environments. One of the main differences between corrosion fatigue and inert-environment fatigue is that there is no "safe stress range" at which metal has infinite life. As the number of cycles to failure is increased, the fatigue strength of the metal in corrosive environment continues to fall [5].

A study of numerous industrial failures has shown that 77% of failures are due to fatigue. The share of each failure mechanism, in the total of 242 investigated cases has shown that simple fatigue (58%) is the biggest contributor, but low-cycle fatigue (8%) and thermal, corrosion and low-cycle fatigue are not negligible (11%) [6]. It has been estimated that the United States Department of Defense spends between $10 billion and $20 billion annually (Under Secretary, 2005) in corrosion-related activities [7]. The direct maintenance cost of corrosion for the United States Air Force was approximately $1.14 billion [8]. The major aim of this study is to review the corrosion fatigue testing devices in order to investigate the feasibility of designing and manufacturing of a corrosion fatigue testing set-up that would allow the designer to compare the performance of different materials exposed to corrosion fatigue, permitting also the comparison with results from dry fatigue testing.

2. Mechanism of Corrosion Fatigue

The relative contributions to the failure made by the corrosion fatigue depend upon the nature of corrosive environment, the level of the cyclic stress and load frequency.

Mainly four mechanisms have been exposed in the attempt of explaining the process of corrosion fatigue. Although every mechanism is able to cover some of the aspects of this complex phenomenon, none of them is able to completely explain the whole process [9].

2.1 Pitting Corrosion

One of the first mechanisms proposed as an explanation for the marked reduction in fatigue endurance in corrosive environments was the formation of corrosion pits on the surface of the material, which acted as stress concentration spots where cracks were nucleated easily. Corrosion fatigue cracks start to grow from these corrosion pits and cause the final failure of the specimen. Particles and grain boundaries within the material microstructure play an important role on the formation and growth of corrosion pits and subsequent fatigue cracks, particularly for the low loading. Hostile chemical environments causes cracks to grow faster by chemical reactions and dissolution of material [10].

The constant presence of the corrosive media causes the most damaging effect, compared to situations at which the aggressive environment was only present until the formation of corrosion pits. In the latter cases, the corrosion pits act as mechanical notches on the specimen, presenting considerably higher fatigue strengths at long endurance compared to those having the corrosive media applied continuously throughout the entire test [11].

2.2 Corrosion at Preferential Locations

This mechanism proposes that corrosion attacks spots where fresh metal is exposed to the aggressive media, making the material vulnerable to corrosive damage. Such weak spots are created by intrusions and extrusions caused by persistent slip planes. The attack produces a stress concentrator where the material was already highly strained, causing a decrease in the fatigue strength of the material [9]. Some studies have shown that highly deformed spots on the material are anodic with respect to un-deformed areas, enhancing the electrochemical process [12]. Although this phenomenon is not thermodynamically favored, the fresh metal is believed to present a lower activation energy and therefore is more prone to react with the corrosive environment [9].

2.3 Hydrogen Embrittlement

When an alley is strained in the presence of hydrogen, the

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material microstructure undergoes a dangerous process known as hydrogen embrittlement, which consists on the diffusion of dissolved hydrogen atoms into the metal lattice, causing its dilation and weakening its atomic bonds. In the presence of hydrogen, the material microstructure undergoes a dangerous process known as hydrogen embrittlement, which consists on the diffusion of dissolved hydrogen atoms into the metal lattice, causing its dilation and weakening its atomic bonds. Finally, the hydrogen atoms absorb into the metal and diffuse ahead of the crack tip into critical locations such as grain boundaries [13]. This causes an embrittlement of the material surrounding the crack tip, which promotes further propagation of the crack.

Hydrogen embrittlement is typical in high-strength alloys. Since this kind of damage depends on diffusion and adsorption, it is considered to be a time-dependent mechanism. Contrary to the dissolution mechanism, this process does not form any kind of passivating oxide layer, so the hydrogen diffusion can occur during the whole load cycle [13]. The addition of oxygen in small amounts is known to practically eliminate the brittle corrosion-fatigue mechanism in crack growth [14].

2.4 Rupture of Oxide Protective Film

Some metals, such as aluminum, copper and stainless steel, form a protective oxide layer, which prevents the material underneath from further corrosive attack. Therefore, this mechanism proposes that corrosion fatigue occurs as this protective film is broken by the tension loading application or by the emergence of slip bands and corrosion fatigue cracks form easily [15].

2.5 Surface Energy Reduction

The reduction of surface energy due to the adsorption of environmental species is known as the Rebinder mechanism [9], which initially stated that the surface-active agent adsorbed into the cracks, increasing its internal pressure, resulting in the propagation of the crack. Later on, this theory was modified to state that the adsorbing species actually reduced the surface energy of the material, allowing for an easier formation of protrusions resulting from slipping bands [9]. To the best of author belief, there is not enough data nowadays to prove its veracity, although these theories seem reasonable.

3. Experimental Methods for Corrosion Fatigue

Since, there is no standard and globally accepted test rig for corrosion fatigue experiments, researchers are forced to design a new corrosion fatigue test device that meets their own specific requirements.

As a result of my literature review, a few typical and interesting designs of corrosion fatigue test setups have been selected. These setups can form a source of inspiration for the development of a seawater corrosion test rig. In the following a description of four test-setups is presented with additional critical discussion.

3.1 K. Berchem and M.G Hocking (2006)

The new design allows the simultaneous testing of more than one test specimen as shown in Figure 1. The box-shaped environmental chamber is made from Perspex. It has three tapped holes at one side for hose connectors and six holes at the bottom through which the bed plate is bolted to the frame of the testing machine, keeping in place both bed plate and tank. The holes in the bottom are sealed with O-rings, the hose connectors with 'liquid gasket'. Two of the three attached hoses are connected to a pump, which is used to circulate the electrolyte solution. The third hose acts as an overflow [16].

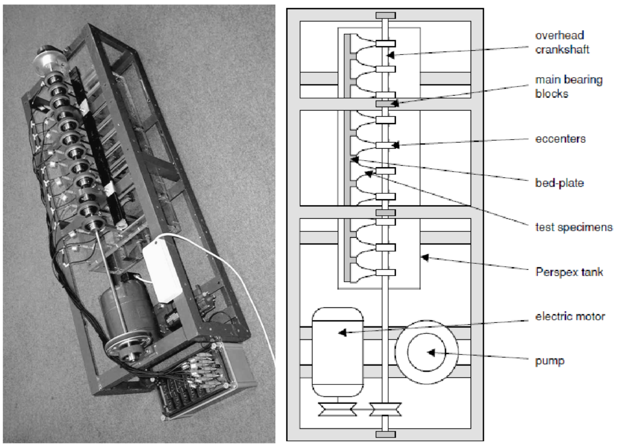

Figure 1. The assembled fatigue and corrosion fatigue testing machine [16]

3.2 Shu-Xin Li , R. Akid (2013)

The test section shown in Figure 2 is sealed in an environmental box to obtain the desired environment. The specimen is not immersed in seawater during the testing. The solution is renewed at intervals to ensure that there is always fresh solution in the corrosion cell. Although there are no dangerous vapors in this setup, the specimen has to be sealed to avoid intrusion of oxygen.

The presence of oxygen is known to be very detrimental for the corrosion fatigue performance of many metals, since it enhances many aggressive chemical processes. Therefore, if the atmosphere has free access

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to the metal surface –allowing oxygen to have contact with the metal- the effect of corrosion will be favoured. For this reason, corrosion fatigue strength will be lower if the specimen is sprayed or dripped with the corrosive fluid than if it is totally submerged in it [12]. A similar effect is observed when the corrosive fluid is aerated (contains dissolved oxygen) compared to when it is de-aerated, being the aerated solution the most aggressive one.

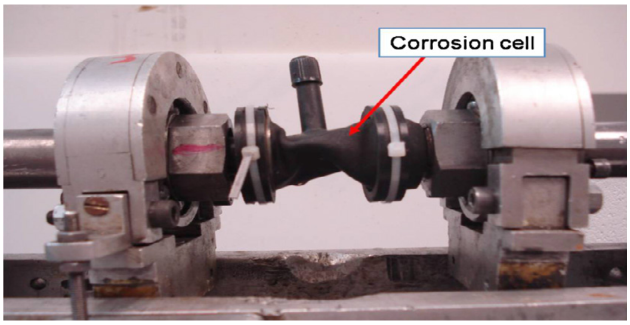

Figure 2. Test configuration for corrosion fatigue testing under rotating bending loading [17]

3.3 Perez Mora Ruben et al. (2015)

In order to perform fatigue crack initiation tests a corrosion cell was manufactured with simultaneous artificial seawater corrosion as shown in Figure 3. The cell is equipped with a tank sealed by a flexible silicon. The seawater is sprinkled on the specimen surface at different flow rates using a peristaltic pump. The flow rate is changed from 7 to 360 mL/min by varying the diameter of the flexible tube of the peristaltic pump [18].

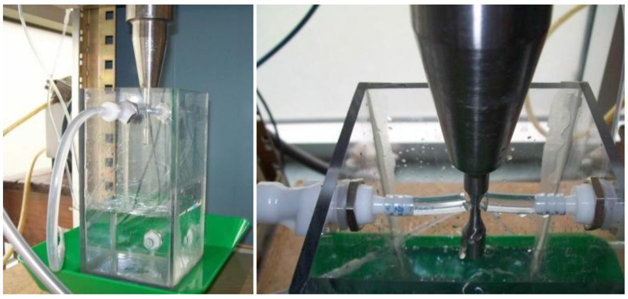

Figure 3. Corrosion cell and pump in order to circulate A3 seawater on the specimen [18]

The liquid circulated for this kind of experiment is the synthetic seawater which is a standard water for aeronautics and offshore industry. In fact, this synthetic seawater is more concentrated in salt than real seawater. That is done to accelerate the corrosion process to compensate with the high frequency of the tests.

3.4 Luis Miguel Bejar Infante (2016)

A picture of this machine is presented in Figure 4. An electric motor drives one of the rotating grips, while the other grip is pulled by a lever connected to dead-weights by pulleys and a cable (see Figure 5), creating the cantilever loading effect on the specimen. The corrosive conditions are created by means of a water supply system, which consists of a stainless-steel water tank attached to the machine, a water pump with maximum flow capacity of 12 l/min installed on one of the sides of the tank, a closed chamber to cover the specimen, a hose connecting the pump with the chamber, and a water collector at the bottom of the chamber which redirects the water into the tank [19].

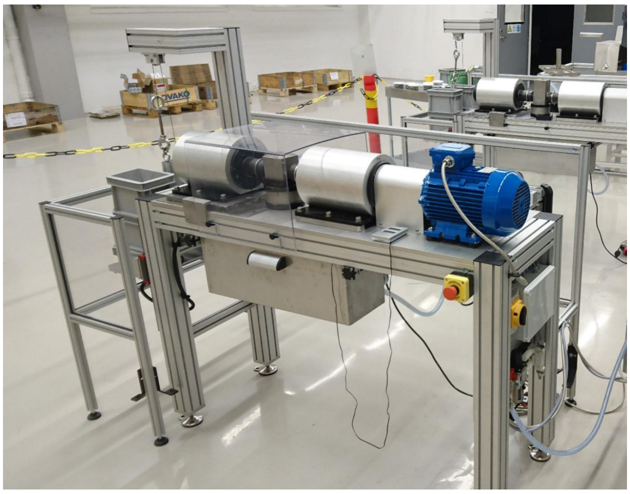

Figure 4. Rotating-bending fatigue testing machine [19]

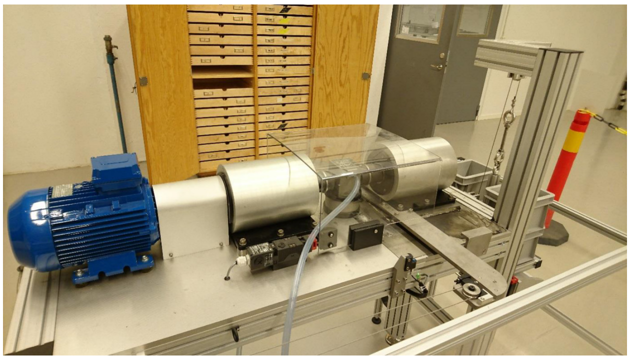

Figure 5. Rotating-bending fatigue testing machine, rear side [19]

Figure 6 shows a specimen mounted in the machine without the chamber housing installed. The two white plastic washer-like parts are put around the specimen to prevent the water from flowing outside the chamber. The water collector is installed under the specimen. The chamber is shown in Figure 7.

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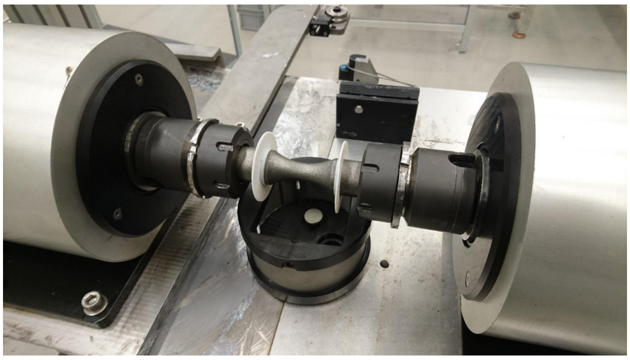

Figure 6. Specimen mounted on the machine and water collector underneath [19]

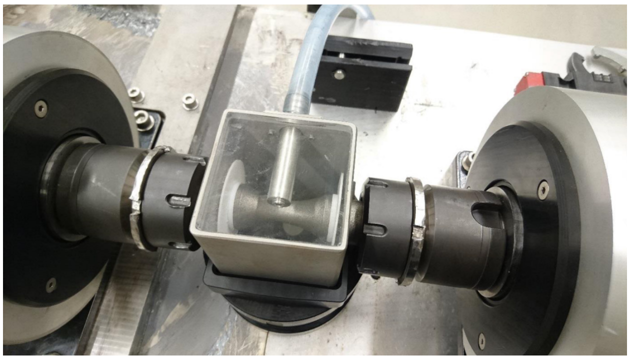

Figure 7. Corrosion chamber [19]

The minimum weight that the machine can loaded with is 2.836 kg, which corresponds to the weight of the basket on which the extra load is carried. This would mean that the basket would be left alone with no extra weight added. For these machines, this minimum load corresponds to a stress of 83.6 MPa on a standard specimen with a waist diameter of 15 mm.

4. Design Standards for Corrosion Fatigue Set-up Component

In order to come up with a design for an environmental chamber for corrosion fatigue testing some standards and considerations have to be set. In the following, the chamber, seawater, pump and instrumentation will be discussed.

4.1 Chamber

The chamber is the part of the test setup which will contain the corrosive fluid and the specimen. In this component the specimen will be fatigue loaded while the seawater flows across it. To this purpose, the chamber will need to meet some requirements. Sealing of the chamber will be important. Leakage of the seawater fluid is not catastrophic but of course it is not desired. Furthermore the chamber will need to be adapted to different sizes of specimens. Yet the dimensions of the chamber will need to be limited. An increase of chamber volume leads to an increase of pumping power, cooling power and filtration capacity.

It is preferable to construct the chamber of a transparent material to have eyes on the specimen while testing. Therefore constructing the chamber out of acrylic is a viable solution.

4.2 Seawater

Seawater has a surprisingly homogenous composition around the world. The salinity is about 3.5% by weight (wt.). The pH ranges between 7.9 to 8.1 [20]. Artificial seawater is a mixture of dissolved mineral salts that simulates seawater which is prepared according to the ASTM standard (ASTM D1141) synthetic seawater [21].

4.3 Pump

As a matter of fact, the function of the pump is to circulate the seawater. It is critical for the pump to be corrosion resistant. Pumps used in aquariums of sea fish are designed to operate under these conditions and form a cheap solution. The flow rate has to be high enough to clean debris out of the chamber but it is not the intention to have water flowing across the specimen at high speed. Increasing flow velocity of the water will increase the corrosion rate [22]. To regulate the flow a bypass over the pump will be installed.

4.4 Instrumentation

The test setup needs to be able to control these dominating parameters. It is important to monitor these variables in order to have a representative test result. The temperature in the chamber needs to be monitored. Normally the cooling unit will keep the temperature of the setup constant but it is safer to have a direct control inside the chamber as well. A pH meter will control the acidity of the seawater. In nature the seawater has a stable pH-value of 8.3 [23]. It is logical to keep the pH level constant in order to simulate real-life conditions. Furthermore a control of salinity will be required. The salinity might increase by evaporation and escape of water vapor.

5. Corrosion Fatigue Crack Detection and Propagation

There are many different methods used in fatigue testing for experimental crack growth measurement such as DCPD (Direct Current Potential Drop), infrared thermography, Digital Image Correlation (DIC), optical camera, replica, ultrasonic surface waves, strain gauges, clip-on

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gage, etc. Seawater is also not transparent in the infrared spectrum making infrared thermography inapplicable in the test-setup. Strain gauges however will be submerged and therefore used to monitor crack growth. In addition, for the specimen which is used at seawater environment, transparent anticorrosion tape would be attached on the surface of the specimen for the convenience of crack observation. Crack growth data will be obtained by taking replicas of the surface at selected number of cycles, and inspecting the replicas using an image analysis system.

Another device for capturing the crack propagation in fatigue experiments is optical camera/microscope. Figure 8 shows a picture of this set up. As shown in Figure 8, an optical microscope is used in order to verify the crack length after applying cyclic loading. In order to avoid any heating, compressed air is flowing onto the specimen surface and in the notch.

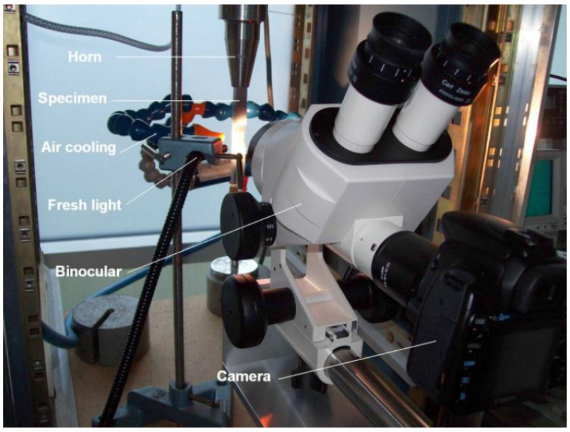

Figure 8. Configuration of optical binocular microscope for crack growth tests [17]

Crack lengths will be measured also by the compliance technique (DCPD) as shown in Figure 9. The DCPD technique measures the change in electrical resistance of the specimen, which directly correlates to crack growth. For DCPD there will be interference with the measurement probes for salinity and pH as these are based on the conductivity of the water. To avoid immersion in the saltwater, the clip-gauge used for displacement measurements is mounted on a scissors-like extension [24].

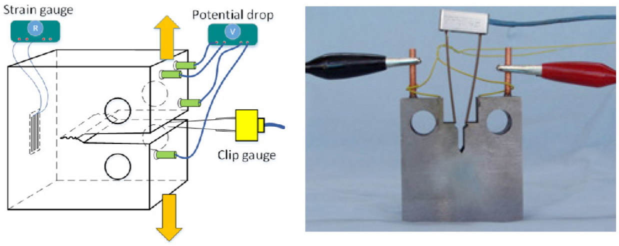

Figure 9. Direct Current Potential Drop (DCPD) technique for crack growth measurement [24]

6. Corrosion Fatigue Crack Modeling

The phenomenon of fatigue is generally divided into three steps: (1) crack initiation, (2) crack growth/propagation and (3) final fracture. The first two steps of the process are not easy to characterize and a great amount of work on research has been performed to try to understand the mechanisms involved on each one of them; it is even hard to identify a sharp limit to divide when the crack initiation ends and the crack propagation starts [25-27].

Although the steps of the fatigue process are generally accepted, there is no general agreement on when the crack initiation process ends and when the crack propagation starts, or at which crack length the crack initiation turns into propagation [28]. In the past it was believed that as much as 95% of the total life of a fatigue-failure was spent in crack initiation [29-31], however, better methods of crack detection have appeared and nowadays it is possible to observe that cracks nucleate after the first 10% of the total life of the component [32]. In dry conditions, this is mainly dependent on the level of applied stress. Since a large fraction of the life is spent on crack growth on low cycle fatigue, it has become more interesting to study this phenomenon in terms of the mechanical behavior of the crack growth, i.e. by studying the crack growth and characterizing it by linear elastic fracture mechanics, elastic-plastic fracture mechanics, or fully plastic fracture mechanics. In such cases, the entire crack initiation process is taken as nucleation phase, and the crack propagation is then expressed in terms of crack growth rates [33-35].

The corrosion fatigue process is simplified into the three main stages: pit growth N_{pit}, small crack growth N_s and long crack growth N_l. The total fatigue life is the sum of the each individual regime, expressed by:

$$N = N_{pit} + N_s + N_l \qquad (1)$$

In equation 1, N_{pit} will be calculated using Faraday's law [36]:

$$N_{pit} = \left(\frac{a_{pc}}{A} \right)^{1/B} \left(\frac{10^{9.19}}{e^{0.036\sigma_a}} \right) \qquad (2)$$

Where a_{pc} false is the critical pit size, A, B false are pit growth parameters were interpolated using experimental data and σ_a false is stress amplitude.

However, N_s and N_l both will be estimated by Fracture Mechanic theory. For long crack, the Stress Intensity Factors (SIFs) history is extracted and subsequently the crack propagation lifetime is computed over a post-processing stage using the Paris model [30]:

$$\frac{da}{dN} = C\Delta K^n \Rightarrow N_l = \int_{a_0}^{a_f} \frac{da}{C\Delta K^n} \qquad (3)$$

Where dN false is the number of applied fatigue cycles for a crack to grow da false, C false and n false are the fatigue constant and ductility exponent, respectively and ΔK false is the effective stress intensity factor range.

Crack propagation life of the specimen, N_l false, is the number of cycles for a crack to grow from an initial length, a_0 false, to the final length, a_f false, where the final rupture occurs due to unstable crack growth and over loading due to decrease in cross section of the specimen. Eventually, N_l falsewill be calculated by sum up the life of each individual crack growth increment, during the simulation.

7. Conclusion

In this article, the corrosion fatigue mechanism is described in more detail and a short presentation of some typical lab-scale corrosion fatigue test setups is given. The following conclusions are drawn:

- There is a need for research of corrosion fatigue in seawater. Thereto the development of an environmental chamber in a traditional fatigue testing rig is a sound solution. The design of such a test setup is feasible as illustrated by the discussed test setups in this article.
- Monitoring of environment variables i.e. temperature, pH and salinity would be done by the appropriate sensors, crack growth is monitored by transparent anticorrosion tape, Digital Image Correlation (DIC), strain gauges, DCPD and optical microscope.
- According to the literature review, testing with pre-filtered seawater will give a more real-life result than testing with artificial seawater. By using a circulating circuit the use of seawater would be limited.
- The test setup may be consist of a chamber where the actual testing takes place, a pump, filter unit, cooling unit and instrumentation to monitor the environmental variables.
- For corrosion fatigue in seawater conditions, the fluid is harmless leading to a simpler and cheaper design. A design with a triple containment chamber is not necessary.
- It is the author view that a fully functioning setup will be capable of producing test results leading to an increased knowledge of corrosion fatigue of offshore structures.
- The literature review revealed that, corrosion fatigue life estimation will be carried out using combination of Faraday's law and Paris model.

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