The Effects of Hydrostatic Pressure on Corrosion of Coated Stainless Steel

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Abstract. Underwater steel structure such as Remote Operated Vehicle (ROV) unit was exposed to corrosion element during its operated working hours and at different depth of sea level depending on its operational requirement. The different depth of each operational indicates the different pressure effects under water. The coated material was affected by the corrosion and may have changed in its micro substructure thus decreases the corrosion resistance. The aim of this study was to analyse the corrosion rate of the pressure effects on the coated materials through several testing. The type of coated material used is Commercial Anti-Corrosion spray. The tests done by pressurized the specimen at 2, 6 and 10 atm. The corrosion rates are determined by using immersion and weight loss. The specimens were soaked in the sea water with timeline of 24 hours. Scanning Electron Microscope (SEM) and microstructure observation are used to observed and determine the corrosion morphology of the specimen changes before and after immersion test. As a result, the pressure plays a major role on the corrosion effect and coating materials. The increments of pressure will deteriorate the corrosion resistance of the specimens. However, the coating materials can only slow down the deterioration process of the specimen.

1. Introduction

Autonomous submarine robots have been a rising interest in roaming the oceans freely and on an unprecedented scale. The robot is called Remotely Operated Vehicle (ROV) are safer, faster and efficient equipment for exploring especially in hazardous environment [1]. They are common in deep water industries such as oil and gas exploration. The deep sea is a complex environment, exposing any materials into high hydrostatic pressure and face huge challenges in the deep-sea environment [2]. High hydrostatic pressure has been becoming one of the biggest challenges in deep sea industries because it brought serious corrosion problem to the materials [3][4][5][6].

Traverso and Canepa (2014) studied corrosion performance in some of metallic materials that are commonly used in deep sea environments [2] and found out that all the alloys, including high strength steel, stainless steel, aluminium alloy etc., showed a decreased corrosion resistance in deep sea environments compared to ambient condition. Therefore, the reason for pressure promoted corrosion in deep water or sea environments are still arguing. Stainless steel has many types of grades in the industries, but not all of these are suitable for deep sea application. The most suitable type is authentic stainless steel and duplex stainless steel for deep sea structures. It is because of its good combination of corrosion resistance, high strength and wear resistance with good resistance to stress corrosion cracking. [7]
There are two types of corrosion observed in deep sea piping, which are pitting and crevice. The most recognizable type of corrosion is pitting and can be caused by any number of factors. However, crevice corrosion is much harder to identify. Pitting is simply the breakdown of the passive layer, followed by localized corrosion that can cause cracking of steel vessel or pipes [8]. In 1985 DeBerry found that polyaniline electrochemically deposited on the ferritic stainless steel and provided a form of anodic protection that significantly reduce the corrosion rate [9]. The use of anti-corrosion coatings in one of the main strategies to prevent or minimize the corrosion effects of metallic structures [10].

Deep ocean exploration is harsh environments imply corrosive environments for structural materials because of the higher hydrostatic pressure. Thus, corrosion problems of materials in deep ocean condition must be considered. Some researchers have done some experimental laboratory and revealed that an increase in hydrostatic pressure improves that pitting susceptibility of metals. It is because of the increasing activity of chloride ions and their penetration into the passive film, the oxide and leads to the formation of pitting initiation sites [11]. However, our knowledge is insufficient for the better understanding the effect of hydrostatic pressure on the corrosion of metals.

The Remote Operated Vehicle (ROV) unit was exposed to corrosion element most of the time of its operated working hours. The ROV also operated at different depth of sea level depending on its client requirement. Different depth of operational indicates the different pressure effects under water. Unfortunately, the corrosion was the main problem. The coated material was affected by the corrosion and may have changed in its micro substructure thus decreases the corrosion resistance. In this study, we focus on the type of coated material used which is Commercial Anti-Corrosion spray. The tests consist of by pressurized the specimen at 2, 6 and 10 atm. The test solution used is sea water.

Therefore, there are many factors that contribute to the formation of corrosion such as exposure to the salt, air and water. The aim of this study was to analyse the corrosion rate of the pressure effects on the coated materials through several testing.

2. Experimental Method

2.1. Material
The investigated material used was stainless steel 304L plate. The dimension of the specimen was 50mm (length) x 25mm (width) x 4.5mm (thickness). The stainless-steel specimen was sprayed or coated with anti-rusting primer on all the surfaces.

2.2. Experimental Setup
The pressure chamber was fabricated using air regulator, safety valve and on/off valve. The main cylinder was made from carbon steel materials with a 4 inches diameter x 6 inches long in dimension. The bottom of the pressure chamber was welded with a 120 mm x 4 mm pcd flange, while the top of the pressure chamber was removable 120 mm x 4 mm pcd flange. The air regulator and the safety bar were place at the top of the pressure chamber to set the pressure inside the pressure chamber. The O-ring was used to prevent air or water going out from the gap of the chamber and the top flange. The chamber was closed and tightens using 4 bolts and 8 lock nuts. The finished product was shown in Figure 1.
2.3. Pressure Test
The specimen was put inside the pressure chamber with the sea water solution. The pressure was introduced inside the chamber using an air compressor. The tests were done by pressurized the specimen at 2 atm, 6 atm and 10 atm.

2.4. Immersion Test
The immersion test was used to obtain the corrosion rate by calculating the weight loss of the specimens before and after the immersion test. The soaking time of the specimen was in total of 24 hours. The solution that was used is sea water.

| Specification of Immersion Test. |
|-------------------------------|
| **Apparatus** | **Pressure Chamber** |
| Solution | Sea water |
| The time parameter | 24 hours |
| Pressure rating | 2 atm, 6 atm, 10 atm |

The specimen has weighted before and after the test. The whole specimen is soaked with a solution to make sure to get accurate results. The corrosion rate has calculated using the formula given below:

\[
\text{Corrosion Rate} = \frac{W \times t}{A \times 365}
\]

Where;

\begin{align*}
W & = \text{Weight loss (g)} \\
A & = \text{Total area exposure (mm}^2) \\
t & = \text{Exposure time in hours} \\
g/mm^2/yr & = \text{gram per square mm per year (CR unit)}
\end{align*}

2.5. Microstructure Observation
The microscopic corrosion morphologies of the stainless-steel surface after 24 hours immersion in seawater solution at a different hydrostatic pressure were observed by Scanning Electron Microstructure.
(SEM). The specimen was grind, polished and etches before the testing was done. The specimen was also air dried clean before placing it in the SEM machine.

SEM process uses electron microscope that focused the beam of electron to produce images of the surface topography and composition of the specimen. The machine that was used for this testing is TM-3000. SEM can achieve resolution better than nanometers, and for this research it was used x500 of magnificent.

3. Result and Analysis

3.1 Corrosion rate from weight loss.

The specimens were expose to the liquid environment and pressure that can accelerate the process of corrosion. This is because of the chemical reaction occurs with oxygen and water that produce corrosive effects on metals by releasing metal ions to the water surrounding. The corrosion effects are boosted with the pressure supply inside the chamber that will create a hydrostatic pressure under the water. Table 2 shows that 2 atm pressurized specimen have loss 0.003 grams of weight after the immersion test. While, 6 atm and 10 atm pressurized specimen have loss 0.007 grams and 0.013 grams respectively. This reduction in weight is consistent with the increasing of pressure, which indicates the corrosion does occur.

Table 2. Corrosion rate calculated through weight loss.

| Pressure, atm | Hours | Weight before, Wi (g) | Weight after, Wf (g) | Wi-Wf (g) | Corrosion rate mmpy |
|---------------|------|-----------------------|---------------------|-----------|---------------------|
| 2             | 24   | 36.213                | 36.210              | 0.003     | 6.213e-8           |
| 6             | 24   | 37.264                | 37.257              | 0.007     | 1.45e-7            |
| 10            | 24   | 36.482                | 36.469              | 0.013     | 2.692e-7           |

Figure 2. The corrosion rate of the specimen after the immersion test with different hydrostatic pressure which are 2 atm, 6 atm and 10 atm.

The corrosion rate of coated material 304 stainless steel have increased from 6.213e-8 mmpy for 2 atm pressure rating to 1.45e-7 mmpy and 2.692e-7 mmpy for 6 atm and 10 atm pressure rating respectively. This demonstrates that the corrosion rate increases with the increase of pressure applied on the specimen as shown in Figure 2. This outcome is same as the polarization where corrosion resistance decreases in high pressure environment. Based on past research study, this result promises to
Yange Yang & et al during weight loss test which indicated that increasing hydrostatic pressure from 1 atm to 60 atm deteriorated the corrosion resistance of Ni-Cr-Mo-V steel [11].

3.2 Microstructure Observation
The surface coating of the stainless-steel corrosion morphology has shown in Figure 3. The most obvious type of corrosion present in the specimen is pitting corrosion. This can be observed in Figure 3(b) on the 2 atm specimen there are almost no presents of pitting with 20x magnifier. The coated surface does not change or develop any corrosion effects.

However, in Figure 3(c) on the 6 atm specimen, the present of pitting on the surface are minimal and hardly identified. Besides that, there are some spot on the surface where the colour of the stainless steel has seen through the small crack on the coating surface. This may cause by the rapture of the passive layer except for the small patch in contact with the electrolyte. This sighting is using 20x magnifier. Figure 3(d) shows that 10 atm specimen has a uniform pitting corrosion that clearly seen on the coating surface. The areas where the pitting occurs on the surface are larger and bigger than has seen under microscope. There are also in some spot where the sighting of the larger crack at the surface of the stainless steel has found.

The evidence found on the other researcher’s studies, where the zinc coating was smooth, compact and completely cover the specimen surface. There is also no corrosion was found on the surface. Then after 14 days in a solution with different pressure shows that pitting corrosion occurred on the surface of specimen [12].

![figure3](image)

**Figure 3.** The microscopic corrosion morphology of coated stainless steel at (a) the surface before immerion, (b) with corrosion product at 2 atm, (c) with corrosion product at 6 atm and (d) with corrosion product at 10 atm.

3.3 Scanning Electron Microscope (SEM)
SEM has used to examine the corroded surfaces of specimens after 24 hours of immersion with corrosion products. The corrosion product can be seen in Figure 4(a) and Figure 4(b) where the nucleation stage of pitting is present at 2 atm. In this stage, the pitting corrosion is just initiated (nucleated). The nucleation of pits is influenced by surface defects that may be due to manufacturing or environment changes. The sight of pitting nucleation may be caused by the damaged protective layer,
environmental factors that cause the layer to break down. These factors lead to anode and cathode site for corrosion.

Pitting growing sighted at the 6 atm specimen in Figure 4(c) and Figure 4(d). This stage of pitting shows the pits grow and have the potential to increase beyond the thickness of coating and lead to leaks. Pitting begins when the potential of the cell exceeds the pitting potential of the material in a given environment. This creates a self-propagating system where the increase acidity in the pit cavity increases the corrosion of the specimen.

This self-propagating clearly shows in Figure 4(e) and Figure 4(f) where the specimen has tested with hydrostatic of 10 atm. The coating fails to withstand the pitting corrosion occurred at 10 atm because the colour of the stainless steel has obviously seen through the pit. The area around the pit hole are surrounded by a uniform pitting and the pit area is getting bigger with increasing pressure. Furthermore, Figure 4(f) also shows the localized corrosion that can lead to accelerated failure of structure by acting as an initiation site of cracking. Based on Bin Liu & et al, the suggested that hydrostatic pressure did not change the mechanism of pitting formation. Besides that, the increasing in hydrostatic pressure accelerates the pitting generation rate [13].

**Figure 4.** The SEM micrographic of coated stainless steel (a) and (b) at 2 atm, (c) and (d) at 6 atm and (e) and (f) at 10 atm with a corrosion product after the immersion in seawater for 24 hours

4. Conclusions
The aim of this study was to analyse the corrosion rate of the pressure effects on the coated materials through several testing. The type of coated material used is Commercial Anti-Corrosion spray. The tests done by pressurized the specimen at 2, 6 and 10 atm. The specimens have done immersions and weight loss test to determine the corrosion rates. As we know, there are two types of corrosion observed in deep-sea materials, which are pitting and crevice. These types of corrosion have observed in this research by using microstructure observations and Scanning Electron Microscope (SEM) test. The
corrosion morphology of the specimen changes before and after immersion test has been determined. As a conclusion, the pressure plays a major role on the corrosion effect and coating materials. The increments of pressure will deteriorate the corrosion resistance of the specimens. However, the coating materials can only slow down the deterioration process of the specimen.

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