Corrosion Performance of Inconel 625 in High Sulphate Content

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Abstract. Inconel 625 (UNS N06625) is a type of nickel-chromium-molybdenum alloy with excellent corrosion resistance in a wide range of corrosive media, being especially resistant to pitting and crevice corrosion. However, in aggressive environment, Inconel 625 will suffer corrosion attack like other metals. This research compared the corrosion performance of Inconel 625 when exposed to higher sulphate content compared to real seawater. The results reveal that Inconel 625 is excellent in resist the corrosion attack in seawater. However, at increasing temperature, the corrosion resistance of this metal decrease. The performance is same in seawater with high sulphate content at increasing temperature. It can be concluded that sulphate promote perforation on Inconel 625 and become aggressive agents that accelerate the corrosion attack.

Keywords: Pitting Corrosion, Seawater, Passivity, Breakdown Potentials, Current Density, Passive Film

1. Introduction
Corrosion is the physicochemical interaction between a metal and its environment that results in changes in the properties of the metal, and which may lead to significant impairment of the function of the metal, the environment, or the technical system, of which these form a part. It is known that every substance interacts differently with the environment in which it is used. Furthermore, each ionic species present in the environment behaves uniquely. While no general theory has been established, so far, that accounts with certainty for the corrosion interaction between metals and the environment, it is realized that there is more than one factor that influences the corrosion of metals in aqueous solutions.

It is generally recognized that chromium oxide plays an important role as corrosion protection on passive alloys. For Inconel 625, despite of having nonmagnetic properties, is also has excellent fatigue strength and stress corrosion cracking (SCC) resistance to chloride ions. Most typical applications of Inconel 625 are in chemical processing, aerospace and marine engineering, pollution-control equipment and nuclear reactors. For passivation to occur and remain stable, minimum chromium content should be about 11% by weight, above which passivity can occur and below which it is impossible [1].
Wu et al., studied the passive films formed on Alloy 690 in different pH solutions at high temperatures using potentiodynamic polarization, Auger electron spectroscopy, thermodynamic diagrams and the Mott–Schottky relation. They found that the chemical compositions and electronic structures of the passive films were to be strongly pH-dependent and the passive films were a mixture of Cr₂O₃ and FeCr₂O₄ [2]. According to Kawashima et al., the surface films formed on nickel-based alloy at lower potentials in 1.5 M H₂SO₄ solution contain S²⁻ ions other than SO₄²⁻ ions, whereas S²⁻ ions were not incorporated in the passive film.

This makes it necessary to study the effects of the ions in the solution on the corrosion phenomenon, with due consideration to such factors as the type of the metal, temperature, pH, oxygen and ions.

In contrast to general corrosion, attack by pitting sometimes occurs in some particular environmental conditions. These problems result from the presence of specific aggressive species such as chloride, sulphate or nitrate[3]. Each of these species alone can produce pitting corrosion in alloy but with different levels of aggressiveness. For some corrosive resistance alloy such as copper, sulphate ions appear more aggressive than chloride ions and nitrate ions are more aggressive than sulphate ions[4].

El-Naggar[5], who studied the aggressive anions Cl⁻, NO₃⁻ and SO₄²⁻ on the corrosion and passivation behaviour in 0.50 M sodium bicarbonate solutions found that the presence of these aggressive anions stimulates the anodic dissolution rate in both the active and pre-passive potential regions. Pitting corrosion was only observed in the presence of Cl⁻ anions, while the presence of NO₃⁻ and SO₄²⁻ anions was only facilitated by the oxygen in the water without themselves participating in the cathodic process. The effect of SO₄²⁻ anion exerts an indirect effect on increasing the cathodic reaction and influence the anodic reaction [5]. Increasing the concentration of SO₄²⁻ ions in the range from 0.0 to 0.2 M in deaerated 0.5 M NaHCO₃ solutions shows no pitting and he elucidated that the role of SO₄²⁻ ions is to facilitate repassivation depending on the potentials and passivation currents on the nature of SO₄²⁻ ions [5]. From his study obviously shows that the rate of anodic dissolution increase continuously in the passive region until the concentrations of SO₄²⁻ ions reach 0.20 M, the corrosion rate increase and it decreases with further increase in potential. Therefore, 0.20 M of SO₄²⁻ ions is the limiting concentration concentrations and this can be consider as 0.02 M to 0.18 M SO₄²⁻ ions is low concentration range whereas 0.2 M SO₄²⁻ ions is high concentration range as indicative to the changes in the mechanisms of the passivation process [5]. With the evidence of anions effect in increasing and retarding the corrosion rate, therefore, some of these anions in seawater were studied in this research. The effects were studied by increasing the sulphate content (SO₄²⁻) in seawater in terms of corrosion rate and breakdown potential.

2. Experimental

Inconel 625 is nickel alloy and the main reason for nitrogen alloying in Inconel 625 is to increase the mechanical strength of the steel and to replace some of the expensive nickelalloying element. In addition, increased nitrogen content can also increase the resistance to localised corrosion and retard the precipitation of the carbide and intermetallic phases [6]. Table 1 presents the composition and mechanical properties of Inconel 625.

| Composition       | Cr  | Ni  | Mo  | C   | S   | P   | Mn  | Si  | Others                  |
|-------------------|-----|-----|-----|-----|-----|-----|-----|-----|-------------------------|
| Density, ρ (kg/m³) (X1000) | 8.44| 205.8| 940 | 430 | 88(HC) |
| Mechanical Properties | Density, ρ (kg/m³) | 8.44 |
| Elastic Modulus (GPa) | 205.8 |
| Tensile Strength (MPa) | 940 |
| Yield Strength (MPa) | 430 |
| Hardness | 88(HC) |
The corrosion mechanism was characterized according to breakdown potential \(E_b\) of Inconel 625, which is the potential once it reaches a sufficiently positive value, also known as the pitting potential. \(E_b\) is also known as the surface potential at which the passive film on the surface breaks down. This leads to an active electrochemical reaction, which causes corrosion or repassivation of the surface in certain conditions. This is the point of localized corrosion for evaluating and considering the potential, which could be an appropriate point according to any given combination of material/ambient/testing methods. The \(E_b\) values were identified at 4°C, 20°C, 50°C and 80°C, and each anodic polarisation scan was reversed once the current reached a set current \(i_{\text{rev}}\) of 500µA/cm\(^2\). The scan rate was set at 0.25mV/sec in static condition. The degree of increase in the current beyond \(i_{\text{rev}}\) gives an indication of the propensity for the propagation of corrosion [7]. An indication of the extent of propagation is therefore obtained by consideration of \(i_{\text{max}}\), which represents the maximum current attained should the current not begin to fall immediately after scan reversal.

3. Results and Discussion
The specific electrochemical parameters, are labelled on the graph, which include Open Circuit Potential (OCP), passivation potential \(E_{pp}\), breakdown potential \(E_b\), protection potential \(E_p\), critical current density \(i_{cc}\) and passive current density \(i_p\) (Fig. 1). Inconel 625 also exhibited a passive region right from the corrosion potential, \(E_{corr}\). Fig. 2 gives the potentiodynamic of Inconel 625 in real seawater whereas the results in Fig. 3 using artificial seawater which was synthesis in lab with same composition as real seawater. The results reveal that at 20°C, the electrochemical parameters for both conditions are almost a same. Therefore, the experimental was continued using artificial seawater to avoid microbiology activities.

3.1. Inconel 625 in seawater and high sulphate
For passive alloys, corrosion resistance is provided by a very thin surface film, known as passive film that is an invisible film of oxide, formed by the metal reacting with the ambient environment. Normally these films are free of pores, but their stability may be weakened locally in the environment contained aggressive anions. Fig 3 presents the potentiodynamic polarization for Inconel 625 in artificial seawater and Fig. 4 in high sulphate content at 4°C, 20°C, 50°C and 80°C respectively. Despite of having small hysteresis (the forward and reverse scan) value which indicate the small disruption of surface passivity [8], Inconel 625 also present to have a metastable pitting before the passive film breaks at 80°C as shown in red marked.
Fig. 3. Inconel 625 in normal seawater at 4°C, 20°C, 50°C and 80°C (metastable pitting image from optical microscopy).

Fig. 4. Inconel 625 in high sulphate content at 4°C, 20°C, 50°C, 80°C respectively and its microscopic image.
The corrosion properties were defined from breakdown potentials \( E_b \) of Inconel 625 in seawater and seawater with high sulphate content. The highest value represents a more stable of the metal in corrosion media. A set of electrochemistry results are presented in Table 2. The value of OCP increased as the temperature increased reveals that the metal surfaces were attack by pitting corrosion. The \( E_b \) value shows that passive film built by Inconel 625 was diminished as the sulphate ion increased. Therefore it can be concluded that sulphate is an aggressive anion that penetrates passive film on metal surface and causing localized attack [9]. It causes the distribution of available pit sites to be shifted to a higher potential, which causes pit propagation in both metastable and stable states. At high temperature, Inconel 625 presents to have secondary \( E_b \) and as predicted, the \( E_b \) values of Inconel 625 decreases as the temperature increase in both solutions. However, these values are not drastically reduced indicate that Inconel 625 is stable at increasing temperature.

### Table 2 The electrochemical data of Inconel 625

| Solution         | Temp (°C) | OCP (mV) | \( E_{pdp}(mV) \) | \( E_b(mV) \) | \( i_p(\mu A/cm^2) \) | \( i_{cc}(\mu A/cm^2) \) | \( I_{max}(\mu A) \) |
|------------------|-----------|----------|-------------------|---------------|------------------|------------------|-------------------|
| Seawater         | 4         | -323     | -260              | 1028          | -4.69            | -5.57            | 1608               |
|                  | 20        | -296     | -233              | 699           | -4.54            | -5.19            | 1660               |
|                  | 50        | -192     | -120              | 527           | -4.63            | -5.48            | 1470               |
|                  | 80        | -182     | -122              | 391           | -4.94            | -6.12            | 1470               |
| High sulphate    | 4         | -239     | -167              | 686           | -4.62            | -5.83            | 1516               |
|                  | 20        | -209     | -149              | 674           | -4.89            | -6.35            | 1506               |
|                  | 50        | -300     | -249              | 614           | -4.52            | -5.67            | 1574               |
|                  | 80        | -229     | -190              | 512           | -4.94            | -6.14            | 2250               |

**Fig.5.** The breakdown potential of Inconel 625 in (a) seawater and (b) high sulphate content as a function of temperature.

### 4. Conclusion

It can be concluded that, the corrosion attack increased as the temperature increased by shifting the \( E_b \) to lower value in both medium. Localised corrosion may attack the metal surface in static condition. Higher sulphate content mitigate the corrosion attack and therefore, sulphate is one of the aggressive ions that accelerate corrosion attack in seawater.
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