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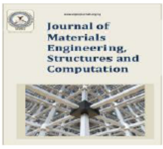

Sustainability of Steel weld joints in Seawater Environment-A Critical Review

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ABSTRACT

Seawater environments present a multifaceted challenge for steel weld joints, requiring a nuanced approach to ensure their sustainability. A review of existing literature reveals that various factors influence the long-term performance of these weld joints. Microstructure, environmental conditions and alloy composition play a major role in the sustainability of steel weld. There are several promising ways to mitigate these detrimental effects, including protective coatings, cathodic protection, surface treatment, corrosion-resistant alloys, monitoring and maintenance, and proper material selection. Welding processes, including methods and parameters, affect steel weld joints' sustainability. To design and preserve durable steel weld joints in seawater, it is crucial to recognize the intricate relationship between mechanical properties, microstructural changes, and environmental conditions. Continued research and development are imperative for enhancing the reliability of marine infrastructure.

1. Introduction

Steel stands as one of the most prevalent materials worldwide, primarily due to its affordability and widespread availability. Its extensive use can be observed, notably in saline conditions, such as in petroleum production, refining, pipelines, etc. Despite its susceptibility to corrosion [1–6], steel remains a favoured choice for structural purposes. Its ready accessibility, cost-effectiveness, and commendable mechanical attributes justify this preference. In most cases, steel is exposed directly to environments during its use, resulting in general corrosion, which accounts for 50% of corrosion losses [7]. In several industries, corrosion poses a significant economic challenge, particularly those whose infrastructure is heavily dependent on metallic components, such as the oil and gas industry (including platforms, pipelines, and storage tanks), shipyards, and water utilities. In seawater environments, corrosion risks escalate due to aggressive chloride ions and diverse indigenous microorganisms [7, 8].

Furthermore, corrosion often leads to the failure of welded steel structures, notably in the oil and gas industry. Stress corrosion cracking necessitates both formed stress and a corrosive environment.

Residual tensile stress, typically accompanied by a welding process, is a primary cause for this corrosion form in steel structures employed within the oil and gas field. When exposed to seawater containing highly corrosive ions, such as chloride ions, welded structures corrode rapidly and severely [10, 11]. Localized corrosion tends to occur in structures with a heterogeneous heat-affected zone (HAZ) due to welding [12–14]. Welded areas are generally more susceptible to stress corrosion cracking compared to unwelded steel [15, 16]. To enhance the reliability of high-performance steel welded structures, it becomes crucial to enhance weld quality. Additionally, environmental factors like temperature, salinity levels, and pH in seawater environments present significant corrosion challenges for steels [17].

2. Key factors Affecting steel weld joints corrosion in seawater environment

2.1 Temperature

The effect of temperature on seawater corrosion of steel weld joints is significant. Higher temperatures can accelerate corrosion processes. It has been shown that steel weld joints can corrode more quickly at elevated temperatures [10,14]. Fluctuations in temperature can cause thermal cycling, which can accelerate the formation of corrosion products and increase stress on the weld joint. Steel and seawater have different coefficients of thermal expansion. This can lead to differential expansion and contraction, potentially causing stress corrosion cracking in the welds. Higher temperatures can promote the formation of localized corrosion cells, such as pitting corrosion, which can be especially damaging to weld joints. Elevated temperatures can also reduce the protective passive film on the steel's surface, making it more susceptible to corrosion [17].

2.2. Salinity level

Corrosion accelerates significantly in high-salinity conditions. In electrochemical corrosion, chloride ions are also aggressive, in addition to hygroscopic salts like NaCl and $MgCl_2$. It is known that chloride anions compete with hydroxyl ions in iron metal to bind the cations formed in the anodic reaction between chloride anions. According to Frankel and Sridha [18], chloride salts are less susceptible to chloride corrosion than iron salts because they are less soluble. The pitting may be exacerbated if the chloride concentration of the chemical is raised. Numerous metal cations are very soluble in chloride solutions. Leckie and Uhlig [19] found that high concentrations of chloride shifted the critical porosity of stainless steel to more active values when anions were added. Anions such as ClO_4^-, SO_4^{2-}, NO_3^-, and OH^- also acted as spike inhibitors when their concentrations reached high levels [20, 21].

2.3. Conductivity

Seawater has a high salt content, almost all of which is in the ionization state of the salt, which makes the seawater a good conductor of the electrolyte. When a steel weld joint is immersed in seawater, it creates a conductive path for these reactions to occur. This can lead to corrosion processes such as galvanic corrosion, which is the accelerated corrosion of one metal in the presence of another metal in an electrolyte. The weld joint can act as an anode or a cathode, depending on environmental conditions and the presence of other metals. This can result in localized corrosion, pitting, or even the complete failure of the weld joint. Seawater has a higher conductivity compared to freshwater, which means it can enhance the transport of ions and increase the corrosion rate of steel. The presence of chloride ions, specifically, plays a significant role in accelerating corrosion processes. Chlorides can initiate pitting corrosion, which can rapidly penetrate through the protective oxide layer on the steel surface, leading to localized attack and potential failure of the weld joint [24].

2.4. Dissolved oxygen

Most metals and alloys do not undergo corrosion in saline water without dissolved gases (oxygen, carbon dioxide, or sulphur dioxide) at temperatures below 100 °C [25]. Except for magnesium and aluminium, the majority of common structural metals resist corrosion from high-purity water and steam, even at 450 °C [26, 27]. Electrochemical corrosion is enhanced in strong electrolytes like oil-field brines, but the main corrosive agents in injection waters are oxygen, free carbon dioxide, and hydrogen sulphide. Warren [28] found that dissolved oxygen accelerated steel corrosion in water. Dissolved oxygen from ambient air is a corrosion-relevant water component. Oxygen depolarizes and oxidizes cathodes as a cathodic depolarizer; dissolved oxygen removes hydrogen from the cathode and accelerates corrosion. Dissolved oxygen can be reduced on the metal surface and participate in electrochemical reactions. Sridhar et al. [29] studied 316L stainless steel, and the results showed that less than 0.06 ppm oxygen is required to prevent localized corrosion. Uhlig et al. [30] also studied the effect of dissolved oxygen on the absorption of mild steel corrosion inhibitors. Their results show that the effectiveness of the inhibitors depends on the level of dissolved oxygen. Caceres et al. [31] agree that the kinetic properties of carbon steel are significantly dependent on dissolved oxygen and NaCl concentrations, studying the corrosion kinetics as a function of dissolved oxygen and NaCl concentration. Due to faster reaction kinetics, increased temperatures favour steel corrosion. The temperature increases the dissolved oxygen and increases the corrosion of the metal. The higher the dissolved oxygen content of the sea, the higher the electrode potential of the metal in the sea, and the faster the corrosion rate of the metal. But for aluminium and stainless steel, a class of metal, when it is oxidized, the surface forms a thin layer of oxide film to protect the metal, that is, to maintain a passive state. In addition, in the absence of dissolved oxygen in the sea, copper and iron have almost no corrosion.

2.5 pH

The pH of seawater can also have a significant effect on steel weld joints. pH is a measure of the acidity or alkalinity of a solution. Seawater typically has a pH range of 7.5 to 8.4, which makes it slightly alkaline. The pH of seawater can influence the corrosion potential of steel weld joints. Lower pH levels (more acidic conditions) can increase the corrosion potential, leading to accelerated corrosion rates. This is because acidity can facilitate the breakdown of the protective oxide layer on the steel surface, making it more susceptible to corrosion attacks. Just like conductivity and chloride levels, pH can also contribute to localized corrosion processes such as pitting corrosion. Lower pH values can promote the initiation and progression of pits on the steel surface. Pits act as localized sites for corrosion and, if not mitigated, can lead to the failure of the weld joint. Steel surfaces often develop a passive oxide layer (primarily iron oxides) that provides a certain level of protection against corrosion. The pH of seawater can affect the stability and quality of this passive oxide layer. Maintaining a slightly alkaline pH in the seawater can aid in stabilizing the passive oxide layer and enhance its protective qualities. However, if the pH drops below a certain threshold (around 6.5 to 7), the passive oxide layer can become less stable, leading to increased corrosion rates [32].

2.6 Seawater as corrosive environment

There are lots of constituents that make up seawater; they consist of salts, water, and smaller quantities of different chemicals, such as dissolved natural and inorganic factors. In addition, it consists of a small quantity of gases commonly found in the atmosphere. The average salinity of seawater is about 3.5%. In other words, a kilogram of seawater consists of approximately 35 grams of dissolved salts. The salinity of seawater is measured by using the grams of salt dissolved per kilogram of the liquid. Chloride, sodium, sulphate, magnesium, calcium, and potassium ions are the most commonly determined ions in seawater. It is due to the presence of these ions that seawater is so corrosive. Seawater is one of the most aggressive and complex media. Many elements affect seawater corrosion, such as chemical, organic, and mechanical effects. An understanding of those factors and parameters is crucial to the layout of metallic systems and components that might be employed in marine environments. Anti-corrosion technology and material overall performance can both benefit from it. The integrity of metallic systems is jeopardised as a result of localised corrosion. A little or no quantity of substances can cause large industrial disasters because of severe localised degradation. Steel metallic corrosion in seawater is commonly localised because of lots of causes, such as material heterogeneity (grain boundaries, inclusions, welds, etc.) [33–37], differential aeration [38–40], and organic activity [41–49]. Differential aeration and microorganism consortia activity [46–48] integrate to create the well-known ALWC (Accelerated Low Water Corrosion) phenomenon. When it comes to marine applications, steel is a common preference due to its broad availability, affordability and extremely good mechanical characteristics. They are also at risk of uniform corrosion and have been studied for many years to estimate and predict their corrosion rate and lifespan in various marine settings with a high degree of accuracy. According to Melchers and Wells [51] phenomenological model, a massive number of information factors have been analysed in depth. When it involves the non-uniformity of carbon metallic corrosion in seawater, microbiologically influenced corrosion (MIC) is often referred to as the basic cause. There are lots of aerated and deaerated zones in the biofilm that forms on any substance that is submerged in seawater, which creates aeration cells and supports dangerous microbes' growth and activity. Corrosion rates can be directly influenced by electroactive microorganisms that may even take electrons from the steel. Sulphate-decreasing microorganisms (SRB) are anaerobic microorganisms that prefer momentarily localized corrosion processes; however, they quickly colonize the whole metallic surface, resulting in greater or much less uniform corrosion [52–55]. They are also permeable, making them the perfect housing for microbes that thrive in certain conditions [49, 56– 59]. It is likewise feasible that the long-term composition of the corrosion product layer can alter because it varies with the exposure zone [63–70]. At a certain quantity of seawater acidity or alkalinity, metals that come into contact with seawater have a certain electric potential. The corrosion current is due to a change in electric potential because the anodic region corrodes and current is discharged from the metallic surface. Because of its higher conductivity and the chloride ion's capacity to penetrate metallic surface coatings, seawater is usually more corrosive than freshwater. Chloride content, oxygen availability, and temperature all affect the rate of corrosion [71].

2.7 Corrosion mechanism of seawater

Metal corrosion refers to a localized electrochemical process that occurs on the surface of a metal. During this process, electrons are released due to the dissolution of the metal and are then transferred to another location on the surface to reduce hydrogen ions. This gradual degradation ultimately leads to the failure of the metal. Before delving into various methods for evaluating corrosion mechanisms, it's essential to grasp the fundamental principles of corrosion in a steel/seawater environment. Similar to many other metals, the corrosion of iron can be divided into two primary electrochemical half-reactions [72-74]. One of these reactions is the anodic reaction, involving the oxidative dissolution of iron. The overall chemical reaction of iron immersed in a seawater environment is summarized in Equations (1) - (7) [75,76].

I. overall chemical reaction:

$$Fe(solid) + 2H^+ \Leftrightarrow Fe^{2+} + H_{2(gas)} \quad (1)$$

II. oxidative dissolution:

$$Fe + H_2O \Leftrightarrow [FeOH]_{ads} + H^+ + e^- \quad (2)$$

$$[FeOH]_{ads} \Leftrightarrow [FeOH]^+_{ads} + e^- \quad (3)$$

$$[FeOH]^+_{ads} + H^+ \Leftrightarrow Fe^{2+} + H_2O \quad (4)$$

III. oxidative dissolution in Chloride Environment

$$Fe + H_2O + Cl^- \Leftrightarrow [FeClOH]^-_{ads} + H^+ + e^- \quad (5)$$

$$[FeClOH]^-_{ads} \Leftrightarrow [FeClOH]_{ads} + e^- \quad (6)$$

$$[FeClOH] + H^+ \Leftrightarrow Fe^{2+} + Cl^- + H_2O \quad (7)$$

Observing the reactions in the mentioned reactions, it becomes evident that iron tends to dissolve, releasing positive Fe ions into the electrolyte. This dissolution process also generates free electrons capable of traversing the metal. The intermediates $[FeOH]_{ads}$ and $[FeClOH]_{ads}$ play crucial roles in determining the rate of iron dissolution, as described in equations (2) and (7).

2.8 Corrosion of Steel in Seawater

Seawater corrosion of steel is a common issue in marine environments. In the oil and gas industry, steel is one of the most cost-effective structural materials. The primary issue is that it is susceptible to corrosion. When steel and air react chemically, iron oxide and other corrosion products are produced [77]. Ueda [78] stated that carbon steel can corrode uniformly and severely in small areas in a CO_2 atmosphere at 100 °C. The term for this is "mothball corrosion." Yang et al. [79] discovered that the amount of carbon content in carbon steel and the presence of carbon-rich grain make it more corrosion-resistant. Both changes on the metal and the lattice structure influence how corrosion behaves. In terms of corrosion resistance, the radial cubic (FCC) structure is superior to the centered cubic (BCC) structure due to its more compact atomic structure.

Andijani and Turgoose [80] measured the rate of corrosion of carbon steel at 25 °C and a pH of 7 using a 1 M solution of desalted NaCl and simulated seawater. The rate of corrosion was lower in longer-term tests at 50 ^{0}C and pH 8.5 than in shorter-term tests. This occur because a layer of hydroxide forms on the metal's surface. Lee et al. [81] studied how carbon steel corrodes in rising seawater. They found that the iron oxide-coated surface remained intact and lasted for 396 days in aerobic seawater, but the sulphide did not do as well in anaerobic seawater. This shows that air is a very important criterion of steel corrosion. Also, Nesmeyanova [82] showed that under degassed and oxidized conditions at 280 °C, the corrosion rate decreased with continuous oxygen supply because a protective layer formed on the surface of the material. This shows that anaerobic conditions do not mitigate corrosion and that oxygen is not needed for aggressive localised corrosion. Table 1 present recent studies on steel weld joints corrosion in seawater environment.

Table 1: Recent research study on steel weld joints in seawater environment

Authors details	Methods Employed	Outcomes from study	Ref.
Liu et al.,2023	Salt spray test,potentiodynamic polarization(PDP),electrochemical impedance spectroscopy(EIS)	The A6 carbon steel component exhibited notable accelerated corrosion at the interface, causing the interface samples to corrode more rapidly than the underlying carbon steel substrate. Nevertheless, during the electrochemical tests, the composite interface displayed superior resistance to corrosion compared to the carbon steel substrate.	[83]
Wang et al.2022	potentiodynamic polarization,electrochemical impedance spectroscopy	The corrosion products found on the surface of vertical electro-gas welding (VEGW) joints are denser compared to submerged arc welding (SAW) joints. This difference contributes to the superior corrosion resistance exhibited by VEGW joints over SAW joints.	[84]
Li et al.,2023	potentiodynamic polarization,electrochemical impedance spectroscopy	The corrosion resistance of both the Heat-Affected Zone (HAZ) and the fused zone of the steel experienced degradation, possibly attributable to grain boundary ferrite affecting the HAZ's corrosion resistance. On the other hand, the coarser microstructure of granular bainite demonstrated improved corrosion resistance within the welded steel's fused zone.	[85]
Liu et al.,2023	immersion test,potentiodynamic polarization,electrochemical impedance spectroscopy	This highlights a distinct connection between microstructure and susceptibility to Microbially Influenced Corrosion (MIC) in marine steel design alloys. These alloys exhibited an enhanced corrosion resistance to MIC in marine environment	[86]
Ma et al.,2023	potentiodynamic polarization,electrochemical impedance spectroscopy	The study indicates that a 100% coating results in the lowest current density and maximum polarization. This observation suggests that corrosion resistance improves as the coating thickness increases.	[87]
Abdo et al.,2022	potentiodynamic polarization,electrochemical impedance spectroscopy and raman measurement	The corrosion resistance properties of the laser-welded 2205 duplex stainless steel sample exhibit improvement in the alkaline direction of the solution. In other words, higher acidic solutions are more likely to cause corrosion.	[88]
Zhao et al.,2023	Slow strain rate test,potentiodynamic polarization,electrochemical impedance spectroscopy	The steel displayed minimal susceptibility to stress corrosion cracking, primarily because of the inhibition of anodic dissolution.	[89]
Yap et al.,2023	potentiodynamic polarization,electrochemical impedance spectroscopy	The coating significantly enhanced the corrosion protection of the carbon steel in seawater.	[90]

Li et al.,2022	weight loss (WL), potentiodynamic polarization,electrochemical impedance spectroscopy	The Concentration of Cl- affected the corrosion resistance potential of steel by affecting the reaction process of anode and cathode	[91]

Lee et al., [41] measured the corrosion of carbon steel over 396 days in stagnant seawater. The results showed that oxygen was not required for aggressive localized corrosion and that anaerobic conditions did not inhibit corrosion. It is noteworthy to observe that corrosion on a carbon steel coupon that had previously been kept under completely anaerobic conditions became more aggressive when oxygen was added. Liu et al. [92] study on the corrosion behavior of high-strength steel welded joints in seawater using electrochemical and scanning vibrating electrode techniques is as follows, the surface of the ultra-high-strength steel corroded and showed calcareous deposits, while the surface of the high-strength steel and welded metal zones corroded uniformly. The calcareous deposits on the ultra-high-strength steel's surface resulted in pitting corrosion. In their study, Xing et al. [94] investigated the corrosion characteristics and corrosion product formation of 90-10 cupronickel welded joints submerged in seawater. Within a flowing seawater environment, the metal zone (MZ), heat-affected zone (HAZ), and welded zone (WZ) regions generate protective corrosion product films. Over the course of the experiment, corrosion resistance steadily increased, reaching its peak value after 20 days. No tably, the HAZ exhibits minimal adhesion, resulting in the lowest corrosion resistance among these regions. Additionally, the HAZ-WZ interface demonstrates varying levels of corrosion resistance and galvanic corrosion tendencies. Zang et al. [95] conducted a comprehensive analysis of B10 copper-nickel alloy welded joints during the erosion process in seawater pipes. Their findings indicate that the corrosion rates of the weld metal (WM), base metal (BM), and heat-affected zone (HAZ) decrease over time. Through SEM and EDS analysis, it is evident that extended exposure time results in the decomposition and buildup of corrosion products, progressively enhancing the corrosion resistance of the welded joints. At the submicroscopic level, the weld metal (WM) functions as a cathode, effectively mitigating corrosion during the later stages, particularly under high flow rates.

Zhou and Tian-jiang,[96] conducted an investigation into the microstructure and corrosion impact of seawater on X70 pipeline welded steel. The findings reveal that the microstructure varies across different zones of the welding joint, leading to noticeable differences in corrosion rates and electrochemical behavior. Throughout the corrosion process, the corrosion potential and rate in these various zones fluctuate, forming coupled corrosion between the heat-affected zone (HAZ) and the welding base metal. Additionally, the predominant form of corrosion observed in the welded joint is spot corrosion. In their research, Gericke et al. [97] evaluated the fatigue strength and corrosion resistance of structural steel-welded connections coated with arc-sprayed aluminum coatings in a seawater environment. The corrosion investigations revealed that thermally sprayed Al99% coatings exhibit remarkable resistance to corrosion in seawater, effectively serving as planar sacrificial anodes and polarizing bare steel below 0.8 V. This combination of enhanced fatigue strength and corrosion protection renders thermally sprayed aluminum coatings a promising choice for the design and operation of structures such as offshore installations.Pastorac et al. [98] study examined the butt weld joints of AH36 ship building steel in seawater. Overall, the results showed that pitting was most prevalent around the base metal (BM), heat-affected zone (HAZ), and weld metal (WM) of the welded joints. The authors suggested that this was due to microstructural changes in the materials caused by the welding process, such as grain coarsening and precipitate formation. The HAZ and WM showed a higher tendency for localized corrosion than the BM.

In the study by Li et al. [99], the effects of welding and alternating wet-dry seawater on the hydrogen embrittlement (HE) susceptibility of a new nanoparticle-reinforced high-strength steel, dispersion-strengthened-high-strength (DSHS) steel, were investigated. The results showed that the welding process led to the transformation of the granular bainite microstructure in the DSHS steel to tempered martensite, which increased the HE susceptibility of the material. Bai et al. [100] conducted an investigation into the impact of residual stress on the corrosion behavior of welded X65 steel structures. The findings revealed that elevated levels of residual stress could expedite corrosion damage in the weld joint, heat-affected zone (HAZ), and the parent metal of the welded structures. However, this influence on the overall corrosion rate of the welded structures was minimal. Furthermore, the presence of varying levels of residual stress led to different corrosion morphology developments on the surfaces of the weld joint, HAZ, and parent metal. Consequently, the corrosion characteristics in these different regions of the welded structures differed. Notably, the HAZ eventually exhibited the most severe corrosion damage compared to the weld joint and parent metal.

3. Corrosion-preventive approach to steel weld joints in seawater

Steel weld joints are susceptible to corrosion in seawater, which can lead to reduced performance, damage, and failure of the structure. Fortunately, several corrosion prevention methods can be employed to provide protection against corrosion.The following are some common methods [101-105]:

i. Protective coatings: Protective coatings provide a barrier between the steel surface and the corrosive seawater environment. Coatings such as epoxy, polyurethane, and zinc-rich systems are commonly used on steel structures to prevent corrosion. The coating's thickness, adhesion, and resistance to abrasion and chemical attack contribute to its effectiveness in preventing corrosion.

ii. Cathodic protection: Cathodic protection is an electrochemical process that involves providing a more negative electrical potential to the steel surface compared to the seawater environment. This process reduces the corrosion potential of the steel weld joint and slows down the corrosion rate. Cathodic protection can be achieved by impressed current or sacrificial anode systems

iii. Corrosion-resistant alloys: The use of corrosion-resistant alloys (CRA) is an effective method to prevent corrosion in steel weld joints exposed to seawater. CRA such as stainless steel, nickel-based alloys, and titanium-based alloys have excellent resistance to corrosion in marine environments. However, this method can be costlier compared to other prevention methods.

iv. Surface treatment: Surface treatment methods such as pickling, passivation, and polishing can enhance the corrosion resistance of steel weld joints in seawater. These treatments remove the contaminants and impurities on the surface of the steel and improve the protective oxide layer's quality.

v. Monitoring and maintenance: Regular monitoring and maintenance of the steel weld joints can help prevent corrosion. Inspection and testing for corrosion, cracks, and other signs of damage should be conducted regularly. Any issues should be addressed immediately to prevent further damage.

These corrosion prevention methods can be used alone or in combination to provide effective protection against corrosion in steel weld joints exposed to seawater. A comprehensive understanding of the corrosion mechanisms and the specific environment in service is necessary to select the appropriate prevention method.

4. Conclusions

In conclusion, the sustainability of steel weld joints in seawater environments presents a multifaceted challenge that requires a nuanced approach. Through an extensive examination of the existing literature, it becomes evident that numerous factors influence the long-term performance of these weld joints. The review has highlighted several key findings.

i. Corrosion remains a primary concern, impacting the integrity and longevity of steel weld joints. Various factors such as microstructure, environmental conditions, and alloy composition play pivotal roles in corrosion susceptibility.
ii. Advances in corrosion-resistant coatings, cathodic protection, surface treatment have shown promise in mitigating the detrimental effects of seawater exposure on weld joints.
iii. The welding process, including the choice of welding method and welding parameters, has a significant impact on the overall sustainability of these joints.
iv. Understanding the complex interplay of factors, including mechanical properties, microstructural changes, and environmental conditions, is crucial for designing and maintaining sustainable steel weld joints in seawater.

In light of these findings, achieving sustainability in steel weld joints within seawater environments necessitates a holistic approach that combines materials selection, corrosion prevention strategies, and meticulous welding practices. It is clear that ongoing research and development efforts are essential to continue improving the durability and reliability of these vital structural components in marine applications.

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