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Filtration-UV irradiation as an option for mitigating the risk of microbiologically influenced corrosion of subsea construction alloys in seawater

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ABSTRACT

The effect of filtration-UV irradiation of seawater on the biofilm activity on several offshore structural alloys was evaluated in a continuous flow system over 90 days. Biofilms ennobled the electrode potential by +400–500 mV within a few days of exposure to raw untreated seawater. Filtration-UV irradiation of the seawater delayed the ennoblement of the steels for up to 40 days and lowered localized corrosion rates in susceptible alloys. Ennobling biofilms were composed of microbial cells, diatoms and extracellular polymeric substances and the bacterial community in biofilms was affected by both the alloy composition and seawater treatment.

1. Introduction

Virtually any metal surface exposed to water is susceptible to microbial colonization and biofilm formation. Biofilms are sessile communities of microbial cells and extracellular products associated with a substratum [1–3]. Biofilms seem to be a preferential mode of life for microorganisms as it offers a more sustainable environment for their survival, growth and reproduction [4–6]. In addition, biofilm development allows mutualistic and synergistic interactions between microorganisms and affords protection from external harsh conditions [5,7]. Within these biofilms, microorganisms can initiate, facilitate or accelerate metal corrosion reactions in a phenomenon known as microbiologically influenced corrosion (MIC) [8–10].

In the construction of subsea pipelines, carbon steel has been the dominant metallic material since it has tremendous advantages of a large experience base and strong technical background along with moderate cost. However, corrosion resistant alloys such as stainless steels and nickel-based alloys are becoming more important structural materials due to their combination of high strength and resistance to corrosion in aggressive offshore environments. Corrosion resistant alloys suffer negligible general corrosion in seawater due to a protective, predominantly chromium oxide, film that forms immediately on the surface with exposure to air [11,12]. However, these alloys do still suffer localised corrosion in seawater, i.e. pitting corrosion, crevice corrosion, stress corrosion cracking (SCC) and microbiologically influenced corrosion (MIC) [13–16].

Microorganisms do not produce a unique type of corrosion but rather they influence or shift the existing mechanisms for corrosion. Most studies report MIC as a mode of localized corrosion [17–19]. Previous studies on MIC have postulated several mechanisms through which microorganisms can aggravate localized corrosion on active–passive alloys. It has long been known that natural biofilms are able to shift the E_{corr} of active–passive alloys in the noble direction, a phenomenon collectively known as ennoblement. Ennoblement has been widely studied and numerous reports from geographically diverse sites have been published over the years [20–24]. The significance of this phenomenon lies in its influence on the susceptibility to corrosion of anode materials in galvanic couples and the initiation and propagation of localized corrosion [25,26]. Other MIC mechanisms include biodeposit formation leading to a crevice type of attack [15], acceleration of propagation rates for crevice corrosion and decrease of the critical potentials for pitting and crevice corrosion initiation [14,27].

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The use of natural seawater in the hydrotesting of subsea pipelines prior to commissioning is becoming an issue of increasing importance to the oil and gas industry. This practice can contaminate the internal surface with microorganisms, sand and salts, even after the water has been removed, increasing the possibility of internal localized corrosion, particularly MIC [28–30]. Therefore, hydrotest seawater must be properly treated in order to reduce the possibility of contamination and severe corrosion damage and to prolong pipeline and equipment service life [31,32].

Generally, the risk of MIC can be minimized by using chemical biocides to control the growth of suspended cells and further biofilm formation on steels [33,34]. However, environmental concerns associated with chemical disinfection and biocide disposal have led to the consideration of physical methods for treatment of industrial waters. Furthermore, factors such as chemical incompatibilities, persistence, toxicity, cost and degradation associated with the use of chemical biocides are becoming an issue of increasing importance to the oil and gas industry. Filtration and ultraviolet (UV) light disinfection can be a good supplementary method to traditional chemical treatments for management of industrial waters as it can greatly reduce the amount of chemical biocides required for water disinfection. Filtration and settlement reduce the amount of sediments, larger organisms and non-soluble organic matter which increases the UV light disinfection capacity. UV radiation damages proteins and membranes and indirectly damages DNA by creating reactive oxygen compounds (e.g., H_2O_2, O_2^-, etc.) causing single-strand breaks in DNA which ultimately leads to the death of the microorganisms [35].

In this study, several offshore construction alloys were exposed to slowly flowing natural seawater that ensured a constant loading rate of nutrients and promoted the formation of mature and active biofilms in a test rig established in New South Wales, Australia [36]. The particular design of the test rig allowed for the evaluation of the alloys corrosion performance in raw untreated seawater as well as filtered-UV irradiated seawater. The corrosion performance of the alloys was investigated by monitoring corrosion potential over time and conducting surface analyses. Bacterial diversity in biofilms formed on the different alloys in raw and treated seawater was examined by polymerase chain reaction (PCR) of bacterial 16S rRNA gene fragments followed by denaturing gradient gel electrophoresis (DGGE). Molecular characterization of biofilm communities has become crucial to understand the complexity of the interactions of biofilms with substratum surfaces and the surrounding environment [16,37–41]. The sensitivity of this technique allowed an assessment of the degree to which exposure conditions and material composition affect the bacterial community and shift the diversity in the biofilms.

2. Experimental details

2.1. Specimen preparation

Commercial carbon steel, stainless steels UNS S31603, UNS S31803, UNS S32750, UNS S31254 and the nickel-base alloys UNS N08825 and UNS N06625 were used in this study. The chemical composition of the alloys in weight per cent is presented in Table 1. Square coupons (20 mm × 20 mm × 5 mm thick) were cut from the supplied plate samples and a 2 mm diameter hole was drilled in one corner. An electrical connection was established via a copper wire soldered to one side of the coupon. To prevent crevice corrosion, samples were electrocoated with a protective epoxy (Powercron® 6000CX, PPG Industrial coatings) at the surface area where the spot weld was made for electrical connection and uncovered weld areas further covered by epoxy resin (Belzona 1391, Belzona polymerics Ltd.). Prior to exposure, coupons were wet ground to a 600 grit finish, soaked in Decon® 90 (Decon laboratories Limited) for 3 h and sterilized by immersion in 70% ethanol for 1 h. Coupons were finally dried with nitrogen, weighed in triplicate and total coupon areas were measured using a digital gauge. Coupons were suspended by nylon strings in the experimental tanks.

2.2. Test conditions

Two lots of triplicate coupons of each material were exposed to streams of continuous low velocity (<1 mm s^{-1}) natural coastal seawater in a test rig established in a field laboratory within the Port Stephens Fisheries Centre site at Taylors Beach, New South Wales, Australia. A detailed description of the experimental rig is given elsewhere [36]. One stream was untreated and passed straight into a sealed 200 L experimental tank (referred to as raw seawater). A second stream was pumped into settling tanks followed by a series of filters down to 5 μm, passed over ultra violet lamps in tandem before going into another sealed 200 L experimental tank. This tank was continuously irradiated with ultraviolet (UV) light (lamp placed above water) in order to kill microorganisms without changing the chemical properties of the water (referred to as treated seawater). The UV lamps used were 40 W input UV-C light lamps (254 nm wavelength). UV-C irradiation has been shown to be very effective in controlling marine biofouling development [42]. Lamps were checked daily.

The chemical composition of the seawater is shown in Table 2. Water temperatures in the experimental tanks were recorded daily for the duration of the experiment (Tinytag Aquatic, Gemini Data Loggers, UK).

2.3. Electrochemical studies and determination of corrosion rates

The corrosion potential (E_{corr}) of each electrode was measured against a type CCS1-PORT Ag/AgCl portable seawater reference electrode (Silvion Limited, accuracy Vs SCE in 3% NaCl at 20 °C: −5 mV ±5 mV) and recorded every four hours using a multichannel data logger (dataTaker DT605, dataTaker Pty. Ltd.). Coupons were withdrawn after 90 days immersion, cleaned following the standard procedure [43] and weighed in triplicate to calculate weight loss and corrosion rates of each sample [43]. The average corrosion rate over the 3 month exposure is calculated according to the following equation (Eq. (1)):

Table 1
Test materials and their chemical composition.

Material	Type	C wt%	Mn wt%	Fe wt%	Cr wt%	Ni wt%	Mo wt%	N wt%	Nb wt%	S wt%
UNS S31603	Austenitic SS	0.022	1.76	Bal	17.4	10	2.03	0.046	–	0.001
UNS S31803	Duplex SS	0.015	1.53	Bal	22.35	5.72	3.16	0.18	–	0.001
UNS S32750	Super Duplex SS	0.019	0.819	Bal	24.74	6.61	3.73	0.262	–	0.0003
UNS S31254	Super austenitic SS	0.01	–	Bal	20.18	18.15	6.1	0.2	–	0.010
UNS N08825	Nickel base alloy	0.05	0.85	22	22.5	Bal	3	–	–	0.03
UNS N06625	Nickel base alloy	0.1	0.45	5	22.5	Bal	9	–	3.85	0.015
Carbon steel	ASTM A572-50	C 0.155, Al 0.025, Mn 0.65, P 0.020, S 0.010, Si 0.15.								