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Surface Treatment of Marine Underwater Power Unit Anti-Corrosion Research Status and Future Development Trend

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As terrestrial resources dwindle, marine development is becoming increasingly vital for sustainable human progress. Underwater power units, however, face the dual challenges of seawater corrosion and microbial corrosion. Commonly used metals, such as carbon steel, stainless steel, titanium alloy, and aluminum alloy, encounter various forms of corrosion and complex mechanisms in the marine environment. Currently, several anti-corrosion technologies—including coating protection, cathodic protection, material selection optimization, and laser treatment—show promise, yet each has its limitations. In practical applications, shallow sea environments often utilize a combination of coating and cathodic protection, while deep-sea applications tend to favor new materials and advanced surface treatment technologies. Looking ahead, anti-corrosion technology is expected to evolve toward the integration of multiple technologies, smart solutions, and environmentally friendly practices. This paper serves as a reference for future in-depth research aimed at enhancing the anti-corrosion performance of underwater power units.

Keywords: *Surface treatment, Surface microstructure, Corrosion resistance, Microbial corrosion*

1. Introduction

1.1 Background and Significance of the Study

With the gradual scarcity of land resources, the development and utilization of oceans and seas, as a huge treasure trove of resources, is of key strategic significance to the sustainable development of human society. China's vast sea area is rich in resources, and under the promotion of the strategy of ‘Ocean Power’, ocean development activities have been carried out vigorously in a variety of fields, such as marine oil and gas extraction, renewable energy use, fishery, transport and scientific research [1].

As key equipment for marine development, underwater power units are widely used in various fields, including underwater vehicles, marine exploration equipment, operating robots and submarine pipeline cable laying and maintenance and other fields, to provide power support for the development of marine resources and scientific research. For example, they drive pumps and compressors in deep-sea oil and gas extraction and compressors to achieve oil and gas transmission, marine scientific research for unmanned aerial vehicles to complete the monitoring and data collection. However, the marine environment is complex and harsh. Underwater power units operating in this environment for long periods face serious corrosion problems. Seawater contains various salts, dissolved oxygen, and microorganisms, making it a strong electrolyte solution. Corrosion not only leads to metal material loss, performance degradation, reduce structural strength and stability, increase the risk of failure and accidents, but also reduce efficiency and performance, increase energy consumption and operating costs, shorten the service life, increase the frequency of maintenance and replacement, resulting in huge economic losses, the world’s annual loss of hundreds of billions of U.S. dollars due to marine corrosion, the corrosion loss of the underwater power unit accounted for a high proportion [2].

Therefore, to solve the corrosion problem of underwater

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power unit in the marine environment is of great significance to ensure the safety and efficiency of marine development, reduce costs and extend the life of the equipment. Domestic and foreign scientific research and engineering personnel to carry out a lot of research, explore and develop a variety of anti-corrosion technology, and achieved a series of results. However, due to the complexity and diversity of marine corrosion, there are still many problems and challenges to be solved. The purpose of this paper is to comprehensively review the current research status of surface treatment in the corrosion protection of marine underwater power units, analyses the advantages and disadvantages of each anti-corrosion technology and application prospects, and to explore the future development trend, in order to enhance the corrosion protection performance of underwater power units to provide reference.

1.2 Corrosion Pain Points of Underwater Power Units in Marine Environment

Underwater power units face complex problems such as seawater corrosion and microbial corrosion in marine environment, which seriously threaten the operation and life of the equipment. Meanwhile, seawater corrosion is the main form of corrosion, seawater as an electrolyte solution rich in sodium chloride, magnesium chloride and other salts, conductivity and corrosivity. Chloride ions have a small radius and high activity; they can adsorb on the metal oxide film, destroy the film structure, generate chlorine complexes to accelerate metal dissolution. For example, in seawater, chloride ions destroy the rust layer on carbon steel the rust layer into soluble $FeCl_3$. Seawater temperature, salinity, dissolved oxygen content, pH value, and flow rate significantly impact the corrosion rate, as shown in Fig. 1. Elevated temperature accelerates the corrosion reaction; salinity increases to accelerate electrochemical corrosion. Dissolved oxygen to promote metal oxygen corrosion, increased concentration of cathodic reaction to accelerate. Seawater is weakly alkaline, and carbon steel is less affected by pH variations in this environment, which mitigates its corrosion rate; metals such as aluminum and zinc can independently form a dense hydroxide protective film on their own surfaces in weakly alkaline seawater, a corrosion resistance characteristic inherent to these metals. An increase in seawater flow rate accelerates the diffusion of dissolved oxygen and the role of the scouring, more than the critical value of the destruction of the protective film triggered by the corrosion of the scouring [4].

Microbial corrosion is another important issue. Various microorganisms in the ocean, such as sulfate-reducing bacteria, etc., which attach to the metal surface to form a biofilm, changing the chemical and electrochemical environment of the metal surface to trigger corrosion. And microbial corrosion often interacts with seawater corrosion; biofilm impedes the diffusion of oxygen to form an oxygen concentration battery to accelerate local corrosion. Microbial secretion of organic substances and metal ions to form complexes to increase the solubility of the metal. Microbial metabolism to change the electrochemical properties of the metal to affect the rate of corrosion and the mechanism shown in Fig. 2. These corrosion problems bring serious damage and impact, so that the metal wall thickness thinning, strength reduction, threatening the stability of the structure, increase the risk of leakage, rupture, affect the mechanical properties, reduce

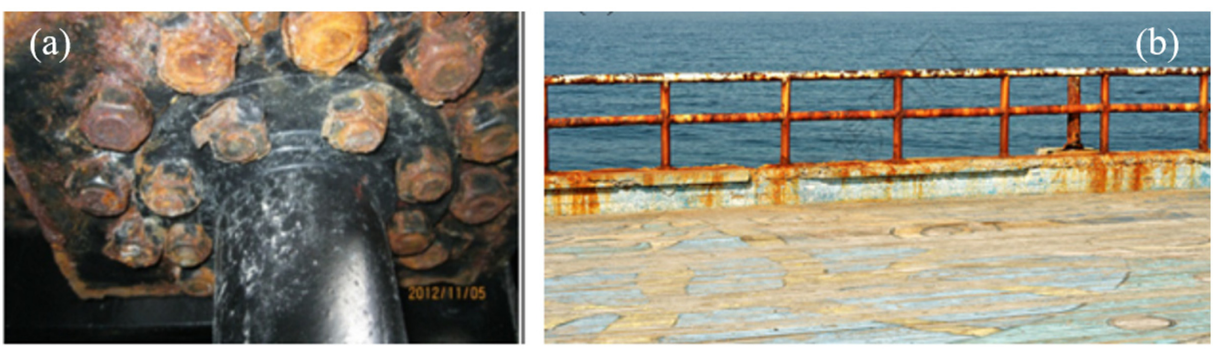

Fig. 1. (a) Corrosion of flange fasteners on a ship; (b) Corrosion of a ship's enclosure

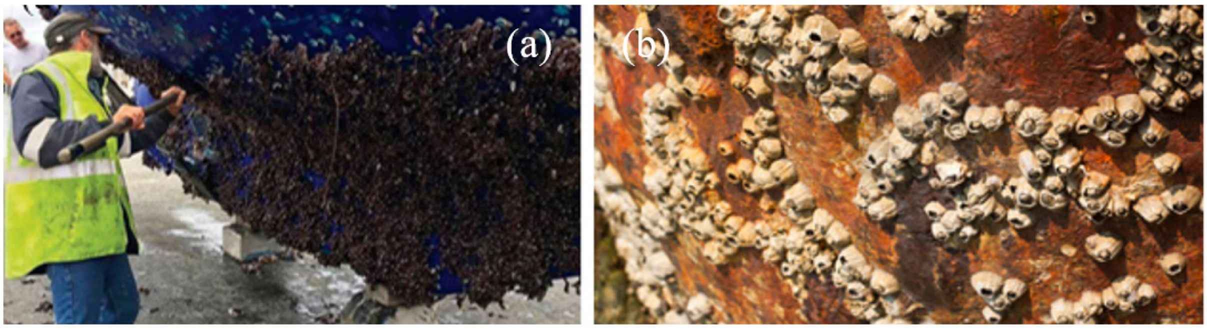

Fig. 2. (a) Microbial corrosion of mussels; (b) Microbial corrosion of barnacles

sealing performance, power transmission efficiency, increase energy consumption, corrosion products accumulate to block the pipeline, valves and other components to affect the operation and frequent corrosion maintenance and equipment replacement to increase the cost of marine development, resulting in production interruptions caused by economic losses. Therefore, to solve the corrosion problem of underwater power unit in the marine environment should not be delayed, need to take effective measures to deal with seawater corrosion and microbial corrosion, to ensure the safe and stable operation of the equipment, reduce economic losses, and promote the smooth progress of marine development.

1.3 Current status of domestic and overseas research

A large number of researches have been carried out at home and abroad on the corrosion protection challenges of underwater power units in complex marine environments, covering a wide range of technical fields.

Coating protection technology is widely used. Organic coatings, such as epoxy resin, form a physical barrier and chemical stability in the metal surface to form a physical barrier, can effectively reduce the corrosion rate of mild steel in the simulated seawater environment. Ceramic coatings, with high hardness, high temperature resistance and chemical inertness, have excellent protective performance in high temperature and high flow rate seawater areas, which can extend the service life of key components of underwater power units. However, the coating is easily affected by seawater washing, microbial adhesion and temperature fluctuation, and is prone to aging and peeling, resulting in protection failure. Cathodic protection technology is based on electrochemical principles. Sacrificial anode cathodic protection method is easy to operate: zinc-based alloys with more negative potentials are connected to the underwater power unit, and the anodes corrode preferentially to protect the substrate. This method is widely used in shallow sea areas and can effectively reduce the corrosion rate, but the anodes are consumed rapidly and need periodic replacement, resulting in high maintenance costs. With the aid of an external power supply, the impressed current cathodic protection method can precisely regulate the cathodic protection potential with a stable protection effect and a wide application range, which is especially suitable for large-scale underwater power systems. However, this method has high requirements for equipment and involves complicated installation and maintenance. Material composition selection and optimization is an important direction. The research and development of new corrosion-resistant alloys is a growing trend, containing molybdenum, copper stainless steel alloy pitting and crevice corrosion resistance [9], new nickel-based alloys by virtue of the special composition and microstructure, corrosion resistance and excellent mechanical properties in the deep-sea extreme environment. Fiber-reinforced polymer matrix composites are lightweight, have high specific strength and good corrosion resistance, can be used to manufacture underwater power unit non-load-bearing but high corrosion resistance requirements of the components, but some of the new materials are costly, limiting the large-scale application. Surface treatment technology continues to innovate. Laser processing technology is developing rapidly, laser strengthening can change the metal surface structure to enhance corrosion resistance, such as laser surface quenching to form a fine crystal reinforced layer, laser cladding corrosion-resistant alloy layer [10], laser descaling without secondary pollution. However, laser equipment is expensive, and the process parameters need to be precisely controlled. Chemical treatment such as phosphating, passivation can form a stable protective film on the metal surface, easy to operate, low cost, applicable to a variety of metals, but the treatment process may produce pollution, the durability of the protective film in the complex marine environment to be improved. Ion etching is an emerging technology, the use of high-energy ion beam sputtering etching of metal surfaces, improve the microstructure and chemical composition, reduce the corrosion initiation sites, such as reducing the tendency of pitting corrosion of aluminum alloys in seawater and intergranular corrosion [11], can also be synergistic with other surface treatment technologies to improve the adhesion of coatings. However, the complexity and high cost of the equipment, the harsh requirements on the operating environment and process parameters, large-scale application faces challenges.

Overall, all types of anticorrosion technologies have effectiveness and limitations, and in the future, it is necessary to explore the synergy of multiple technologies to develop efficient, long-lasting and environmentally friendly anticorrosion solutions to cope with the increasingly stringent anticorrosion requirements of underwater power units.

2. Corrosion Challenges of Metallic Materials Commonly Used in Underwater Power Units in the Marine Environment

2.1 Corrosion challenges of carbon steel in the marine environment

2.1.1 Seawater Corrosion

Carbon steel is one of the commonly used metal materials in underwater power units. However, in the marine environment, carbon steel is highly susceptible to the effects of seawater corrosion [12].

When carbon steel is immersed in seawater, the presence of iron and a small amount of carbon leads to the formation of many tiny primary cells in seawater. Chloride ions in seawater accelerate carbon steel corrosion. Chloride ions have a small radius, high activity, and strong penetration ability, can be adsorbed on the surface of carbon steel oxide film, penetration damage to the membrane structure, and metal to generate soluble chlorine complex, accelerate the dissolution of the metal, so that the oxide film to lose the protective effect as shown in Fig. 3. At the same time, chloride ions enrich at surface defects the formation of local high concentration environment, triggering pitting, pitting pit metal ion hydrolysis to reduce pH value, further accelerate the development of pitting. In addition, various seawater factors significantly affect the corrosion of carbon steel. For example, the temperature rises, promote the corrosion reaction rate accelerated, usually every 10 ºC, the rate of

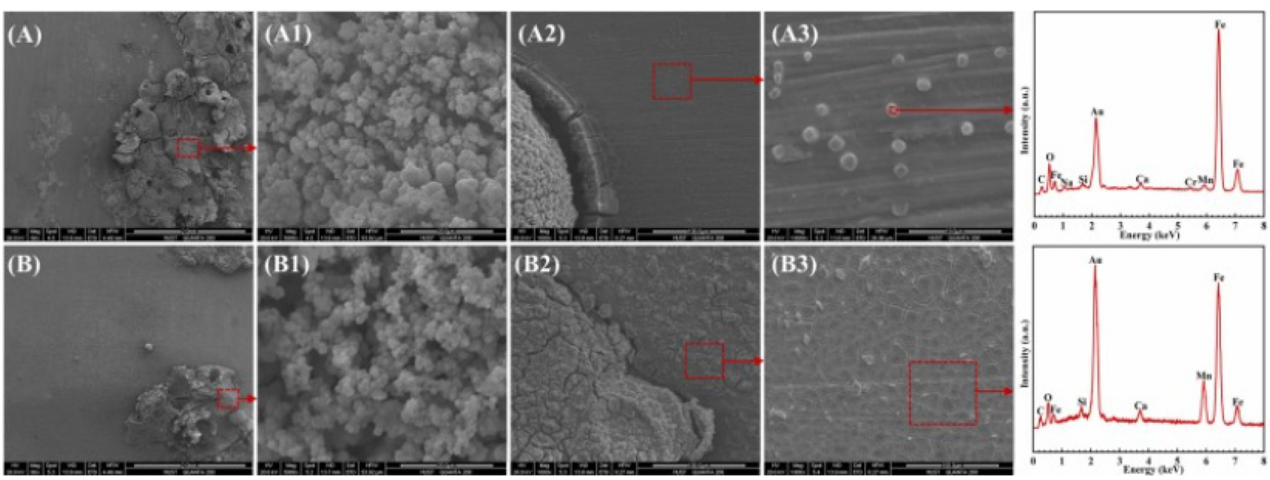

Fig. 3. ESEM images and EDS spectra of 25Mn steel after 14 days of immersion in sterile system (A, A1, A2, A3) and IOB system (B, B1, B2, B3) [18].

about 1-3 times [15]. An increase in salinity within a certain range accelerates electrochemical corrosion. Salinity is too high due to dissolved oxygen to reduce and slow down the corrosion [16]. Sufficient dissolved oxygen promotes oxygen-absorbing corrosion, while very low dissolved oxygen may change the corrosion type. Weakly alkaline seawater environment is conducive to the formation of carbon steel stable iron hydroxide protective film, slowing down corrosion, acidic damage to the protective film to accelerate corrosion. Increase in seawater flow rate so that the diffusion of dissolved oxygen and scouring intensified, more than the critical value of the destruction of the protective film triggered by the scour corrosion [17], mechanical scouring and electrochemical corrosion to promote each other, resulting in a substantial increase in the corrosion rate of carbon steel. These factors interact with each other to determine the degree of corrosion of carbon steel in seawater.

2.1.2 Microbial corrosion

In addition to seawater corrosion, microbial corrosion of carbon steel in the marine environment cannot be ignored. In which the sulfate reducing bacteria (SRB), iron-reducing bacteria (IRB) and iron-oxidizing bacteria (IOB) have a significant impact.

In the marine environment, different microorganisms corrode carbon steel in different ways and have different effects. Sulfate-reducing bacteria (SRB) are anaerobic microorganisms that, under anoxic or micro-oxic conditions, use hydrogen from carbon steel corrosion as an electron donor and react with seawater sulfate to generate hydrogen sulfide (H_2S) via hydrogenase. H_2S then reacts with iron ions to form a large volume of ferrous sulfide precipitate, destroying the protective film and directly corroding the steel shown in Fig. 4. Iron reduction bacteria with iron ions as the electron acceptor from the surface of carbon steel to obtain electrons, so that the carbon steel oxidation corrosion, its metabolic secretion of organic acids to lower the pH value of the surface of low carbon steel, destroy the protective film and accelerate the dissolution of the change in the chemical and electrochemical environment in order to accelerate the corrosion. Iron oxidation bacteria oxidation of ferrous iron ions to obtain energy and the formation of a rust layer on the surface of carbon steel, although it can be slowed down to a certain extent, but the rust layer has defects, and the corrosion of the carbon steel. Corrosion, but the rust layer has defects when the formation of oxygen concentration battery to accelerate local corrosion, and its metabolism affects the carbon steel surface pH value and dissolved oxygen content. Microbes on the surface of carbon steel formed by microorganisms and extracellular polymers composed of biofilm, hindering the diffusion of oxygen to form an oxygen concentration battery, the microbial secretion of organic substances and iron ions to form a complex to increase the solubility of carbon steel, but also to change the roughness of the surface and the distribution of carbon steel charge It also changes the surface roughness and charge distribution of carbon steel, affects the deposition of corrosion products and the formation of protective film, and further aggravates the corrosion of carbon steel.

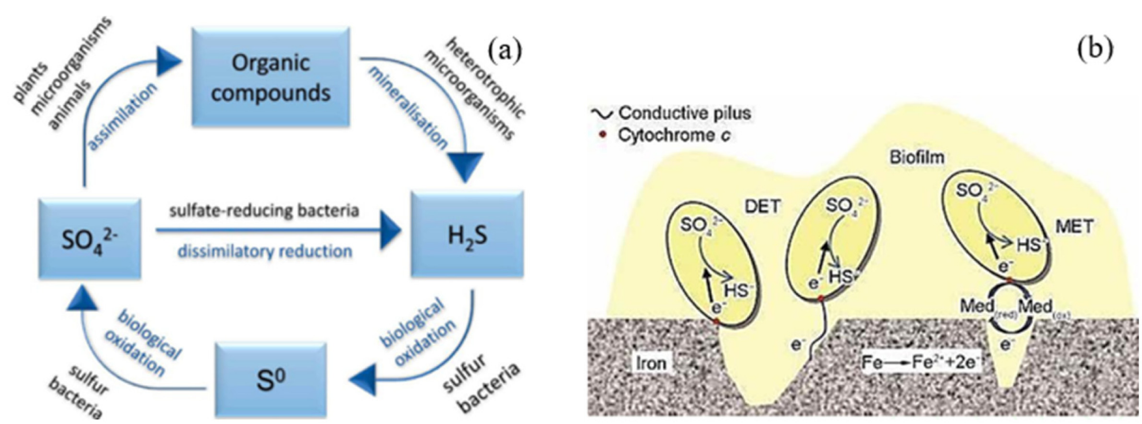

Fig. 4. (a) Schematic diagram of microbial sulphury cycle [19]; (b) Schematic diagram of SRB corrosion [20]

2.2 Corrosion Challenges of Stainless Steel in Marine Environments

2.2.1 Seawater Corrosion

Stainless steel is also widely used in underwater power units due to its good corrosion resistance and mechanical properties. However, in the marine environment, stainless steel also faces the problem of seawater corrosion. The corrosion form of stainless steel in seawater is mainly pitting, crevice corrosion and stress corrosion cracking, etc., of which pitting and crevice corrosion are more common. Pitting is one of the most common forms of local corrosion of stainless steel in seawater, which is closely related to chloride ions in seawater. Chlorine ion radius is small, high activity, can penetrate the passivation film, in the membrane weak or defective adsorption reaction, the formation of soluble metal chloride, damage to the membrane integrity to pitting corrosion occurs as shown in Fig. 5. Crevice corrosion is also a common form of corrosion of stainless steel in seawater. When the stainless-steel components have crevice, seawater dissolved oxygen and corrosion media difficult to enter the crevice, the formation of anoxic environment, inside and outside the formation of oxygen concentration battery, crevice metal anodic oxidation, outside the metal cathodic reduction. Corrosion in progress, the crevice metal ion concentration increases, chloride ions into the combination of the formation of metal chloride, hydrolysis to reduce pH value, accelerate corrosion. Its occurrence and crevice characteristics (the smaller the width, the greater the depth of the more likely to occur, because it is easy to form anoxic and occluded battery) and seawater environment (chloride ion concentration increases, temperature increases significantly accelerate the corrosion rate; seawater flow rate in a certain range will accelerate the increase in the high or scouring corrosion product inhibition) related.

2.2.2 Microbial corrosion

The corrosion of stainless steel by microorganisms is mainly achieved by destroying the passivation film on the surface of stainless steel. The passivation film on the surface of stainless steel is a key factor for its good corrosion resistance; However, the presence of microorganisms can have a destructive effect on the passivation film. SRB is one of the main microorganisms that initiate microbial corrosion of stainless steel. The hydrogen sulfide produced by its metabolism has strong reducing properties, which can react with the metal oxides in the stainless-steel passivation film, such as reducing Cr_2O_3 to $Cr(OH)_3$ in the chromium-containing passivation film, which destroys the structure and integrity of the passivation film. Moreover, the biofilm formed by SRB changes the electrochemical properties of the stainless-steel surface, forming an oxygen concentration battery to accelerate local corrosion, and the organic substances secreted by microorganisms in the biofilm will also complex with the metal ions, increasing the solubility of the metal to promote corrosion as shown in Fig. 6. Iron-reducing bacteria (IRB) also affect stainless steel corrosion. They use iron ions as electron acceptors, in the reduction process from the stainless-steel surface to obtain electrons, so that the stainless-steel oxidation reaction. IRB metabolic

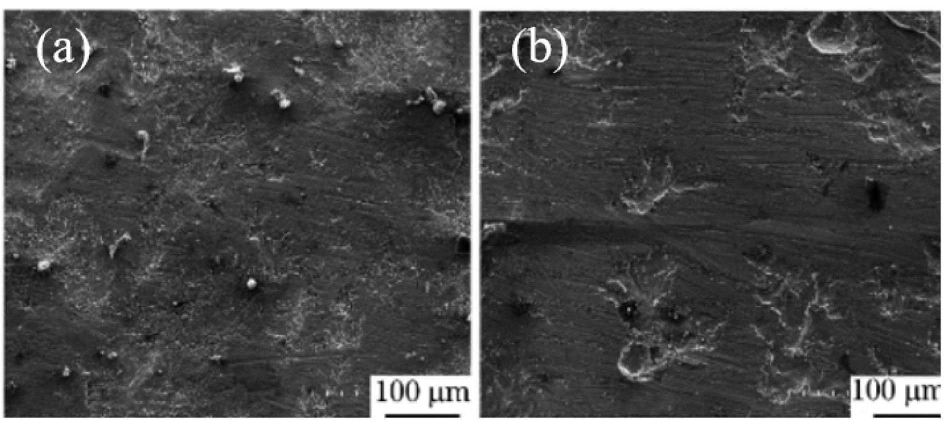

Fig. 5. SEM morphology of the surface of (a) 310S and (b) 800H stainless steels after electrochemical corrosion tests [21].

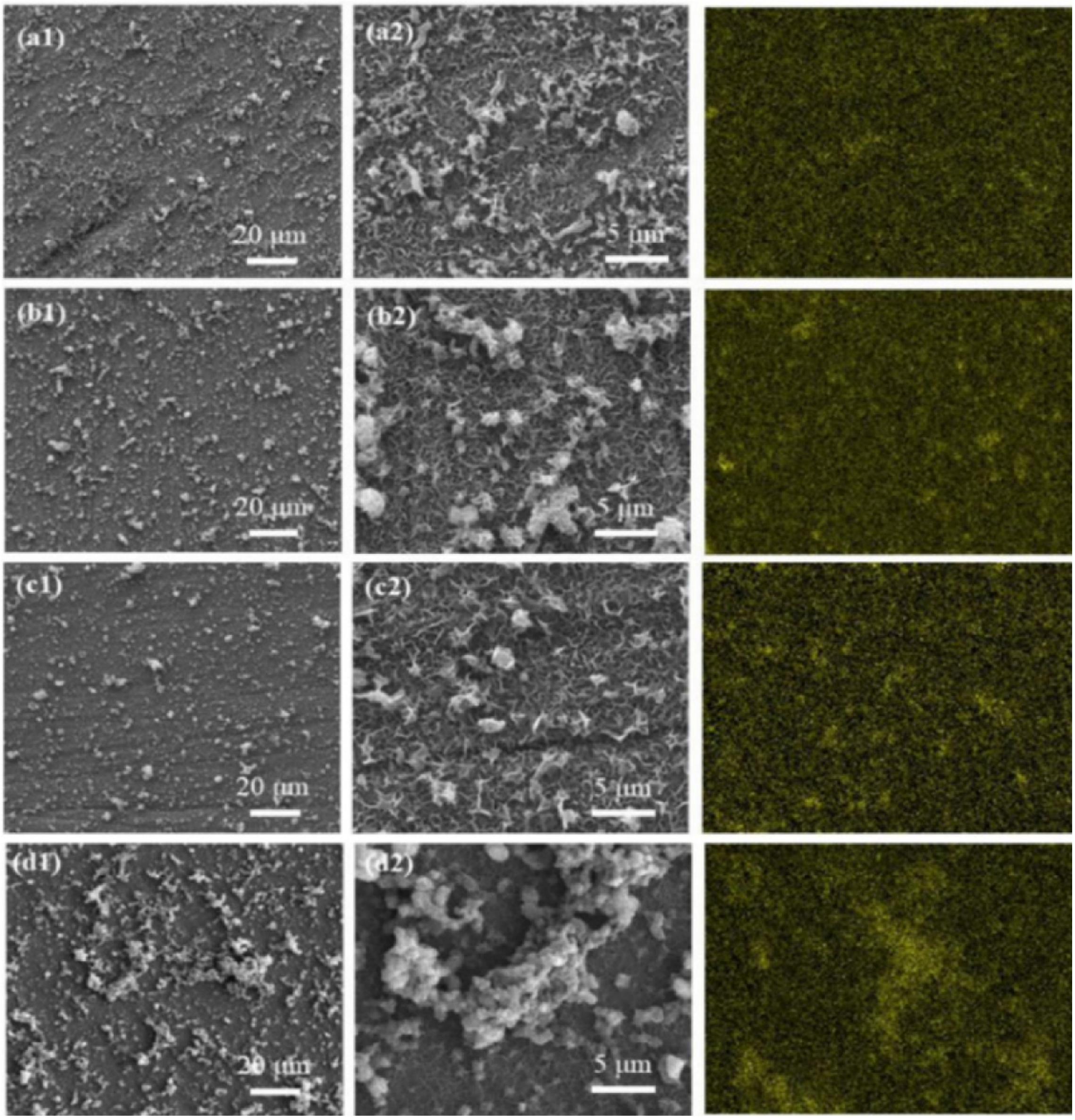

Fig. 6. SEM morphology and Fe surface scan of biofilm and corrosion products obtained from different types of stainless steel cultured in SRB medium for 14 days [22] (a) 2205 SS, (b) 316 L SS, (c) 304 SS, and (d) 410 SS (initial bacterial volume 1.8 × 106 cells/mL, experimental temperature 37°)

activities to change the surface chemical and electrochemical environment of stainless steel, so that its potential changes to accelerate corrosion. For example, its metabolic secretion of organic acids to reduce the pH value of the stainless-steel surface, destroying the passivation film, accelerating the dissolution of stainless steel. Iron oxidizing bacteria (IOB) are involved in microbial corrosion of stainless steel, forming a rust layer on the surface of stainless steel composed of iron hydroxide and iron oxide. The rust layer can block oxygen and other corrosive media to a certain extent, slowing down corrosion, but there are defects in the formation of oxygen concentration battery, accelerating local corrosion. Microbial biofilm formed on the surface of stainless steel is composed of microorganisms and extracellular polymers. Biofilm impede the diffusion of oxygen, the formation of oxygen concentration battery to accelerate local corrosion, microbial secretion of organic substances and metal ion complexation to increase the solubility of the metal, and at the same time to change the surface roughness of stainless steel and charge distribution, affecting the deposition of corrosion products and the formation of a protective film to further exacerbate the corrosion of stainless steel.

2.3 Corrosion Challenges of Titanium Alloys in Marine Environment

2.3.1 Seawater Corrosion

Titanium alloy is widely used in the field of marine engineering to manufacture key components of underwater power units, such as pressure-resistant shells for deep submersibles, joints and transmission parts for underwater robots, because of its advantages of low density, high specific strength and good corrosion resistance. However, even with its outstanding corrosion resistance, it still faces seawater corrosion problems in complex marine environments. In the general seawater environment, the surface of titanium alloy can quickly form a dense, stable and high hardness, high chemical stability and good adhesion TiO_2 oxide film, effectively blocking the corrosion medium, slowing down corrosion. But in the deep-sea special environment, it faces a serious test. The high pressure of the deep sea increases the solubility of gases in seawater, dissolved oxygen and other corrosive media are more likely to come into contact with the surface of titanium alloys, accelerating corrosion. Low temperature reduces the growth of the oxide film and the ability to repair, weakening the role of the protection. High salinity increases the electrical conductivity of seawater, promoting electrochemical corrosion, such as deep-sea simulation experiments, the pressure reaches a certain level, the oxide film of titanium alloys will be ruptured, triggering localized corrosion as shown in Fig. 7a. In addition, special ions or compounds in seawater also affect the corrosion resistance of titanium alloy. High concentrations of fluoride ions will react with the oxide film to generate soluble fluoride, destroying the film structure to accelerate corrosion. Heavy metal ions, organic pollutants, etc., in the industrially polluted sea, will also have a chemical reaction with titanium alloy, reducing its corrosion resistance. Stress on titanium alloy seawater corrosion behavior should not be ignored. Under the action of tensile, bending or alternating stress, the oxide film on the surface of titanium alloys may rupture, allowing corrosive media to intrude into the matrix, triggering stress corrosion cracking (SCC) [23] as shown in Fig. 7b. SCC is often carried out without any obvious premonition, leading to sudden fracture of the material, which is a serious threat to the safe operation of the underwater power unit. The susceptibility of titanium alloys to stress corrosion cracking is closely related to the alloy composition, microstructure, stress level and seawater environment. For example, hydrogen increases the susceptibility because hydrogen atoms accumulate in titanium alloys to form hydrides under stress, resulting in material embrittlement.

2.3.2 Microbial Corrosion

Microorganisms are widely present in the marine environment, and they are able to attach to and from biofilms on the surface of titanium alloys, thus influencing the corrosion behavior of titanium alloys. The process and structure of biofilm formation on the surface of titanium alloys may be different compared to carbon and stainless steels, but the mechanisms of their influence on corrosion are somewhat similar. One of the main microorganisms responsible for microbial corrosion of titanium alloys is the sulphate-reducing bacterium (SRB), which produces hydrogen sulphone (H_2S), during its metabolism, which reacts with the oxide film on the surface of titanium alloys and reduces titanium oxides in the oxide film, thereby destroying the structure and integrity of the oxide film. It was found that in seawater containing SRB, the thickness of the oxide film on the surface of titanium alloys was significantly reduced and the surface roughness increased, which indicated that the oxide film was damaged as shown in Fig. 8. In addition, the biofilm formed by SRB on the surface of titanium alloys can change the electrochemical properties of the metal surface, forming an oxygen concentration cell and accelerating the occurrence of localized corrosion. Moreover, iron-reducing bacteria (IRB) and iron-oxidizing bacteria (IOB) also participate in the microbial corrosion process of titanium alloys, in which IRB obtain electrons from the surface of titanium alloys, leading to oxidation and corrosion of titanium alloys, while the metabolic activities of IRB change the chemical and electrochemical environment on the surface of titanium alloys, which makes the potential of titanium alloys surface change, thus accelerating corrosion. Meanwhile, in this process, IOB will form a layer of rust

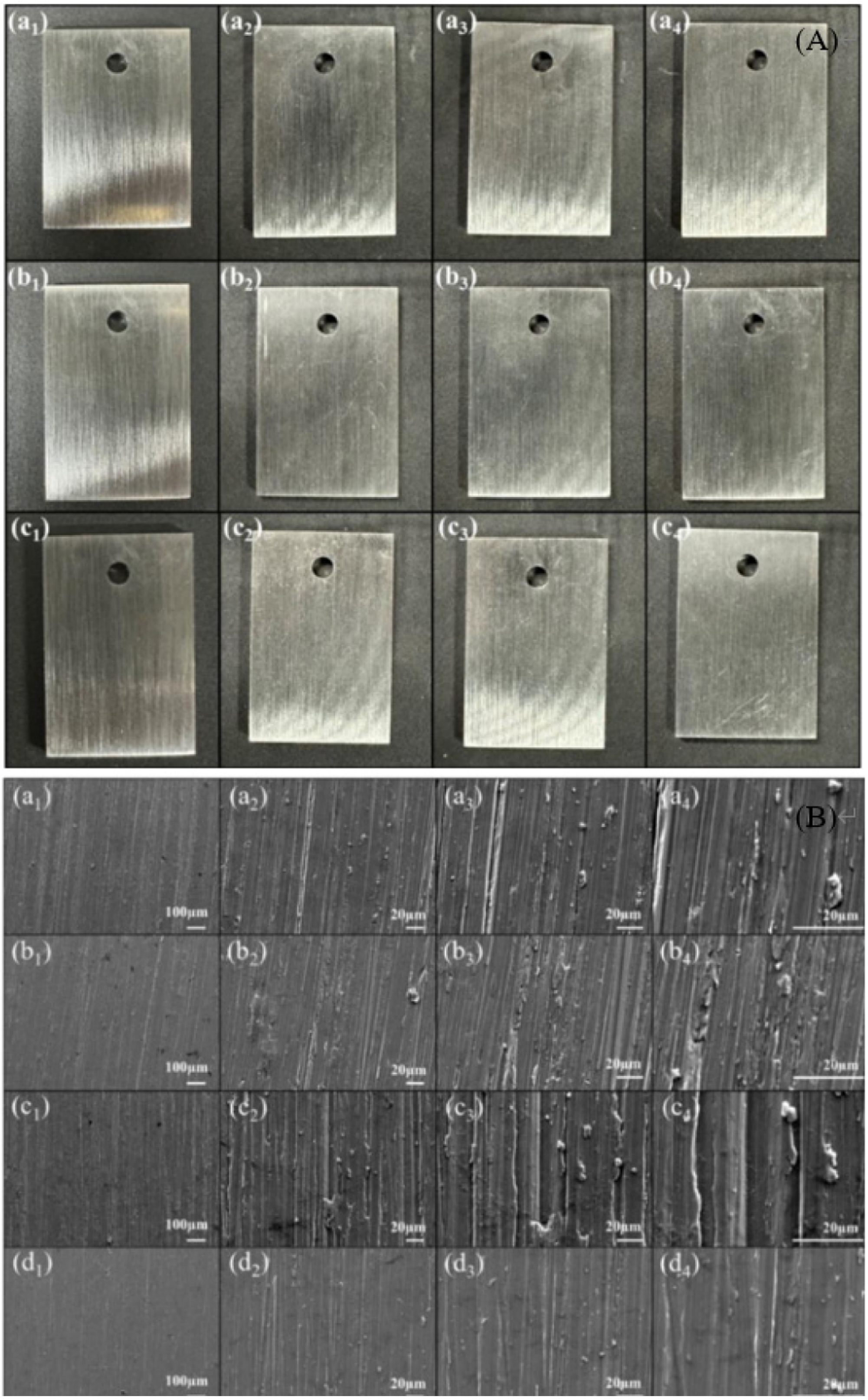

Fig. 7. (A) Macro-photographs of (a1, a2, a3, a4) TA5, (b1, b2, b3, b4) TA24 and (c1, c2, c3, c4) TC4 titanium alloys with different immersion times: (a1, b1, c1) unimmured; (a2, b2, c2) immersed 10d; (a3, b3, c3) immersed 25d; (a4, b4, c4) immersed 35d (B) Surface micromorphology of TA5 titanium alloys: (a1, a2, a3, a4) unsoaked; (b1, b2, b3, b4) soaked for 10d; (c1, c2, c3, c4) soaked for 25 d; (d1, d2, d3, d4) soaked for 35d [24]

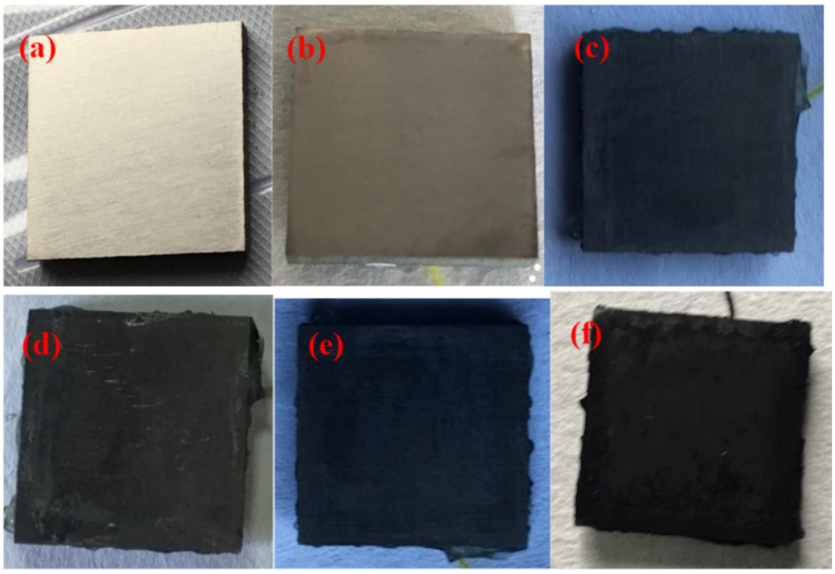

Fig. 8. Macroscopic morphology of Ti-6Al-4V titanium alloy specimens immersed in SRB-containing medium for different days [25]. (a) 0d, (b) 4d, (c) 10d, (d) 17d, (e) 24, (f) 31d

on the surface of titanium alloy composed of iron hydroxide and iron oxide, although the rust layer can prevent the diffusion of oxygen and other corrosive mediums to the surface of titanium alloy to a certain extent, thus slowing down the corrosion, but when there are defects or breakage in the rust layer, it will form an oxygen-concentration battery, accelerating the occurrence of local corrosion. Biofilm formed by microorganisms on the surface of titanium alloy has an important influence on the corrosion process. Biofilm is a complex structure composed of microorganisms and their secreted extracellular polymers (EPS). The presence of biofilm will hinder the diffusion of oxygen to the surface of titanium alloy, leading to the formation of oxygen concentration battery on the surface of titanium alloy, accelerating the occurrence of local corrosion. The microorganisms in the biofilm also secrete some organic substances, which may form complexes with the metal ions on the surface of the titanium alloy, increasing the solubility of the metal and thus promoting corrosion. The presence of biofilm will also change the surface roughness and charge distribution of titanium alloy, affecting the deposition of corrosion products and the formation of protective film, further aggravating the corrosion of titanium alloy.

2.4 Corrosion challenges of aluminum alloys in the marine environment

2.4.1 Microbial corrosion

In the marine environment, in addition to seawater corrosion, microbial corrosion of aluminum alloys is also prominent. Of which sulfate reducing bacteria (SRB), iron-reducing bacteria (IRB) and iron-oxidizing bacteria (IOB) have significant influence. Sulfate-reducing bacteria are anaerobic microorganisms that, under anoxic or micro-oxic conditions, use hydrogenase on the aluminum alloy surface to generate hydrogen sulfide by taking hydrogen generated from corrosion of aluminum alloy as electron donor and reacting with sulfate in seawater. Hydrogen sulfide reacts with aluminum alloy metal ions to form metal sulfides, such as Al_2S_3. Their volume is larger than that of the metal, generating stress on the surface on the surface of the aluminum alloy, resulting in the rupture of the surface protective film, and hydrogen sulfide corrosive, can be directly reacted with the aluminum alloy, so that the aluminum alloy corrosion rate of the seawater containing sulphate-reducing bacteria is several or even tens of times higher than that of the sterile seawater, as shown in Fig. 9. Iron-reducing bacteria take iron ions as the electron acceptor, and obtain electrons from the surface of aluminum alloy in the process of reducing it to ferrous ions, so that the aluminum alloy undergoes

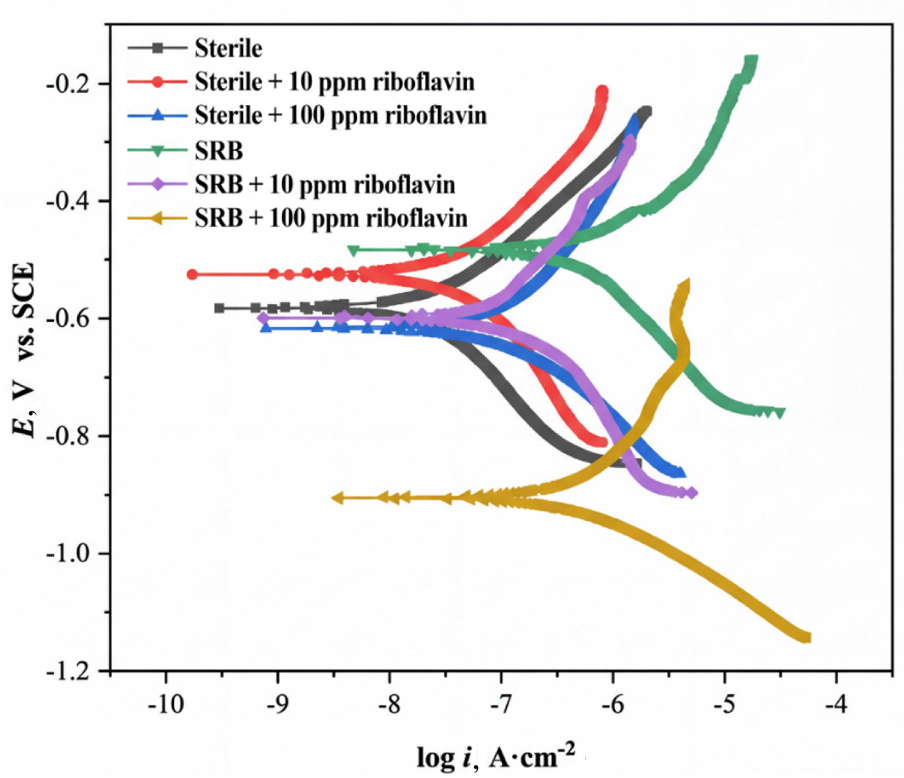

Fig. 9. Polarization curves of 2024 aluminum alloy after 14d immersion in media with different riboflavin concentrations [26].

oxidation reaction and is corroded. Its metabolic activities change the chemical and electrochemical environment on the surface of aluminum alloy, leading to changes in surface potential to accelerate corrosion. For example, the organic acid secreted by metabolism reduces the pH value of aluminum alloy surface, destroys the protective film and accelerates the dissolution of aluminum alloy. Iron oxidizing bacteria ferrous oxide ions obtain energy and form a rust layer on the surface of aluminum alloy composed of iron hydroxide and iron oxide. Although the rust layer can prevent the diffusion of oxygen and other corrosive media to a certain extent and slow down the corrosion, but when there are defects or damage, it will form an oxygen concentration battery and accelerate the local corrosion, and its metabolic activities change the pH value and dissolved oxygen content on the surface of the aluminum alloy and affect the corrosion behavior. In addition, microorganisms form biofilm on the surface of aluminum alloy, and the biofilm hinders the diffusion of oxygen, leading to the formation of oxygen concentration battery on the surface of aluminum alloy and accelerating the local corrosion. Moreover, the organic substances secreted by microorganisms in the biofilm will form a complex with the metal ions on the surface of aluminum alloy, which increases the solubility of aluminum alloy and promotes the corrosion. Lastly, the biofilm also changes the roughness of the surface of aluminum alloy and the distribution of electric charge, which influences the corrosion products deposition and finally, the biofilm also changes the surface roughness and charge distribution of aluminum alloy, which affects the deposition of corrosion products and the formation of protective film, and further aggravates the corrosion of aluminum alloy.

2.4.2 Seawater Corrosion

Aluminum alloys are extensively employed in the fabrication of underwater power units for marine environments owing to their low density, high strength, good electrical and thermal conductivity, corrosion resistance, and ease of processing; however, they encounter severe corrosion challenges in complex marine settings, manifesting in forms such as uniform corrosion, pitting, intergranular corrosion, and stress corrosion cracking [27]. Uniform corrosion results from the

Table 1. Material-wise summary of metallic materials for marine underwater power units

Metallic materials	Dominant corrosion modes	Key driving factors/conditions	Recommended protection strategies
Carbon steel	Uniform corrosion, Pitting, Scour corrosion, Microbial corrosion	Chloride ions, Dissolved oxygen, Seawater flow/temperature/salinity, Microbial biofilm formation	Coating + sacrificial anode cathodic protection; Laser surface strengthening; Low-alloy composition optimization
Stainless steel	Pitting, crevice corrosion, Stress corrosion cracking (SCC), SRB-induced microbial corrosion	Chloride ion passivation film damage, Oxygen concentration cells, Tensile stress, H_2S-induced film degradation	Impressed current cathodic protection; Laser cladding corrosion-resistant alloy layer
Titanium alloys	Localized corrosion (deep sea), SCC, Mild SRB-induced microbial corrosion	Deep-sea high pressure, Fluoride ions, Tensile/bending stress, Oxide film reduction by H_2S	Ion etching/laser alloying surface modification; High-purity alloy optimization; Deep-sea cathodic protection
Aluminum alloys	Pitting, intergranular corrosion, SCC, Severe SRB/IRB/IOB-induced microbial corrosion	Chloride ions, Alloying element segregation, Microbial sulfide production, Tensile stress	Anodic oxidation + organic coating; Zinc-based sacrificial anode; Laser texturing for anti-biofouling

dissolution of the surface oxide film by seawater ions, while pitting is initiated by chloride ions penetrating the film and forming soluble metal chlorides, leading to acidification within pits that accelerates propagation. Intergranular corrosion arises from uneven alloying element distribution, creating galvanic cells at grain boundaries, and stress corrosion cracking occurs under combined tensile stress and corrosive media, where stress-induced cracks in the oxide film are exacerbated by the environment. The underlying mechanism is primarily electrochemical, involving micro-galvanic cells formed by metallic elements in the alloy, with dissolved oxygen participating in cathodic reduction and metal ions combining with hydroxide ions to form corrosion products. Furthermore, seawater parameters-temperature, salinity, dissolved oxygen content, pH, and flow rate-significantly influence corrosion behavior: elevated temperature accelerates reaction rates, salinity within a range promotes electrochemical corrosion while excessive salinity reduces dissolved oxygen, adequate dissolved oxygen facilitates oxygen-absorbing corrosion but extremely low levels may shift toward microbial corrosion, weak alkalinity favors a protective hydroxide film whereas acidity destroys it, and increased flow rate enhances oxygen supply and scouring, potentially exceeding a critical threshold to trigger erosion corrosion, where mechanical and electrochemical actions synergistically amplify the corrosion rate. To facilitate a clear comparison of the corrosion characteristics and protective strategies for the typical metallic materials discussed above, a concise summary is presented in Table 1.

3. Corrosion Mechanisms in the Marine Environment

3.1 Microbial Corrosion Mechanisms

In the marine environment, sulfate-reducing bacteria (SRB), iron-reducing bacteria (IRB) and iron-oxidizing bacteria (IOB) are important species that trigger microbial corrosion of metals, and each of them has a unique corrosion mechanism. SRB, under anaerobic or microaerobic conditions, the metabolic process is divided into three stages: decomposition, electron transfer and oxidation. Organic matter is both its carbon source and energy source, and sulfate acts as the final electron acceptor. Its corrosion of metals is varied. Under cathodic depolarization, SRB reduces sulphate to hydrogen sulphone using hydrogen generated by metal corrosion, consuming cathodic hydrogen, weakening cathodic polarization, accelerating metal corrosion, and significantly increasing metal corrosion current and rate. The metabolically produced hydrogen sulfide has strong reducing properties, and metal reaction to generate metal sulfide, such as carbon steel and hydrogen sulfide reaction to generate ferrous sulfide, metal sulfide volume, destroy the protective film on the surface of the metal, and hydrogen sulfide will also react with other corrosion products to affect the corrosion process. In addition, the biofilm formed by SRB on the metal surface changes the electrochemical properties of the metal surface, impedes the diffusion of oxygen to form an oxygen-concentration battery, and the organic substances secreted by microorganisms increase the solubility of the metal, change the roughness of the metal surface and the distribution of charge, and exacerbate the corrosion of the metal. Meanwhile IRB can use iron ions as electron acceptor and reduce them to ferrous ions and adsorbs on the metal surface and obtains electrons from the metal to make it oxidize and corrode. Organic acid secreted by IRB metabolism reduces the pH value of the metal surface, speeds up the dissolution of the metal and destroys the protective film, e.g., when it grows on the surface of carbon steel, it makes the iron rust layer dissolve and accelerates the corrosion of carbon steel. At the same time, the reduction of iron ions by IRB changes the potential distribution of the metal surface, forming microcells, accelerating local corrosion, making the metal surface more prone to pitting pits. The growth of IRB on the metal surface also affects the structure and composition of the biofilm, and synergistic effects with other microorganisms, such as the existence of SRBs, to promote the corrosion of metals, so that the corrosion process is more complex and accelerated rate. IOB are autotrophic microorganisms that use oxygen as the final electron acceptor, carbon dioxide as a carbon source, through the oxidation of ferrous ions to obtain the energy of autotrophic microorganisms, its biological enzyme catalyzed ferrous ion oxidation rate far exceeds the rate of chemical oxidation. IOB oxidize ferrous ions from metal corrosion to ferric ions, and then the formation of ferric hydroxide precipitation on the surface of the metal to accumulate into a loose layer of rust, the layer of rust to a certain degree can stop the corrosive medium diffusion, but there are IOB metabolism changes the metal surface pH value and dissolved oxygen content, ferrous oxide ions consume hydrogen ions to raise pH value, pH value changes affect the metal surface reaction and corrosion product properties, too high when the passivation film may be damaged to accelerate the corrosion of the growth of metabolic consumption of dissolved oxygen, so that the type of corrosion of metals may change. In the actual marine environment, IOB and SRB, IRB and other microorganisms co-exist in the biofilm, and interact with each other to affect metal corrosion. For example, IOB and SRB form a mixed biosphere, and IOB consume oxygen to create an anaerobic environment to promote SRB growth and exacerbate the corrosive effect of SRB. IOB and IRB interact with each other in a complex way, which affects the distribution of potential and chemical environment on the metal surface, and alters the corrosive behavior of the metal. In conclusion, these three microorganisms have complex and significant effects on metal corrosion in the marine environment through their respective corrosion mechanisms and their interactions with each other.

3.2 Seawater corrosion mechanism

Seawater is a strong electrolyte solution containing a variety of salts, the main components are sodium chloride, magnesium chloride, sodium sulfate, etc., the salts are almost completely ionized so that its conductivity is good, when the metal material is immersed in which electrochemical corrosion will occur. Electrochemical corrosion involves electrochemical reactions between the metal and the seawater electrolyte, metal as the anode electron loss oxidation, seawater dissolved oxygen and other cathodic electron reduction. Carbon steel, for example, the anodic reaction is the iron loss of electrons to generate ferrous ions, the cathodic reaction is the dissolved oxygen to get electrons to generate hydroxide ions, followed by ferrous ions and hydroxide ions combined to generate ferrous hydroxide, and its instability and then oxidized to ferric hydroxide, the decomposition of ferric hydroxide to form iron rust. In actual seawater corrosion, the metal surface to form a multitude of tiny primary cells, due to the potential difference between different regions to produce local current corrosion, and the uneven distribution of dissolved oxygen in seawater to form an oxygen concentration battery, such as metal crevices, small holes in the oxygen concentration is low for the anode, around the oxygen concentration for the cathode, accelerating the corrosion of the anode metal.

Seawater corrosion is affected by a variety of factors; The process is complex. Salinity, generally increased salinity, ion concentration and conductivity rise, local corrosion current increases, such as sodium chloride concentration increases chloride ions destroy the metal oxide film, but the salinity is too high when the dissolved oxygen to reduce inhibition of oxygen-absorbing corrosion, slowing down the corrosion rate. Temperature effect has two sides, the temperature increases the material diffusion coefficient increases, the electrode reaction over-potential and solution viscosity decreases, the reactant activity and diffusion rate increases, the reaction activation energy decreases, the corrosion rate is usually every 10 °C about 1 -3 times, but the temperature increases and makes the concentration of dissolved oxygen decreases in the sea water circulating cooling system, the oxygen diffusion dominates in low temperatures, the corrosion rate accelerates with the temperature rises, 77 °C. In seawater circulating cooling systems, oxygen diffusion dominates at low temperatures and the corrosion rate accelerates with increasing temperature, while at 77 °C, oxygen solubility decreases and corrosion rate decreases with increasing temperature. Dissolved oxygen content is critical, for not passivated metal such as carbon steel, oxygen content increases to accelerate cathodic depolarization, corrosion rate and oxygen concentration is proportional. For the passivation film corrosion resistant metals such as aluminum and stainless steel, the oxygen content increases to facilitate the formation of passivation film and repair, reduce pitting and crevice corrosion tendency, and oxygen concentration of oxygen concentration of different corrosion batteries will form the oxygen concentration of oxygen concentration of the area of low accelerated corrosion. Seawater flow rate on different metal corrosion rate impact is different, for the metal cannot be passivated, such as carbon steel, the flow rate increase to accelerate the diffusion of dissolved oxygen, scouring effect intensified, supercritical value of the destruction of the protective film triggered by scouring corrosion, mechanical and electrochemical corrosion to promote each other. For the passivation of the metal such as stainless steel, a certain range of flow rate to promote the passivation of improved corrosion resistance, plus the corrosion inhibitor of the circulating cooled seawater, certain the circulating cooled seawater with corrosion inhibitor, a certain flow rate is conducive to dissolved oxygen supplementation and corrosion inhibitor diffusion, but the supercritical value of shock corrosion aggravation. In addition, seawater microorganisms such as sulfate-reducing bacteria attached to form a biofilm to change the metal surface environment to accelerate corrosion. Seawater acidity and alkalinity have a significant impact on the formation of hydroxide protective film to slow down the corrosion of some metals, the pH value of acidic when the protective film is destroyed to accelerate corrosion; high pressure of the deep sea so that the gas in the seawater to increase the solubility of dissolved oxygen and other corrosive media are more likely to come into contact with the metal and accelerate corrosion. In short, the salinity of seawater, temperature, dissolved oxygen content, flow rate, as well as microorganisms, acidity and alkalinity and pressure and other factors interact to jointly affect the metal corrosion process in seawater, so that seawater corrosion presents complex and diverse characteristics. Fourth, the underwater power unit of the anti-corrosion treatment technology.

4. Multi-dimensional Corrosion Protection Technology for Underwater Power Units

4.1 Laser treatment technology

As an advanced means of material surface modification, laser treatment technology realizes the precise regulation of metal surface properties through the interaction of high-energy laser beams and materials, which mainly includes two major fields: laser strengthening technology and laser descaling technology. In laser strengthening technology, laser surface quenching, laser cladding and laser alloying are the three core processes. Laser surface quenching uses a laser beam to rapidly heat the metal surface above the phase transition point (heating rate up to 10^5-10^9 °C/s), followed by self-cooling quenching to form a fine and uniform martensitic organization, which significantly improves the hardness, wear and corrosion resistance of the material. For example, the surface hardness of carbon steel can be increased by 2-3 times after treatment, which effectively extends the service life of vulnerable parts such as shafts and gears in underwater power units. Laser cladding involves pre-placing cladding material on the metal substrate, through laser melting to form a high-performance coating metallurgically bonded to the substrate, the composition of the cladding layer can be designed according to the needs of the combination of high strength, low dilution rate, suitable for the repair and strengthening of complex shapes of parts. For example, the alloy powder containing chromium and nickel is melted and coated on the surface of titanium alloy, which can enhance its corrosion and wear resistance [32]. Laser alloying involves adding alloying elements to the metal surface and laser melting to make it uniformly integrated into the matrix [33], thus changing the surface chemical composition and structure, such as aluminum alloy with zinc, magnesium added to the strength and corrosion resistance significantly improved, especially for the surface modification of metal materials in the marine environment. Laser strengthening technology has significant advantages: first, the processing efficiency is very high, the laser beam energy concentration, can be completed in milliseconds within the time of heating and cooling, significantly shorten the process cycle. Second, the surface quality is excellent, rapid heating and cooling to avoid oxidation, decarburization and deformation of the traditional heat treatment, the formation of the strengthened layer of clean and fine tissue; third, process flexibility, can be achieved through the precise control of the laser parameters Thirdly, the process is flexible and can be achieved through precise control of laser parameters to achieve local strengthening of complex components to meet diversified engineering needs. However, the technology also has limitations: the high cost of laser equipment, the initial investment is large, and the operator's professional skills require high, strict control of the parameters to avoid damage to the equipment or poor processing results; in addition, the high temperature, high pressure and glare generated during laser processing need to be supported by perfect safety measures.

Laser descaling technology is based on the photothermal effect and shock wave effect, the use of high-energy laser beam irradiation of the rust layer, so that it absorbs energy after rapid heating, gasification or stripping, so as to achieve efficient descaling. In the field of anticorrosion of underwater power units, laser descaling has been applied to the surface treatment of underwater pipelines, marine platforms and other metal structures to provide a clean interface for subsequent anticorrosion coatings and extend the service life of the structures. Compared with traditional chemical or mechanical descaling, laser descaling has the advantages of non-pollution, no damage to the substrate, high efficiency, etc.: the process does not require chemical reagents, avoiding environmental pollution. By controlling the laser parameters, it can reduce the thermal impact on the substrate at the same time as removing the rust layer. The laser beam energy is concentrated, so that it can quickly remove large areas of the rust layer and improve the operational efficiency. However, laser descaling also faces challenges: the high cost of equipment limits its application in projects with limited budgets. There are certain requirements for the thickness and type of the rust layer, and thicker layers need to be processed several times and different layers need to be matched with the corresponding laser parameters. In addition, the glare, high temperature and dust generated during the operation need to be safeguarded through protective measures to ensure personnel safety.

4.2 Coating protection technology

Coating protection is a commonly used anti-corrosion method for underwater power units. The principle is to apply corrosion-resistant coating on the metal surface to isolate the metal from the corrosive medium, and the common coating materials are epoxy resin, polyurethane, organosilicon and so on. Epoxy resin coating adhesion is excellent, the molecular epoxy group can react with metal oxides to form chemical bonds, chemical corrosion resistance, good mechanical properties, seawater, salt spray, acid and alkali resistance, in the marine environment can form a dense film to slow down the corrosion [35], there is also a good abrasion resistance and impact resistance, resistance to mechanical damage, but poor weathering, long-term ultraviolet and high temperature is easy to aging, cracking, reducing the anticorrosive properties. Polyurethane coating flexibility, abrasion resistance, water resistance, good, molecular urethane bond gives its flexibility and elasticity, can adapt to the metal deformation, seawater, moisture resistance, commonly used in the need for frequent movement or friction parts of the surface, such as the shell of the underwater vehicle, etc., but also resistant to oil, solvent resistance, but chemical resistance is weak, in the strong acidic and alkaline environment performance is affected. Silicone coating weathering, high temperature resistance, excellent hydrophobicity, silicone-oxygen bonding high bonding energy so that its stability and weathering is good, can maintain performance in harsh environments, the surface can be low hydrophobicity, can prevent seawater adhesion infiltration, there are also good insulating and anti-fouling to prevent the adhesion of marine organisms and the accumulation of dirt [36], but the adhesion is weak, the need for special treatment to enhance the bonding force with the metal.

In the underwater environment, the coating application effect is affected by the thickness, uniformity, construction technology and other factors. Thickness should be selected reasonably according to the environment and requirements, the thicker the better the corrosion protection, but the cost and difficulty increase; uniformity is related to local corrosion. Construction technology affects the adhesion and corrosion protection effect [37]. Therefore, the choice of coating protection should be considered comprehensively, select the appropriate materials and processes to protect the anti-corrosion effect.

4.3 Cathodic protection technology

Cathodic protection technology applies a cathodic current to the protected metal to make its potential shift negatively, in order to slow down or prevent the corrosion of the metal, there are mainly sacrificial anode method and applied current method. The sacrificial anode method uses a metal or alloy with a more negative potential (such as zinc-based, aluminum-based, magnesium-based alloys) as the anode and the protected metal connected to a corrosion battery, the anode oxidation corrosion, cathodic polarization of the protected metal to be protected. Zinc-based alloy anode potential stability, high current efficiency, long life, suitable for seawater, freshwater protection of iron and steel. Aluminum-based alloy anode density is small, negative potential, large capacity, used in marine engineering anticorrosion. Magnesium-based alloy anode potential is the most negative, driving voltage is high, suitable for soil, freshwater and other high resistivity environment. This method does not need external power supply, simple installation and maintenance, low cost, but the output current is limited, the protection range is small and the anode needs to be replaced periodically. The external current method is through the external DC power supply, the protected metal with negative electrode as cathode, auxiliary anode (such as graphite, high silica cast iron, platinum plated titanium) with positive electrode as anode, the current to make the protected metal cathodic polarization anticorrosion [38]. Graphite anode conductivity, high chemical stability, low price but low mechanical strength; high silicon cast iron anode corrosion resistance and conductivity, suitable for a variety of environments, but brittle texture, processing and installation is difficult; platinum-plated titanium anode catalytic activity, conductivity and corrosion resistance, long service life, but high cost. This method of protection current can be adjusted, the range of large, suitable for large underwater power unit or complex structure, but need external power supply, equipment complexity, high investment and operating costs and the need for professional maintenance.

Cathodic protection technology is widely used in the anticorrosion of underwater power unit. The actual application needs to choose the method according to the situation, small or protection requirements are not high choose sacrificial anode method, large and important choose applied current method. And often used in conjunction with the coating protection technology, coating corrosion current reduction, lower cathodic protection current demand, cathodic protection to make up for the coating defects, the two together to enhance the effect of anticorrosion.

4.4 Material composition selection and optimization

Selection of corrosion-resistant materials is a key measure to address corrosion problems in underwater power units. It must consider the corrosion resistance, mechanical properties, processing performance and cost of the material and other elements, and the material should have good resistance to seawater and microbial corrosion. Carbon steel can be alloyed to enhance corrosion resistance, adding chromium, nickel, molybdenum and other elements can form a dense oxide film, low-alloy high-strength steel to add niobium, vanadium, titanium and other elements, both to enhance the strength and improve corrosion resistance, but also through the control of chemical composition and heat treatment to optimize the organizational structure. Stainless steel corrosion resistance depends on the chromium content, chromium to form a protective film to prevent the invasion of corrosive media, increase the chromium content and the addition of nickel, molybdenum and other elements can improve corrosion resistance, different types of stainless steel for different marine environments. Titanium alloy corrosion resistance is excellent, can form a stable oxide

Table 2. Technology-wise summary of anti-corrosion approaches for marine underwater power units

Anti-corrosion approaches	Typical application scenarios	Main advantages	Main limitations	Practical considerations
Coating protection	Shallow sea; Deep sea	Wide applicability, Physical isolation of corrosive media	Prone to peeling, Poor deep-sea scouring resistance	Match coating type to marine environment; Pre-treat metal surface for enhanced adhesion
Cathodic protection Sacrificial anode Impressed current	Shallow sea: Small/mid-sized units; Deep Sea: complex units	Stable protection effect, Synergistic with coatings; No external power; Adjustable current	Sacrificial anode: Frequent anode replacement Impressed current: High equipment cost, Complex maintenance	Seawater-only use Zn/Al-based anodes Precise potential regulation for impressed current
Laser treatment technology	Shallow sea: Component repair/ descaling Deep sea: Key component surface strengthening	Enhanced surface corrosion/ wear resistance; Clean coating interface	High equipment/ operation cost, Strict process parameter control	Local strengthening for key components; Match laser parameters to metal material properties
Material composition optimization	Shallow sea; Deep sea	Fundamentally improves corrosion resistance, Synergistic mechanical performance	High R&D/manufacturing cost, Limited large-scale application	Balance corrosion resistance, Mechanical properties and cost; Combine with surface treatment for synergy

film, its corrosion resistance and alloy composition, microstructure related, optimize the composition and process or surface treatment can be further enhanced. Aluminum alloy corrosion resistance is relatively poor, through the alloying of zinc, magnesium, copper and other elements, as well as the use of anodic oxidation and other surface treatment technology can enhance corrosion resistance. New corrosion-resistant alloys continue to emerge, nickel-based alloys containing a large amount of nickel, can form a stable passivation film, resistance to high temperature, high pressure and strong corrosion. Copper-nickel alloys are resistant to seawater corrosion, good resistance to cavitation and scouring corrosion performance.

Composite materials such as fiber-reinforced composites have promising applications, glass fiber-reinforced composites are resistant to seawater corrosion and low cost, and carbon fiber-reinforced composites have high strength and modulus. However, problems such as interfacial properties and long-term stability of composites are yet to be solved by in-depth research. A comparative summary of the major anti-corrosion technologies for marine underwater power units, including their application scenarios, advantages, limitations and practical considerations, is provided in Table 2 for quick reference.

5. Future Prospects

5.1 Summary of current treatment technologies

This paper provides an in-depth analysis of the microbial corrosion and seawater corrosion challenges faced by commonly used metal materials for underwater power units, such as carbon steel, stainless steel, titanium alloy, and aluminum alloy in marine environments, and describes in detail the microbial corrosion mechanisms such as SRB, IRB, and IOB and seawater corrosion mechanisms, and comprehensively introduces a variety of anticorrosion technologies, including laser treatment technologies, and their advantages and disadvantages. The study shows that different materials have different corrosion behaviors in the marine environment, and a single anti-corrosion technology has limitations, so it is necessary to comprehensively use multiple technologies to improve the corrosion resistance of underwater power units.

From practical application cases, in shallow sea areas, the combination of coating protection and cathodic protection is more widely used, can effectively deal with the relatively stable seawater environment. In the deep sea, hydrothermal areas and other extreme environments, the synergistic application of new corrosion-resistant materials and advanced surface treatment technology has become a trend. With the development of science and technology, intelligent anti-corrosion technology has emerged, through the sensor real-time monitoring of corrosion, automatically adjust the protection strategy. In the future, anti-corrosion technology will move towards the integration of multi-technology, intelligent, green direction to adapt to the increasingly complex needs of marine development.

5.2 Research Shortcomings and Prospects

The current research is not perfect in the simulation of complex marine environment with multi-factor coupling, and the research on the long-term stability and reliability of new anti-corrosion technology is still insufficient. Future research should focus on strengthening the in-depth investigation of the corrosion mechanism in extreme marine environments, increasing the investment in the research and development of new anticorrosion technologies, especially the development of intelligent and green technologies, to further promote the innovation and development of the anticorrosion technology of the underwater power unit, and to provide a solid guarantee for the cause of global marine development.

Data Availability Statement

No data, models, or code were generated or used during the study.

Conflict of interest

The authors declare that they have no conflict of interest.

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