A new kind of Al photoanode composite based on photocatalytic material and sacrificial anode was proposed and designed to provide new ideas for cathodic protection in marine environment. Fabricated with the traditional Al-Zn-In-Mg-Ti sacrificial anode and Co(OH)$_2$ modified anatase TiO$_2$ nanotubes, a new Al photoanode composite with good photoelectrochemical cathodic protection property was compared with the traditional sacrificial anode, the cathodic protective properties of both the sacrificial anode and Al photoanode composite were evaluated by electrochemical measurements in aqueous 3.5 wt.% NaCl solution. By means of scanning electron microscopy (SEM), X-ray diffraction (XRD), X-ray photoelectron spectroscopy (XPS) and UV-Vis spectrophotometer morphologies, crystal structures, surface compositions and light response range of the photoanode composite during the immersion were characterized, respectively. The generated protective current density of the Al photoanode composite is found to be greater under illumination than that of the traditional Al-Zn-In-Mg-Ti sacrificial anode. Co(OH)$_2$@TiO$_2$ plays an important role in supplemental protection for Q235 carbon steel and improves the current efficiency.

In marine environmental protection, as a traditional method of corrosion protection, sacrificial anode protection is simple to set up, low-cost, and with great protective current; however, it is still faced with the problems of fast anode consumption, short life, low current efficiency and rapid failure. In the 1990s, with the development of research on photocatalytic materials, the photoelectrochemical cathodic protection technology has become a focus of great attention. Tsujikawa and Yuan first reported the effective electrochemical behavior of TiO$_2$ photocatalytic material in carbon steel protection. The TiO$_2$ material acts as a sacrificial anode in cathodic protection by providing electrons. In addition, photocatalytic materials are non-sacrificial and environmentally friendly when protecting metal. Ideally, they have infinite life and can be recycled for a long time.

Despite the progress in corrosion protection, the shortcomings of single photocatalytic materials, such as insufficient protective potential, high recombination rate of photogenerated electron-hole pairs and unclear long-term behavior, still have not been well resolved. Some studies on the addition of hole-scavenger-containing solutions show a good protective performance of the photocatalytic material, but it is difficult to obtain ideal protective potential in marine environment without the additional solutions. Therefore, most photocatalytic materials cannot be applied to protect metals in a single photocatalytic material. We put forward the way to protect the metal by the photoanode composite that fabricated by two materials. The protective potential and current of single photocatalytic material are still difficult to compete with that of the traditional sacrificial anode. The traditional sacrificial anode also has the drawback of short life. Therefore, a promising and powerful combination with the advantages of these two materials is hoped to realize a better protection capability, i.e., the advantages of high current efficiency of the traditional sacrificial anode and non-loss of photocatalytic materials are expected to be combined in a new type of photoanode composite with high current efficiency and long life.

In this work, a new type of photoanode composite material was designed. The material combines the advantages of cost effective and efficient traditional sacrificial anode with non-sacrificial new photocatalytic material. We put forward the way to protect the metal by the photoanode composite that fabricated by two materials. The electrochemical performance of the new material was measured subsequently.

The stable and widely studied TiO$_2$ was selected as photocatalytic material, and the surface modification by Co(OH)$_2$ was carried out to promote the generation and utilization of TiO$_2$ photogenerated electrons. The sacrificial anode was Al-Zn-In-Mg-Ti alloy, which is significantly effective and widely applied in marine environment. A layer of Ti film was covered on the surface of Al-Zn-In-Mg-Ti sacrificial anode by magnetron sputtering. Subsequently an anatase TiO$_2$ nanotube-array film photocatalyst was formed on the surface of Ti layer of the sample through anodic oxidation. Co(OH)$_2$ particles were modified on the TiO$_2$ film by deposition processes. By this way the new Al photoanode composite material was obtained. For Q235 carbon steel protection, electrochemical measurements were used to evaluate the cathodic properties of this Al photoanode composite, compared with that of the traditional sacrificial anode, in aqueous 3.5 wt.% NaCl solution. Meanwhile, to explain the electrochemical cathodic protection mechanism of this new Al photoanode composite material, the changes of morphologies, crystal structures, surface compositions, and light response range of Al photoanode composite during the immersion were characterized, respectively. The composite...
of photocatalyst and the traditional sacrificial anode might provide a new idea for corrosion protection of metals.

**Experimental**

**Specimen preparation.**—As shown in Fig. 1, based on the above design, material preparation process is as follows. After grinding the Al-Zn-In-Mg-Ti sacrificial anode (hereinafter referred to as Al anode) matrix material, a layer of Ti film was prepared by magnetron sputtering on one side of the matrix as the first step. Secondly, a compact and uniform layer of anatase TiO$_2$ nanotube-array film was formed on the surface of Ti layer of the sample through anodic oxidation. Finally, Co(OH)$_2$ nanoparticles were deposited on the as-prepared sample by ionic layer adsorption and reaction method. The sample was immersed in the following solutions in sequence: an aqueous solution of Co(CH$_3$COO)$_2$, deionized water, an aqueous solution of NaOH and deionized water, until the desired amount of Co(OH)$_2$ nanoparticles was deposited successfully. In this way the Co(OH)$_2$ surface modification of TiO$_2$ nanotubes on Al anode material was obtained (hereinafter referred to as Al photoanode composite).

**Preparation of Al photoanode composite electrode, Al anode electrode and Q235 steel electrode.**—Three kinds of electrodes were prepared: Al photoanode composite, Al anode and Q235 carbon steel electrodes. The Al photoanode composite sample was fastened to the copper wire. To ensure that the both surface sides of computable area were exposed to corrosive solution, only edges of the sample were covered with resin-paraffin mixture (1:1). The Al anode and Q235 carbon steel electrodes were prepared in the same size. Edges and back side were all covered to expose only the front surface. The test electrolyte was a 3.5wt% NaCl solution to simulate seawater environment.

**Characterization of Al photoanode composite.**—Surface macro-morphologies of Al photoanode composite before and after the exposure in 3.5wt% NaCl solution were examined. The surface and cross section micromorphologies were also observed during immersion by scanning electron microscopy (SEM, INSPECT F50, FEI, USA). The crystalline structures of the samples were identified by X’pert X-ray diffractometer (XRD, X’pert PRO, Panalytical, Netherlands) using Cu Kα radiation at 40 kV, with 2θ ranging from 10° to 90°. The changes of surface elemental compositions were analyzed through X-ray photoelectron spectroscopy (XPS, ESCALAB250, Thermo VG, USA) with Al Kα radiation and 0.1 eV energy step size. The spectrum decomposition was performed using the XPS PEAK 41 software with Lorentzian-Gaussian functions after subtraction of a Shirley background. The Ultraviolet-visible spectra of the films on Al photoanode composite were collected using a diffuse reflectance UV-vis spectrophotometer (V-770, JASCO, Japan) in the wavelength range 200–900 nm.

**Photoelectrochemical characterization.**—To study the role of Co(OH)$_2$@TiO$_2$ in Al photoanode composite when protecting Q235 carbon steel, three groups of comparative experiments were conducted: (1) photoelectrochemical protection experiment of Q235 by Al photoanode composite, (2) electrochemical protection experiment of Q235 by Al anode, and (3) corrosion experiment of Q235. Because the protection performances for Q235 without and with illumination are different, the first two groups of experiments were performed with and without illumination, respectively. Experiment (3) provided corrosion reaction data of Q235 in its pristine state. This provided a point of reference for the long-term protection experiments: (1) and (2). For Al anode, commonly used in the marine environment, experimental results of the protection of Q235 (experiment (2)) were obtained as reference for Al photoanode composite (experiment (1)). Consequently, the mechanism of Co(OH)$_2$@TiO$_2$ in Al photoanode composite for Q235 protection was observed and explained more clearly.

The schematic diagram of the experimental device for photoelectrochemical measurements is shown in Fig. 2. The photoelectrochemical measurements were performed using potentiostat Autolab PGSTAT302N (Metrohm Autolab, The Netherlands) to record open circuit potentials (OCP) (Fig. 2a). With this method, three kinds of
working electrodes were prepared corresponding to three groups of experiments: (1) a coupled electrode of the Al photoanode composite and Q235, (2) a coupled electrode of the Al anode and Q235, and (3) a single electrode of Q235 itself. A platinum plate was used as counter electrode.

Changes of generated current were measured with the electrochemical noise (ECN) module (Fig. 2b). The Al photoanode composite or Al anode was connected to working electrode, while Q235 was connected to counter electrode (the groundwire was used as counter electrode so that the electrons could flow from working electrode to Q235 in experiment (1) and (2)). In experiment (3), the single electrode of Q235 itself was connected the same way as the test in OCP measurements.

A KCl-saturated silver/silver chloride electrode (Ag/AgCl) was connected as reference electrode. During the photoelectrochemical measurements, all electrodes were at room temperature in 3.5 wt% NaCl solution with a 300 W Xe lamp (PLS-SXE 300, Beijing Perfect-Light Co. Ltd) as the illumination source. For long-term immersion of 29 days, the 3 kinds of working electrodes were kept for 12 h in the dark and 12 h under illumination per day to simulate daily solar light cycle in 3.5 wt% NaCl solution.

All measurements began after the OCP value was stable. The protective current density changes between Al photoanode composite and Q235 electrode were collected in the dark and under the illumination, respectively, without the application of bias voltages. Illumination-induced photopotential changes of the Al photoanode composite were measured with respect to the reference electrode to obtain its photoelectrochemical protection performance. The OCP and current density of Al anode and Q235 itself were also measured as references.

Results and Discussion

Design of the new Al photoanode composite.—The macroscopic feature of the as-prepared Al photoanode composite is blue, smooth and uniform. The material consists of Al-Zn-In-Mg-Ti alloy, Ti layer, TiO2 anatase nanotubes and Co(OH)2 particles in a bottom-up sequence (Fig. 1d). As a traditional Al anode, the matrix Al-Zn-In-Mg-Ti layer provides electrochemical protection through its own anodic dissolution in the dark. The Ti layer is only the substrate for anodic oxidation to prepare TiO2 and has no actual protective effect. With excellent photoelectric protection performance, the TiO2 anatase nanotubes layer itself is non-sacrificial, nonreactive and environmentally friendly. TiO2 can protect metal under illumination, and is expected to achieve efficient protection together with Al anode without illumination. The deposition of Co(OH)2 particles can effectively consume holes and inhibit the recombination of photogenerated holes and electrons, so that the TiO2 can provide more negative protection potential and improve the protective performance. Our previous work on Co(OH)2 modification has achieved promising results in improving properties of photocatalyst.

Characterization of Al photoanode composite.—Micromorphologies.—The structural characteristics of Al photoanode composite are presented more clearly in the SEM images as shown in Fig. 3. The TiO2 grew in the form of vimeinous one-dimensional nanotubes in diameter of 100–150 nm with uniform and continuous distribution (Fig. 3a). The nanotubes are obviously vertical growth with length of 25–30 μm (Fig. 3b). The previous results have shown that one-dimensional nanotubes, with high specific surface area, have good conductivity and obvious quantum size effect. The electrons induced by illumination can move quickly and easily within this structure, which in turn increases the light absorption of this photocatalyst. The nanotubes could also act as surface reaction sites so as to improve efficiency of solar energy conversion, and finally enhance the electrochemical protection performance.

Crystal structure.—As shown in Fig. 4, the XRD pattern indicates that there is a complete layer of anatase TiO2 nanotubes film on the surface of Al photoanode composite. According to the standard anatase TiO2 (JCPDS card no. 21-1272), it is matched with the results of diffraction peaks: (101) (004) (200) (105) (204) (220) planes completely. However, there is no sign of any presence of Co(OH)2 In XRD pattern because of its low content.

Chemical composition analysis.—Fig. 5 shows the complete survey XPS for the high-resolution spectrum and the Co 2p region of Al photoanode composite to further investigate if Co(OH)2 has been deposited successfully on Al photoanode composite. Fig. 5a shows Ti 2p, Co 2p, Al 2p and O 1s peaks, which corresponds to the composition of the sample. In Fig. 5b, the major binding energies of Co 2p3/2 in Co(OH)2 are found to be deconvoluted into two pairs of individual peaks at 781.0 eV and 797.0 eV, respectively. Fig. 5c shows the scanned XPS spectrum of O 1s, and the binding energy positions at 529.8 eV and 531.5 eV are indexed to TiO2 and Co(OH)2, respectively. Co(OH)2 particles has been successfully deposited on the surface of Al photoanode composite.

Figure 3. SEM images of microstructures of prepared Al photoanode composite: (a) surface and (b) cross-section morphology.

Figure 4. X-ray diffraction patterns of prepared Al photoanode composite.
Figure 5. XPS spectra of prepared Al photoanode composite: (a) survey spectrum, (b) Co 2p peak and (c) O 1s peak.

**UV-Vis absorption.**—The bandgap energy of single anatase TiO$_2$ is 3.2 eV, corresponding to the absorption peak of 387 nm, which means anatase TiO$_2$ shows nearly ultraviolet light absorption but with almost no visible light absorption. The UV–vis diffuse reflectance spectrum of the as-prepared Al photoanode composite is shown in Fig. 6. By the intersection of a tangent along the critical falling portion of the spectrum and the horizontal axis, the light absorption threshold can be simply identified. The maximum absorption wavelength of the Al photoanode composite is approximately 440 nm, corresponding to the bandgap energy of 2.82 eV. With TiO$_2$ nanotube structure and deposition of Co(OH)$_2$ on TiO$_2$ surface, the absorption edge of Al photoanode composite is shifted to visible region.

**Performance of photoelectrochemical cathodic protection.**—

**Characterization during long-term immersion.**—By potentiodynamic polarization method, the corrosion potential of Q235 carbon steel in 3.5wt% NaCl solution is approximately −0.5 V, which means for cathodic protection of Q235, the electrode potential should be < −0.5 V. The required minimum current density for Q235 protection is 15 μA/cm$^2$, so the protective current density should reach at least 15 μA/cm$^2$ stably for a long time to protect Q235 efficiently.

Fig. 7 shows results of the long-term corrosion of single electrode of Q235 itself and electrochemical protection results of Q235 protected by Al photoanode composite and Al anode.

The results in Fig. 7a show the potential changes over time. The initial OCP value of Q235 is −0.52 V. With the prolongation of immersion time, OCP value decreases slowly, indicating that the Q235 is uniformly corroded. After 6 days’ immersion, the OCP no longer decreases and remains at around −0.63 V stably, which means the corrosion rate of Q235 is stable at this time. The protective properties of the Al photoanode composite and Al anode are discussed in two cases: in the dark and under illumination. In the dark, the initial potentials of both electrodes are −1.04 V, and Co(OH)$_2$@TiO$_2$ doesn’t show any effect at this time. Under illumination, potentials of the two electrodes increase slightly, and potential of Al photoanode composite is higher. Both under illumination and in darkness, the potential of Al anode first decreases at fast rate; then it begins to increase slowly on the 2nd day, indicating that oxide film may form on the surface of the sample and cover the surface; and finally reaches a relatively stable state. The potential of the Al photoanode composite decreases slightly initially and also begins to increase slowly to stable state on about the 4th day during immersion. In the whole process, the potential of Al photoanode composite is slightly higher than that of Al anode. These two potentials are far below the potential of Q235, which can meet the corresponding cathodic protection potential criterion.

As shown in Fig. 7b, the current density curve can be divided into 3 stages. The results show that the self-discharge current density of Q235 is always maintained at 60 μA/cm$^2$. It can be clearly seen that the current densities of Al photoanode composite and Al anode are basically the same in the dark, while both of them greatly improve under illumination. This proves that illumination can accelerate the current efficiency of Al anode. The current trends of the two materials under illumination are basically same as the trends in the dark; in stage I, the current densities of these four curves increase significantly,
indicating that the Al anode begins to dissolve and is consumed, and its current efficiency increases at the moment; in stage II, on the 4th day of immersion the current densities reach a peak, and then oxide film on the surface is continuously formed from dissolution and oxidation of the Al anode, resulting in the decrease of current densities and current efficiency; in stage III, on the 11th day of immersion, the formation and detachment of oxide film on the surface of Al anode reach a dynamic balance, therefore the current densities gradually stabilize. The above analysis implies that the current densities of Al photoanode composite increase first and then decrease in stage I and II, which mainly shows the discharge performance of Al anode side. Focusing on stage III, the effect of Co(OH)₂@TiO₂ in Al photoanode composite is obvious at this stage: under illumination, the current density of Al photoanode composite is significantly higher than that of Al anode, and can stably remain for a long time to the 29th day. This is due to the large amount of oxide film covering the surface of the sample, which seriously affects the discharge performance of Al anode. The electrons can be generated by Co(OH)₂@TiO₂ under illumination, thus Q235 can be protected with the photoinduced current. This process has played a supplemental part in protecting Q235 in the later stage.

The research of photocatalytic materials in the field of cathodic protection has yielded preliminary achievements in many reports. This combination of photocatalytic materials and traditional Al anode may open up a new field for metal corrosion protection.

### Macro morphologies

Table I. Macro corrosion surface morphologies of the Al photoanode composite (Al anode side) and the Al anode during the immersion (AA: Al anode, APC: Al photoanode composite).

| Time/day | AA | APC |
|----------|----|-----|
| 3        | ![Image](image1.png) | ![Image](image2.png) |
| 5        | ![Image](image3.png) | ![Image](image4.png) |
| 10       | ![Image](image5.png) | ![Image](image6.png) |
| 15       | ![Image](image7.png) | ![Image](image8.png) |

Fig. 8 shows the immersion results of Q235 carbon steel for 15 days. Compared with unprotected Q235 as shown in Fig. 8a, the surface corrosion products of protected Q235 decrease greatly in Figs. 8b and 8c. The surface of Q235 protected by Al photoanode composite is only slightly corroded, indicating that the supplemental protective effect of Co(OH)₂@TiO₂ cannot be neglected.

In addition, no visible changes are observed on the Co(OH)₂@TiO₂ surface side (the upper surface of the sample in Fig. 1) before and after immersion as shown in Fig. 9. This implies the stability and longevity of the photocatalytic material.

### Micromorphologies

Fig. 10 shows the surface morphologies of Al photoanode composite during immersion in 3.5wt% NaCl solution. On the 3rd day of immersion, some needle-like oxidation products can be seen on the surface of TiO₂ nanotubes. They are due to the dissolution and oxidation of Al anode in the lower part of sample, resulting in production of some Al oxide. With the increase of immersion time,
Figure 8. Macro corrosion surface morphologies of (a) unprotected Q235, (b) Q235 protected by the Al anode and (c) Q235 protected by the Al photoanode composite in 3.5wt% NaCl solution for 15 days.

Figure 9. Macro surface morphologies of Al photoanode composite (Co(OH)$_2$@TiO$_2$ side) (a) before and (b) after immersion in 3.5wt% NaCl solution.

on the 5th day and the 10th day, more spherical and needle-like oxidation products are produced, which partly cover the surface of TiO$_2$ nanotubes. After 15 days of immersion in stage III, the surface of TiO$_2$ nanotubes has been completely covered by a thin layer of oxidation products. Although the oxidation products may affect the electron transfer and photoelectrochemical cathodic protection performance of Co(OH)$_2$@TiO$_2$, the current density curve (Fig. 7b) indicates that Co(OH)$_2$@TiO$_2$ still contributes to the supplemental protection for Q235 in later stage.

The corresponding cross-section morphologies in Fig. 11a directly and clearly show the oxidation process of Al anode below Co(OH)$_2$@TiO$_2$: the oxidation products of Al are generated at the interface between the layers of Ti and Al anode in some areas of the sample, and this layer of oxide thickens gradually with the increased immersion time. Based on the surface morphology analysis, the oxidation products partially penetrate the layers of Ti and TiO$_2$ nanotubes, and finally partially cover the surface of TiO$_2$ nanotubes, which decreases the protective performance of Al anode. The thickness of the nanotube layer is also slightly decreased during the immersion process, even a few cracks appear on the 15th day of immersion.

Although the thickness of Al$_2$O$_3$ is increased over time, this phenomenon occurs in some areas of the sample. While in other areas Al

Figure 10. Surface microstructure changes of Al photoanode composite (Co(OH)$_2$@TiO$_2$ side) in different immersion days in 3.5wt% NaCl solution observed with SEM.

Figure 11. Cross-sectional microstructure changes of Al photoanode composite in 3.5wt% NaCl solution observed with SEM: (a) in different immersion days and (b) in 15th day.
is still well covered by Ti layer as shown in Fig. 11b. Not all of the Ti layer is detached, which means the Ti layer is partially detached and partially left. The TiO$_2$ remained part can still provide protective current, so the protective current density can remain at relatively high level up to 28 d (Fig. 7b).

**Chemical composition analysis.**—Fig. 12 shows the changes of XPS spectra for the complete survey spectrum, including Ti 2p, Co 2p, Al 2p and O1s peaks of Al photoanode composite in different immersion days. Evidently the intensity of Co 2p peaks are gradually weakened and finally completely disappear from the surface of sample by the 15th day (more obvious in Fig. 13). This result may lead to the reduction of TiO$_2$ photoelectrochemical performance. The spectra also indicate the Al 2p peaks have changed significantly during the immersion days.

Considering the dissolution and oxidation of Al anode during immersion, Fig. 14 indicates possible states, compounds and changes of Al. The results imply that the initial content of Al is much larger than that of Al$_2$O$_3$ before immersion. The left-shift of Al 2p peak indicates the process of continuous oxidation of Al to Al$_2$O$_3$ with prolonged immersion time. The content of Al$_2$O$_3$ increases continuously, which is consistent with the above morphological results.

**Mechanism analysis.**—Fig. 15 illustrates the proposed mechanism for double cathodic protection performance of Al photoanode composite on Q235 steel. Al photoanode composite provides electrons to Q235 steel from two ways: Co(OH)$_2$@TiO$_2$ photocatalytic material and Al-Zn-In-Mg-Ti sacrificial anode. After the Al photoanode composite is coupled with Q235 steel, since there is a large potential difference between the traditional Al anode and Q235 steel, Al anode is continuously activated and dissolved to provide electrons for Q235 steel and generate protective current. When TiO$_2$ nanotubes are illuminated, photogenerated electrons and holes are separated into different directions, by which the latters are transferred to the surface of TiO$_2$ and then to the Co(OH)$_2$ modifiers to oxidize water while the formers are transported to the bulk of TiO$_2$ and then through Ti layer, Al anode and wire to protect Q235 steel. As a consequence, the electrons are transferred to the surface of the sample (Ti surface), providing electrons together with Al anode to Q235 steel and generating double protective current. As Al anode is covered by a large number of oxide film in stage III, Co(OH)$_2$@TiO$_2$ realizes the supplemental photoelectrochemical protection of Q235 for long-term immersion.
Covered by a thin layer of corrosion product Al2O3 during long-term immersion.

In this work, a new kind of Al photoanode composite based on the traditional Al-Zn-In-Mg-Ti sacrificial anode and Co(OH)2 modified TiO2 of anatase nanotubes was successfully prepared to protect Q235 in aqueous 3.5 wt.% NaCl solution. The electrochemical results indicate that the protective performance of Al photoanode composite is similar to that of Al anode in the preliminary and medium stage (stage I and II), while in the later stage (stage III), the current density of Al photoanode composite is stable but greater under illumination (stage I and II), while in the later stage (stage III), the current density of Al photoanode composite is stable but greater under illumination compared with that of traditional Al anode. With a great photoelectrochemical capability, Co(OH)2@TiO2 plays an important role in supplemental protection for Q235 and improving current efficiency, which may prolong the life of Al anode. It is of great scientific significance to combine the photocatalyst and the traditional Al anode, which provides a new idea for corrosion protection of metals. However, it still needs further improvement on account that TiO2 nanotubes surface is covered by a thin layer of corrosion product Al2O3 during long-term immersion.

Conclusions

In this work, a new kind of Al photoanode composite based on the traditional Al-Zn-In-Mg-Ti sacrificial anode and Co(OH)2 modified TiO2 of anatase nanotubes was successfully prepared to protect Q235 in aqueous 3.5 wt.% NaCl solution. The electrochemical results indicate that the protective performance of Al photoanode composite is similar to that of Al anode in the preliminary and medium stage (stage I and II), while in the later stage (stage III), the current density of Al photoanode composite is stable but greater under illumination compared with that of traditional Al anode. With a great photoelectrochemical capability, Co(OH)2@TiO2 plays an important role in supplemental protection for Q235 and improving current efficiency, which may prolong the life of Al anode. It is of great scientific significance to combine the photocatalyst and the traditional Al anode, which provides a new idea for corrosion protection of metals. However, it still needs further improvement on account that TiO2 nanotubes surface is covered by a thin layer of corrosion product Al2O3 during long-term immersion.

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ORCID

Xuan Xie
https://orcid.org/0000-0001-6050-8541

References

1. Schumacher, Seawater corrosion handbook, Noyes Data Corp (1979).
2. P. Traverso and E. Canepa, Ocean Engineering, 87, 10 (2014).
3. H. Sun, L. Liu, Y. Li, L. Ma, and Y. Yan, Corros. Sci., 77, 77 (2013).
4. W. Li, Y. Yan, G. Chen, and M. Li, Procedia Engineering, 12, 27 (2011).
5. M. Sun, Z. Chen, Y. Bu, J. Yu, and B. Hou, Corros. Sci., 82, 77 (2014).
6. S. Song and Z. Chen, J. Electrochem. Soc., 161, C288 (2014).
7. K. Sharanov, S. Bilde, S. Bilgiş, G. Gece, and Z. Klüg, Corros. Sci., 52, 984 (2010).
8. J. Yuan and S. Tsujikawa, Zairyo-to-Kankyo, 44, 534 (1995).
9. T. Tatsuma, S. Saitoh, Y. Ohto, and A. Fujishima, Chem. Mater., 13, 2838 (2001).
10. M. Sun, Z. Chen, and Y. Bu, Surf. Coat. Technol., 266, 79 (2015).
11. M. Sun, Z. Chen, and Y. Bu, J. Alloys Compd., 618, 734 (2015).
12. Y. Bu, Z. Chen, W. Li, and J. Yu, ACS Appl Mater Interfaces, 5, 5097 (2013).
13. Z. Lin, Y. Lai, R. Hu, J. Li, R. Du, and C. Lin, Electrochim. Acta, 55, 8717 (2010).
14. M. Sun, Z. Chen, and J. Yu, Electrochim. Acta, 109, 13 (2013).
15. X. Wang, Q. Wei, L. Zhang, H. Sun, H. Li, and Q. Zhang, Mater. Sci. Eng., B, 208, 22 (2016).
16. J. Li, C. Lin, Y. Lai, and R. Du, Surf. Coat. Technol., 205, 557 (2010).
17. C. Lei, Z. Feng, and H. Zhou, Electrochim. Acta, 68, 134 (2012).
18. J. Huang, T. Konishi, T. Shinohara, and S. Tsujikawa, Zairyo-to-Kankyo, 47, 193 (1998).
19. J. Li, Y. Liu, Z. Zhu, G. Zhang, T. Zou, Z. Zou, S. Zhang, D. Zeng, and C. Xie, Scientific reports, 3, 2409 (2013).
20. Y. Takahashi, P. Ngaotranakwiwat, and T. Tatsuma, Electrochim. Acta, 49, 2025 (2004).
21. Y. Takahashi and T. Tatsuma, Langmuir, 21, 12357 (2005).
22. T. Tatsuma, S. Saitoh, P. Ngaotranakwiwat, Y. Ohto, and A. Fujishima, Langmuir, 18, 7777 (2002).
23. J. Huang, T. Shinohara, and S. Tsujikawa, Zairyo-to-Kankyo, 48, 575 (1999).
24. N. Wei, Y. Liu, T. Zhang, J. Liang, and D. Wang, Mater. Lett., 185, 81 (2016).
25. X. Wang, Q. Wei, J. Li, H. Li, Q. Zhang, and S. Ge, Mater. Lett., 185, 443 (2016).
26. J. Ren, B. Qian, J. Li, Z. Song, L. Hao, and J. Shi, Corros. Sci., 111, 596 (2016).
27. Q. Liu, J. Hu, Y. Liang, Z. Guan, H. Zhang, H. Wang, and R. Du, J. Electrochem. Soc., 163, C539 (2016).
28. G. Zhang, S. Zang, and X. Wang, ACS Catal., 5, 941 (2015).
29. F. Tao, Y. Shen, Y. Liang, and H. Li, J. Solid State Electrochem., 11, 853 (2006).
30. M. Qorbani, N. Naseri, and A. Z. Moshfegh, ACS Appl. Mater. Interfaces, 7, 11712 (2015).
31. M. R. Nellist, F. A. L. Laskowski, J. Qu, H. Hajibabaei, K. Sivula, T. W. Hamann, and S. W. Boettcher, Nature Energy (2017).
32. H. Liu, Q. Xue, J. Zhao, and Q. Zhang, Electrochim. Acta, 260, 330 (2018).
33. C. Zhen, L. Wang, L. Liu, G. Liu, G. Q. Lu, and H. M. Cheng, Chemical communications, 49, 6191 (2013).
34. D. P. Dubal, G. S. Gund, C. D. Lokhande, and R. Holze, ACS Appl Mater Interfaces, 5, 2446 (2013).
35. C. Zhen, L. Wang, G. Liu, G. Q. Lu, and H. M. Cheng, Chemical communications, 49, 3019 (2013).
36. X. Xie, L. Liu, R. Chen, G. Liu, Y. Li, and F. Wang, J. Electrochem. Soc., 165, H3154 (2018).
37. G. Riegel and J. R. Bolton, J. Phys. Chem., 99, 4215 (1995).