A novel fabrication method of slippery lubricant-infused porous surface by thiol-ene click chemistry reaction for anti-fouling and anti-corrosion applications

Abstract: A novel and simple way for efficiently preparing stable and non-toxic slippery lubricant-infused porous surface (SLIPS) will expand its anti-fouling and anti-corrosion applications in marine environments. Herein, vinyl-terminated polydimethylsiloxane was covalently grafted on the surface of nano-SiO2 by a thiol-ene click chemistry reaction. After that, SLIPS was efficiently prepared at room temperature via the spraying method on various substrate surfaces. Surface wettability results showed that a water droplet (10 μL) can slip on the surface with an inclination of 10° and a stained water droplet can slip without stain during the slide process, which proved that SLIPS displayed excellent slippery performance. The existence of molecular-level slippery silicone oil film on the rough surface. Anti-fouling and anti-corrosion tests showed that the prepared SLIPS exhibited stable and excellent anti-fouling and anti-corrosion performance after immersion in Pseudoalteromonas sp. culture solution for 14 days. The SLIPS exhibited a value of more than 98% of bacterial attachment inhibition efficiency and a value of 99.9% of corrosion inhibition efficiency. This facile method provides guidance to fabricate SLIPS for its anti-fouling and anti-corrosion applications in marine environments.

Keywords: slippery lubricant-infused porous surface, anti-fouling, anti-corrosion, microbially influenced corrosion, interface

1 Introduction

Metallic materials are widely used in marine engineering due to their high mechanical strength and hardness. However, metal corrosion and biofouling occur in marine environments, especially for various marine buildings and projects that cannot be moved for a long time, biofouling and corrosion are more serious under the static state (1,2). Generally, the activity or metabolites of microorganisms often accelerate corrosion, which is called microbial-influenced corrosion (MIC). MIC causes serious economic and security problems for marine engineering and transportation. It is estimated that metal corrosion resulting from MIC accounts for 20% of the total cost of corrosion in marine environments (3,4). Therefore, it is urgent and important to mitigate MIC in practical applications.

Currently, several strategies have been developed to control MIC in the marine environment, such as organic coatings (5,6), biocides (7,8), sacrificial anodes (9,10), and hydrogel (11). However, these conventional methods fail to meet the environmental and energy-saving requirements. From the perspective of the mechanism, MIC is a phenomenon that occurs at the metal/solution interface. The surface properties of metal substrates influence bacterial sedimentation and subsequent corrosion behavior (12,13). Therefore, actively inhibiting the attachment of bacteria on the metal/solution interface is one of the more effective means to solve MIC.

Inspired by Nepenthes, Aizenberg’s group first reported the slippery lubricant-infused porous surface (SLIPS) in 2011 (14).
Over the past decade, SLIPS has garnered extensive research interest in various fields. SLIPS can inhibit the attachment of bacteria on the metal/solution interface as a result of the excellent ultra-slippery property of the surface, thereby opening up a novel avenue for the inhibition of MIC. Studies have confirmed that SLIPS can suppress bacterial attachment and inhibit the occurrence of MIC in seawater (15–20).

Generally, the conventional fabrication process of SLIPS is a synergetic cooperation of the surface rough surface structure, low surface energy materials, and lubricating oils, which satisfies the following three steps: (1) construction of the surface micro-nano rough structure, (2) low surface energy chemical modification of rough structures, and (3) injection of low surface energy lubricants. Among them, the construction of the rough surface structure is fundamental to fabricating SLIPS. Currently, many methods have been developed to fabricate rough surface structures on various substrates, such as the chemical etching method, self-assembling method, electrochemical deposition method, and spray method (21,22). Li et al. reported a simple hydrothermal method and modification process to fabricate a superhydrophobic surface (SHS) on a magnesium alloy substrate, and the preparation of SLIPS can be achieved by injecting lubricant into SHS by the spin-coating method (23,24). Li et al. reported a simple hydrothermal method and modification process to fabricate a superhydrophobic surface (SHS) on a magnesium alloy substrate, and the preparation of SLIPS can be achieved by injecting lubricant into SHS by the spin-coating method (25). Xiang et al. successfully fabricated a slippery zinc phosphate coating composed of homogeneous pores by the electrochemical deposition method on the substrate, and the as-prepared SLIPS displayed an excellent slippery performance. Anti-fouling and anti-corrosion tests showed that the prepared SLIPS exhibited stable and excellent anti-fouling and anti-corrosion performance after immersion in Pseudoalteromonas sp. culture solution. The electrochemical impedance spectroscopy (EIS) test results showed that the $|Z|_{0.01 \text{ Hz}}$ value of SLIPS after 14 days of immersion is $4.89 \times 10^{10} \Omega\text{-cm}^2$, indicating that the SLIPS had a stable anti-corrosion performance. This work provides a simple way for efficiently preparing stable and non-toxic slippery surfaces, which expands the anti-fouling and anti-corrosion applications of SLIPS in marine engineering.

## 2 Materials and methods

### 2.1 Materials

Nano-SiO$_2$, benzoin dimethyl ether (DMPA), yeast powder, and tryptone were purchased from Shanghai Madin Biochemical Technology Co., Ltd. Epoxy resin and polyamide curing agent were purchased from Shanghai Xuanyang Chemical Materials Co., Ltd. 3-Mercaptopropyltrimethoxysilane (MPTS) was purchased from Anhui Zesheng Technology Co., Ltd. Ethanol, n-hexane, and ferric sulfate (FeSO$_4$$\cdot$$7H_2O$) were purchased from Xilong Scientific Co., Ltd. Silicone oil (100 cst) was purchased from Xiya Reagent Company. Vi-PDMS was purchased from Lijun Silicone Materials Co., Ltd. All chemical reagents are analytically pure and used without further purification. The Q235 steel sheets and glasses are commercially available. The Q235 steel sheets and lubricants have potential harm to the environment with long-term use (28).

Silicone oil can be used as an optimal choice for environmentally non-toxic low surface energy lubricants (29). However, its compatibility with fluorine-containing silane coupling agents used during the low surface energy modification process needs to be improved. Therefore, a new surface modification method is needed to improve the compatibility between silicone oil lubricants and hydrophobic-modified surface porous structures (14,30).

In this article, vinyl-terminated polydimethylsiloxane (Vi-PDMS) was covalently grafted on the surface of nano-SiO$_2$ by a thiol-ene click chemistry reaction. The molecular structure of Vi-PDMS is similar to silicone oil, which could improve the compatibility between silicone oil lubricants and hydrophobic-modified surface porous structures, and then SLIPS was prepared at room temperature via the spraying method. Surface wettability results proved that SLIPS displayed excellent slippery performance. Anti-fouling and anti-corrosion tests showed that the prepared SLIPS exhibited stable and excellent anti-fouling and anti-corrosion performance after immersion in Pseudoalteromonas sp. culture solution. The electrochemical impedance spectroscopy (EIS) test results showed that the $|Z|_{0.01 \text{ Hz}}$ value of SLIPS after 14 days of immersion is $4.89 \times 10^{10} \Omega\text{-cm}^2$, indicating that the SLIPS had a stable anti-corrosion performance. This work provides a simple way for efficiently preparing stable and non-toxic slippery surfaces, which expands the anti-fouling and anti-corrosion applications of SLIPS in marine engineering.
were polished to 2,000 grit with dry SiC sandpaper. Then, the Q235 steel sheets and glasses were washed with ethanol in an ultrasonic bath and dried with a blower.

### 2.2 Fabrication of SLIPS via thiol-ene click chemistry reaction

#### 2.2.1 Preparation process of SiO$_2$@MPTS@PDMS

The modification process of nano-SiO$_2$ is shown in Figure 1. To graft sulfhydryl groups on the surface of nano-SiO$_2$, 1.5 g nano-SiO$_2$ and 1 mL MPTS were added to 20 mL ethanol solution under seal and ultrasonication for 5 min and then kept constant stirring at 200 rpm for 3 h. Subsequently, the products were centrifuged at 8,000 rpm for 10 min washed with ethanol three times and dried at 60°C until a constant weight was achieved for further examination. After that, the sulfhydryl group modified nano-SiO$_2$ (SiO$_2$@MPTS) was obtained.

Afterward, Vi-PDMS was dissolved in n-hexane completely to obtain a 15 wt% Vi-PDMS solution, and 1.5 g SiO$_2$@MPTS was added to the above solution with stirring until it was evenly dispersed. As the photoinitiator, DMPA (0.01:1 w/w% initiator/Vi-PDMS) was added to the solution and irradiated for 1 h under UV light to form Vi-PDMS modified nano-SiO$_2$ (SiO$_2$@MPTS@PDMS). The products were centrifuged at 8,000 rpm for 10 min, washed with n-hexane three times, and dried at 60°C until a constant weight was achieved.

#### 2.2.2 Fabrication of SLIPS

To prepare the SHS, the epoxy resin and polyamide curing agent (1:1 w/w%) were first mixed and uniformly coated on the substrate with a brush. Then, it was put on a 60°C heater plate for pre-curing. Subsequently, the SiO$_2$@MPTS@PDMS ethanol solution was sprayed on the epoxy surface with a spray gun under 0.4 MPa air at a spraying distance of 30 cm. Finally, it was placed on a heater plate until it was cross-linked and cured to obtain a SHS. To prepare the SLIPS, the silicone oil was injected into the tilted SHS until the silicone oil infiltrated the rough surface completely.

### 2.3 Surface characterization

Field-emission scanning electron microscopy (FE-SEM, Verios G4 UC, Thermo Fisher Scientific) was performed to characterize the surface morphology of the samples and energy dispersive spectrometer (EDS) characterization. X-ray photoelectron spectrometers (XPS; Axis Supra, KRATOS) were performed to characterize the chemical composition of the samples. The chemical bonds and functional groups of the samples were investigated by the Fourier transform infrared spectroscopy (FT-IR; T27, Bruker). Contact angles (CAs) and sliding angles were measured on the CA system (SDC-100H; Shengding Precision Instrument Co., Ltd.) at room temperature.

### 2.4 Bacterial settlement experiment

The Pseudoalteromonas sp. was used as the model bacteria for the bacterial settlement experiment. The bacterial culture medium was prepared by adding 1,000 g yeast powder, 5,000 g tryptone, and 0.017 g FeSO$_4$·7H$_2$O to 1,000 L seawater. Before use, the bacterial culture medium was sterilized at 121°C by an autoclave for 20 min. After that, Pseudoalteromonas sp. was inoculated in the culture medium and cultivated for 3 days. After sterilizing under UV radiation for 40 min, the samples were adhered to the inner wall of the beaker by hot melt adhesive and immersed in the bacterial solution. To simulate

![Figure 1: Schematic diagram of the preparation process of SiO$_2$@MPTS@PDMS.](image-url)
the static and dynamic marine environments, the beaker was sealed with kraft paper and conducted in a 30°C incubator and orbital shaker with a shaking speed of 120 rpm, respectively.

During the bacterial settlement test, the bacterial culture medium was replaced by the freshly equivalent volume of sterilized culture medium every 3 days to keep the bacteria alive. At every predetermined time, the samples were washed with sterilized PBS solution and stained by DAPI stain at a concentration of 100 ng·mL\(^{-1}\) for 15 min. The stained samples were observed by a fluorescence microscope (DM5000B, LEICA). The bacterial surface coverage was analyzed by ImageJ software.

### 2.5 Electrochemical test

The corrosion behavior of different samples in the *Pseudoalteromonas* sp. bacterial culture medium was measured by EIS and potentiodynamic polarization experiments through the computer-controlled electrochemical system (DH7000) at room temperature. The electrochemical test was performed in a three-electrode system, including the different samples with a test area of 1 × 1 cm\(^2\) as a working electrode, a platinum electrode as a counter electrode, and an Ag/AgCl (3 M KCl) electrode as a reference electrode. The EIS experiment was carried out with a frequency range of 10\(^{-5}\)–10\(^{-2}\) Hz at an open circuit potential and a perturbation voltage of 50 mV amplitude. The EIS results were analyzed by ZsimpWin software.

### 3 Results and discussion

#### 3.1 Chemical characterization of modified nano-SiO\(_2\)

The foundational condition of fabricating SLIPS was to design a hydrophobic micro/nano rough structure. As shown in Figure 2a, the sulfhydryl group was grafted on the surface

![Diagram](Image)

**Figure 2:** (a) SiO\(_2\)-modified chemical reaction process. (b) FT-IR spectrum of SiO\(_2\), SiO\(_2@MPTS\), and SiO\(_2@MPTS@PDMS\). (c) XPS spectrum of SiO\(_2\), SiO\(_2@MPTS\), and SiO\(_2@MPTS@PDMS\).
of nano-SiO$_2$ and MPTS by the hydrolytic condensation reaction between the hydroxyl groups. The sulhydryl-ene click chemical reaction was triggered under UV light to achieve the modification process of nano-SiO$_2$. Figure 2b illustrates the FT-IR spectrum of the SiO$_2$, SiO$_2$@MPTS, and SiO$_2$@MPTS@PDMS. The absorption peak at 476 cm$^{-1}$ of the three samples was the characteristic peak of Si–O–Si symmetric contraction vibration. The absorption peaks at 800 and 1,092 cm$^{-1}$ were corresponding to the symmetric and asymmetric stretching of Si–O–Si, respectively (31). The absorption peak corresponding to the SH group in the spectrum of the SiO$_2$@MPTS sample was not observed due to the relatively low content of thiol and poor sensitivity of FT-IR (32). However, the absorption peaks at 2,933 and 2,850 cm$^{-1}$ of MPTS can be detected, which can be attributed to the C–H stretch of methylenes of the alkyl chain. This proved that the MPTS was successfully grafted on the nano-SiO$_2$ surface (33,34). In the spectrum of SiO$_2$@MPTS@PDMS, the absorption peak at 1,263 cm$^{-1}$ was attributed to the deformation vibration of Si–CH$_3$, and the absorption peaks at 2,963 and 2,904 cm$^{-1}$ resulted from the asymmetric stretching vibration and symmetric stretching vibration of –CH$_3$, respectively (35). These characteristic peaks of PDMS indicated that the Vi-PDMS was successfully coated on the surfaces of the SiO$_2$@MPTS particles. The hydrophobic modification process was further verified by the chemical composition analysis through XPS spectra. As shown in Figure 2c, the area of the C 1s peak in the XPS spectra was observed to be gradually increasing due to the MPTS and Vi-PDMS being grafted individually on the SiO$_2$ surface.

The high-resolution spectra of C 1s, O 1s, and S 2p of SiO$_2$@MPTS are shown in Figure 3a. The fitting curves in the C1s spectrum were divided into three peaks at 284.7, 284.2, and 286.5 eV, which could be assigned to the C–C, C–Si, and C–S bonds of MPTS, respectively. The peaks at 532.9 and 532.3 eV in the O 1s spectrum correspond to the Si–O and C–O bonds in the MPTS, respectively. The peak at 532.6 eV in the O 1s spectrum was attributed to the SiO$_2$ (36). The peak at 163.8 eV corresponded to the S 2p, indicating that the MPTS was successfully modified on the surface of SiO$_2$. The EDS mapping of the SiO$_2$@MPTS is shown in Figure 3b. The distribution of S elements further indicated that MPTS was successfully modified on the original SiO$_2$ surface. The results of the XPS and EDS analysis were identical to the FT-IR test, indicating that sulhydryl groups were successfully grafted to the SiO$_2$ surface after the modification process of MPTS. The sulhydryl groups can further react with the vinyl groups of the Vi-PDMS molecular chains to obtain SiO$_2$@MPTS@PDMS products.
3.2 Surface structure and wettability analysis

A porous micro/nano-rough structure surface was constructed by spraying hydrophobic nano-SiO₂ particles on the surface of a sandblasting steel substrate. As shown in Figure 4a, the FE-SEM images showed a large number of irregular porous structures on the substrate surface, which could be used as a reservoir for lubricating oil through capillary force action. The surface wettability of the prepared samples is presented in Figure 4b. The original SiO₂ exhibits a superhydrophilic property with a water contact angle (WCA) of 0°, which is due to the porous micro/nanostructure with an inherent hydrophilic character. The SHS fabricated on the substrate through spraying hydrophobic SiO₂ particles exhibit superhydrophobic properties with a WCA of 151.4°. As shown in Figure 4c, the stained water droplets stood on the SHS without infiltration, whereas the original surface can be completely wetted by the droplet. The hydrophobicity of the porous structure ensured that the surface was preferentially wetted by the lubricant. After the hydrophobic silicone lubricant was injected and stored in the porous structure of the SHS due to the similar surface energy and chemical composition, SLIPS was successfully prepared, as confirmed by the WCA decreased from 151.4° to 102.3°.

As shown in Figures 5a, 10 μL of water droplets could easily slip off the SLIPS at a low inclination angle (~10°) under a small amount of gravity, indicating the formation of a continuous and stable lubricating oil layer on a porous surface. As can be seen in Figure 5b, the stained droplets could rapidly slip off the surface without staining traces during the slip process, indicating that the prepared SLIPS had an excellent ultra-slippery property. The ultra-slippery property of the SLIPS is the basis for the wide applications for anti-fouling and anti-corrosion.

Figure 4: (a) SEM images of rough structure surface. (b) Water CA of different samples. (c) The surface state of the stained droplet before and after SiO₂ modification.
3.3 Mechanical stability

As we all know, the SLIPS was usually fabricated by infusing lubricant oil into the hydrophobic porous structure. So, the mechanical stability of the hydrophobic porous structure played a crucial role in storing lubricant oil. As expected, the fabricated SHS exhibited excellent mechanical stability through the sandpaper abrasion test. As shown in Figure 6, the WCA of the SHS showed no obvious change after 50 abrasion cycles under 1,000 mesh sandpaper. Furthermore, the WCA of the SHS gradually decreased to a WCA of 130° after 50 abrasion cycles.

We further investigated the impact of wear cycles on the electrochemical performance of SLIPS. As depicted in Figure 7, following 50 wear cycles, the impedance value of SLIPS at 0.01 Hz decreased from an initial magnitude of 11 to approximately 6 orders of magnitude. Despite a reduction by five orders of magnitude after friction cycling, it
remained nearly four orders of magnitude higher than that observed for the control sample, demonstrating exceptional corrosion resistance.

3.4 Anti-fouling performance of SLIPS

Using Q235 carbon steel as the bare substrate, SHS and SLIPS as the target samples, and *Pseudoalteromonas* sp. as the model bacteria, the anti-fouling performance of the different surfaces under simulated static and dynamic marine environment was analyzed by fluorescence microscopy. As shown in Figure 8, during a 14-day immersion in the *Pseudoalteromonas* sp. culture medium (Figure 8a1–a3) under a simulated static marine environment, a large amount of *Pseudoalteromonas* sp. aggregated and attached to the surface of the bare Q235 carbon steel. However, only a very small amount of *Pseudoalteromonas* sp. was attached to the SLIPS after the 14 days of immersion (Figure 8c1–c3), which demonstrated excellent anti-fouling performance of the SLIPS. The lubricating layer infused in the porous rough structure can act as a vital component in inhibiting the adhesion of *Pseudoalteromonas* sp. (37). On the one hand, it is difficult for bacteria to attach and gather on the slippery lubricating layer due to the slippery properties of the surfaces. On the other hand, it is difficult for bacteria to penetrate the hydrophobic lubricating layer and settle on the metal surface (23). Interestingly, Figure 8b1–b3 shows that the bacterial adhesion is more severe on SHS than that on the Q235 carbon steel and SLIPS as a result of the unstable air layer trapped in the rough structure, which was infiltrated by seawater during the immersion process. The porous rough structure of SHS can provide a larger specific surface area for *Pseudoalteromonas* sp. attachment, thus resulting in a more severe bacterial adhesion.

In practice, marine engineering is often used in dynamic environments where water flow generates high shear forces on the surface of the materials, affecting the adhesion of fouling microorganisms to the surfaces. Therefore, we further performed the bacterial anti-fouling tests in simulated dynamic marine environments. As shown in Figure 9, after 14 days of immersion...
dynamic testing, Pseudoalteromonas sp. was still easy to attach to the bare Q235 carbon steel and SHS, which is similar to the results under static conditions. However, it is difficult for Pseudoalteromonas sp. to attach to the SLIPS, indicating that SLIPS still has an excellent ability to efficiently inhibit the attachment of bacteria under a dynamic environment.

Figure 9: Fluorescence photographs of bacterial adhesion on the surface of different samples after immersion in bacterial solution under dynamic conditions (a: BS, b: SHS, c: SLIPS; 1: soak 3 days, 2: soak 7 days, 3: soak 14 days).

Figure 10: Histogram of bacterial coverage rate on the surface of different samples after immersion in bacterial solution for 3, 7, and 14 days under static conditions (a) and dynamic conditions (b).
To make a more quantitative comparison, the anti-biofouling performance of the bare Q235 carbon steel, SHS, and SLIPS under static and dynamic environments is evaluated by bacterial surface coverage. As shown in Figure 10a, after 14 days of static immersion, the bacterial surface coverage of bare Q235 carbon steel and SHS increased from 1.47% and 7.23% to 38.84% and 41.99%, respectively. The bacterial surface coverage of SLIPS after 14 days of immersion was only 0.56%, corresponding to the bacterial attachment inhibition rate of 98.56%. The bacterial surface coverages of the three samples under the dynamic conditions are shown in Figure 10b. The bacterial surface coverage of the bare Q235 carbon steel and SHS reached 17.75% and 37.27% after 14 days of immersion. However, the bacterial surface coverage of SLIPS was only 0.23% after 14 days of immersion with an adhesion inhibition rate of 98.69%, which was lower than that of the static conditions. This is because the shear force generated by the water flow on the SLIPS under the dynamic environments can easily wash away the attached *Pseudoalteromonas* sp., thus enhancing the effect of inhibiting bacterial adhesion. The static and dynamic anti-fouling results showed that SLIPS has an excellent anti-fouling performance with an adhesion inhibition efficiency of more than 98%.

### 3.5 Anti-corrosion performance of SLIPS

Q235 carbon steel is easy to corrode in marine environments due to the erosion of corrosive media and the settlement of marine organisms. Herein, EIS was used to characterize the corrosion protection performance of the bare Q235 carbon steel, SHS, and SLIPS after immersion in *Pseudoalteromonas* sp. culture solution. Figure 11 shows the EIS results of the bare sample (BS), SHS, and SLIPS after immersion in *Pseudoalteromonas* sp. culture solution for 2 h. Generally, the larger the capacitive reactance arc...
radius in the Nyquist plots, the better the corrosion resistance of the surfaces. As can be seen in Figure 11a and b, the capacitive reactance arc radius of SLIPS is much larger than that of the SHS and BS, indicating better anti-corrosion performance of the SLIPS.

Usually, the $|Z|_{0.01 \text{ Hz}}$ value in the Bode plots is a semi-quantitative indicator of corrosion resistance, and a higher $|Z|_{0.01 \text{ Hz}}$ value indicates a superior anti-corrosion performance (38–40). Figure 11c shows that the $|Z|_{0.01 \text{ Hz}}$ value of SLIPS was $8.74 \times 10^6 \Omega \cdot \text{cm}^2$, which is eight orders of magnitude higher than that of bare Q235 carbon steel ($|Z|_{0.01 \text{ Hz}} = 7.12 \times 10^5 \Omega \cdot \text{cm}^2$), and two orders of magnitude higher than that of SHS ($|Z|_{0.01 \text{ Hz}} = 3.83 \times 10^8 \Omega \cdot \text{cm}^2$). These results indicated that SLIPS had the best corrosion protection performance as compared with the bare Q235 carbon steel and SHS. The bare Q235 carbon steel exhibited the lowest slope in the low-frequency region in the Bode plots (Figure 11c), indicating a small interfacial charge transfer occurred at the solution–metal interface. In this case, the corrosive medium can easily corrode the bare Q235 carbon steel (41). The increase in the slope of the bare Q235 carbon steel in the intermediate frequency region in the Bode plots is caused by surface-attached biofilms and corrosion products (42). As shown in Figure 9d, BS showed the lowest phase angle in the high-frequency region and SLIPS showed a wide and high phase angle in the high-medium frequency regions, indicating that the corrosive media was difficult to invade the SLIPS interface (43). This result showed the SLIPS had an excellent anti-corrosion performance.

The EIS results were further evaluated by equivalent circuit models to make a more quantitative comparison. For the BS, SHS, and SLIPS, two-time constants can be observed in the Bode phase angle vs frequency plot; namely, the formation of the corrosion layer (corrosion products and biofilm layer, SHS or SLIPS layer) at the high-medium frequency ranges and the corroded interface at the low-frequency ranges (44). Therefore, the EIS results of BS can be fitted by the equivalent circuit model shown in Figure 12a, and the EIS results of SHS and SLIPS can be fitted by the equivalent circuit model shown in Figure 12b. In these two circuits, $R_s$ represents the solution resistance, $R_t$ represents the resistance of the film layer (corrosion products and biofilm layers, SHS or SLIPS film layer), $R_{ct}$ is the charge transfer resistance of the corroded interface, and $CPE_f$ and $CPE_{dl}$ are used to simulate the constant phase elements of the film layers and the electric double layer, respectively (40).

The fitted electrochemical parameters of the BS, SHS, and SLIPS after immersion in Pseudoalteromonas sp. culture solution for 2 h are shown in Table 1. Besides the values of $|Z|_{0.01 \text{ Hz}}$, $R_{ct}$ is an important parameter that directly reflects the anti-corrosion performance of the materials. Generally, a larger $R_{ct}$ represents fewer electron transfers, which corresponds to better anti-corrosion performance. The $R_{ct}$ value of SLIPS is $3.31 \times 10^9 \Omega \cdot \text{cm}^2$, which is about seven orders of magnitude higher than that of BS ($7.63 \times 10^8 \Omega \cdot \text{cm}^2$), indicating that the SLIPS exhibits excellent anti-corrosion performance. Typically, the $R_{ct}$ analysis of SLIPS is consistent with the results of the semi-quantitative comparison of $|Z|_{0.01 \text{ Hz}}$ values.

Durability is one of the key factors that restrict SLIPS for practical application. To study the durability of applying SLIPS for corrosion protection, EIS measurements of SLIPS immersed in the bacterial culture solution for 2, 3, 7, and 14 days were evaluated, as shown in Figure 13. The $|Z|_{0.01 \text{ Hz}}$ values of SLIPS exhibit a slight decrease with the increased time of immersion. The $|Z|_{0.01 \text{ Hz}}$ value of SLIPS after 14 days of immersion is $4.89 \times 10^9 \Omega \cdot \text{cm}^2$, indicating that the SLIPS had a stable anti-corrosion performance. The EIS results were further fitted by the equivalent circuit model shown in Figure 13d due to the same electrochemical character of SLIPS, and the fitted electrochemical parameters of SLIPS at different days of immersion are shown in Table 2. The $R_{ct}$ value of SLIPS after 14 days of immersion slightly

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**Table 1:** EIS fitting results of three samples soaked in bacterial solution for 2 h

<table>
<thead>
<tr>
<th>Samples</th>
<th>$CPE_f$</th>
<th>$CPE_{dl}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$Y$ ($\Omega^{-1}\text{ s}^n\text{ cm}^2$)</td>
<td>$n$</td>
</tr>
<tr>
<td>BS</td>
<td>$2.18 \times 10^{-5}$</td>
<td>0.7582</td>
</tr>
<tr>
<td>SHS</td>
<td>$6.52 \times 10^{-11}$</td>
<td>1</td>
</tr>
<tr>
<td>SLIPS</td>
<td>$8.07 \times 10^{-11}$</td>
<td>0.9859</td>
</tr>
</tbody>
</table>
dropped to $1.57 \times 10^9 \Omega \cdot \text{cm}^2$, which corresponds to the corrosion inhibition efficiency of 99.99%, indicating that the SLIPS had an excellent and stable anti-corrosion performance after the long-term immersion.

In addition to the EIS experiment, the potentiodynamic polarization experiment was also utilized to quantitatively evaluate the corrosion resistance behavior of SLIPS. The polarization curve described the relationship between corrosion current density ($I_{\text{corr}}$) and corrosion potential ($E_{\text{corr}}$). Generally, the coating with higher corrosion potential and lower corrosion current density possessed superior anti-corrosion performance. After immersion for 14 days in *Pseudoalteromonas* sp. culture solution, as shown in Figure 14, the $E_{\text{corr}}$ of bare Q235 carbon steel and SLIPS was $-0.67$ and $-0.48$ V, respectively, indicating that the bare Q235 carbon steel is more likely to be corroded compared with SLIPS surface coated substrate. Besides, the $I_{\text{corr}}$ of bare Q235 carbon steel and SLIPS was $4.37 \times 10^{-6}$ and $1.15 \times 10^{-8}$ A·cm$^{-2}$, respectively. It was

![Figure 13](image-url)  
**Figure 13:** Results and fitted plots of the BS, SHS, and SLIPS after immersion in *Pseudoalteromonas* sp. culture solution for 2 h, 3 days, 7 days, and 14 days: Nyquist plots (a); Bode-$|Z|$ versus frequency plots (b); Bode-phase angle plots (c); and equivalent circuit (d).

<table>
<thead>
<tr>
<th>Samples</th>
<th>$Y$ ($\Omega^{-1} \cdot \text{s} \cdot \text{cm}^2$)</th>
<th>$n$</th>
<th>$R_f$</th>
<th>$Y$ ($\Omega^{-1} \cdot \text{s} \cdot \text{cm}^2$)</th>
<th>$n$</th>
<th>$R_{ct}$ ($\Omega \cdot \text{cm}^2$)</th>
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<tr>
<td>BS</td>
<td>$2.18 \times 10^{-5}$</td>
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<td>7.18</td>
<td>$1.73 \times 10^{-3}$</td>
<td>0.7625</td>
<td>$7.63 \times 10^2$</td>
</tr>
<tr>
<td>SHS</td>
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<td>1</td>
<td>$3.62 \times 10^7$</td>
<td>$1.22 \times 10^{-8}$</td>
<td>0.6604</td>
<td>$7.87 \times 10^8$</td>
</tr>
<tr>
<td>SLIPS</td>
<td>$8.07 \times 10^{-11}$</td>
<td>0.9859</td>
<td>$1.68 \times 10^{11}$</td>
<td>$9.23 \times 10^{-11}$</td>
<td>0.9801</td>
<td>$3.31 \times 10^9$</td>
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</tbody>
</table>

*Table 2:* EIS fitting results of three samples soaked in bacterial solution for 2 h.
It is obvious that the $I_{\text{corr}}$ of SLIPS was two orders of magnitude lower than that of Q235 carbon steel. This result further demonstrated that SLIPS could effectively mitigate the corrosion rate of the underlying substrate in *Pseudoalteromonas* sp. culture solution.

### 4 Conclusion

In summary, we developed a novel and efficient method for fabricating SLIPS on the surface of base materials. The hydrophobic modification of nano-$\text{SiO}_2$ can be quickly completed under mild conditions by thiol-ene click chemical reaction, and then SLIPS was successfully prepared by injecting silicone oil as a lubricant into the superhydrophobic rough structure. Through the universal spraying method, SLIPS can be quickly constructed on different shapes and material surfaces. The surface wettability results show that 10 µL water droplets can slip on the SLIPS and stained water droplets can slip without any stain mark, which proves that the SLIPS has an excellent slippery property. In addition, the anti-fouling test shows that the SLIPS has a value of 98.56% and 98.69% of bacterial attachment inhibition efficiency under static and dynamic conditions, respectively. This is due to the slippery lubricating oil film forms a molecular-level slippery surface that can effectively hinder the attachment and infiltration of bacteria during immersion in *Pseudoalteromonas* sp. culture solution. The EIS test showed that SLIPS possess stable and excellent anti-corrosion properties after immersion in *Pseudoalteromonas* sp. culture solution, the $|Z|_{0.01 \text{ Hz}}$ value is $4.89 \times 10^{10}$ Ω cm$^2$ and the corrosion inhibition efficiency is 99.99%. This study offers a practical and simple method to prevent the MIC of steel in marine environment. Meanwhile, the conclusions in this work provide rational guidelines for the optimization of slippery surface for long-term anti-corrosion and anti-fouling applications.

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