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Investigation on pitting resistance of Sn-containing ferritic stainless steel with solution simulation method

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Abstract
In this study, Sn$^{2+}$ solution simulation method is used to investigate the effect of Sn on pitting corrosion behavior of tin-containing ferritic stainless steel 430LX. It is found that the correlation between $E_{\text{pit}}$ and [Sn$^{2+}$] is opposite to the correlation between critical potential temperature (CPT) and [Sn$^{2+}$]. After potentiostatic polarization at a specific potential, the correlations become the same. The CPT experiment after a series of potentiostatic steps proves that Sn$^{2+}$ exhibits positive influence only when the pH and potential is within a certain range. All the complicated phenomena can be explained by the under-potential deposition mechanism. SnO$_2$ passivation film that enhances the corrosion resistance is only produced when under-potential deposition occurs.

1. Introduction

Ferritic stainless steels are being increasingly used in various applications and environments due to their excellent corrosion resistance [1]. Allooying elements, including Cr and Mo, play the vital role in the corrosion resistance of stainless steels [2–4]. However, the rising and fluctuating price of these elements make it meaningful to search for substitute elements and develop new steel grades [5].

Sn, conventionally considered harmful to steels in terms of mechanical properties, [6] is found beneficial to the corrosion resistance. Adding trace Sn can improve the uniform corrosion resistance of stainless steels in acidic environment and pitting resistance in chloride-containing solution, which has been reported on both austenitic [7] and duplex [8] stainless steel.

However, the fundamental inhibition mechanism of Sn is still unclear. Existing publications mainly focus on the measurement of the corrosion resistance of Sn and give limited discussion on specific inhibition process or theoretical model. Moreover, some authors pointed out Sn plays the positive role in stainless steels only when its chemical composition was within a certain range [9, 10]. In addition, Zhang found that adding 0.33% Sn to a ferritic stainless steel increased the uniform corrosion resistance but decreased the pitting resistance in sulfuric acid environment [11, 12]. These phenomena have not been well explained.

Pitting is a complicated corrosion form which includes successive steps of passivity breakdown, metastable pitting and steady-state propagation. To clarify the influence of Sn on the pitting resistance, it is necessary to reveal the existence form of Sn in the passive film. It was proposed by some authors that alloying Sn element in ferritic stainless steel formed a protective rust layer on the surface, which would reduce the corrosion rate [13]. On the other hand, Hiraide reported that the addition of a trace amount of Sn$^{2+}$ in sulfuric acid solution can also reduce the corrosion rate of ferritic stainless steel [14]. And the inhibition effect of Sn$^{2+}$ was found more significant in chloride-containing environment [15]. Given that the inhibition effect of Sn$^{2+}$ in solution is similar to that of alloying Sn, the existence of Sn$^{2+}$ may be the key to the corrosion inhibition of Sn. If it’s possible to reveal the existing forms of Sn under different conditions and build a relationship to the corresponding inhibition effect, the mechanism of Sn can be better revealed.

Solution simulation is a commonly used method to study alloy elements and the reliability of solution simulation was proved in the investigations of Cr and Ni [16, 17]. Within a certain range, the content of metal
element in the alloy can be accurately compared with the concentration of the corresponding ion in the solution. By this means the exact inhibition mechanism of Sn in stainless steel can be reasonably explored. In the present study, using a ferritic stainless steel 430LX, this study first compares the inhibition effect of alloying Sn and Sn\(^{2+}\) and proves the feasibility of Sn\(^{2+}\) solution simulation. On this basis, we apply solution simulation and find an interesting phenomenon that Sn\(^{2+}\) plays its inhibitory role only when the specimen is within a certain potential range, which can be explained by the under-potential deposition theory [18].

2. Experimental

2.1. Materials
The experimental materials are tin-free ferritic stainless steel SUS 430LX and three kinds of tin-containing stainless steels, with the Sn contents of 0.10%, 0.28% and 0.47%, respectively. Chemical compositions of these materials are shown in table 1. For brevity, if not indicated specifically, 430LX refers to 0Sn 430LX in the following text.

For electrochemical experiments, the materials are cut from ferritic stainless steels leaving a working area of 10 mm × 10 mm with a thickness of 3 mm, all specimens are grounded to 2,000 grit with emery paper, then polished with 1.5 μm diamond paste, follow by ultrasonic cleaning in acetone, alcohol, and deionized water.

| Materials | C (wt%) | Si (wt%) | Mn (wt%) | P (wt%) | S (wt%) | Cr (wt%) | N (wt%) | Ti+Nb (wt%) | Sn (wt%) | Fe (wt%) |
|-----------|---------|----------|----------|---------|---------|---------|--------|------------|---------|---------|
| 0Sn       | 0.015   | 0.51     | 0.28     | 0.024   | 0.0020  | 16.41   | 0.0070 | 0.28       | —       | Bal.    |
| 0.10Sn    | 0.0053  | 0.30     | 0.23     | 0.0056  | 0.0036  | 16.60   | 0.0065 | 0.27       | 0.10    | Bal.    |
| 0.28Sn    | 0.0085  | 0.35     | 0.23     | 0.0053  | 0.0018  | 16.57   | 0.0081 | 0.28       | 0.28    | Bal.    |
| 0.47Sn    | 0.0051  | 0.34     | 0.24     | 0.0067  | 0.0029  | 16.15   | 0.0077 | 0.27       | 0.47    | Bal.    |

Table 1. Chemical composition of Sn addition stainless steel (wt%).

Figure 1. The critical pitting potential (E_{pct}) curves of ferritic stainless steel with different content of Sn in NaCl solution.

2.2. Electrochemical testing
The electrochemical measurements are carried out with a PARSTAT MC electrochemical system. All the experiments except CPT tests are carried out at 30 °C. The electrochemical measurements are performed in a conventional three-electrode cell. The stainless steel specimens are used as the working electrode, a platinum sheet as the counter electrode, and a saturated calomel electrode (SCE) is used as the reference electrodes [19–22].

This paper designs a potential independent critical pitting temperature (CPT) experiment based on the ASTM G150 standard. The CPT measurements are carried out in 1.0 M NaCl solutions. Before CPT measurements, cathodic polarization at −900 mV versus SCE (all potentials below are relative to SCE) is recorded for 120 s, then open-circuit potential is recorded for 600 s. The anodic potential in the CPT test is 250 mV and the solution temperature is increased at a rate of 1 °C min\(^{-1}\) from the beginning of 15 °C. When the current density increases to 1 mA cm\(^{-2}\), the experiment would stop and the temperature where the current
density equals to 0.1 mA cm$^{-2}$ is the critical pitting temperature. During the test, pure nitrogen gas is bubbled for removing dissolved oxygen. Each test is conducted at least three times to guarantee the repeatability.

The potentiostatic polarization plots and potentiodynamic polarization plots are carried out in 1 M NaCl solution at 30°C. For the solution simulation, different amounts of SnCl$_2$ are added into NaCl solution to obtain a series of Sn$^{2+}$ concentrations from 10$^{-5}$ M to 10$^{-2}$ M, pH is affected but the results don’t change. Before the measurements, cathodic polarization and open-circuit potential are also performed. Potentiostatic polarization measurements are conducted at different potentials from $-0.6$ mV to $-0.3$ mV for 10 min The tested specimens are used for subsequent potentiodynamic polarization tests. Potentiodynamic polarization measurements are conducted with a scan rate of 0.1 mV s$^{-1}$ from $-600$ mV to the potential at which the current indicates that stable pitting or transpassivation occurs. The pitting potential ($E_{pit}$) is defined as the potential at which the current density is over 0.1 mA cm$^{-2}$. All the tests are replicated three times to ensure the accuracy.

3. Results and discussion

3.1. Verification of solution simulation

The pitting potential ($E_{pit}$) is the potential at which stable pits nucleate and grow. The higher the $E_{pit}$, the higher the resistance to pitting corrosion. Figure 1 shows the polarization curves of 430LX with different Sn contents in 1 M NaCl solution. In this experiment, Sn-free 430LX has the lowest $E_{pit}$. As the Sn content increases from 0% to
0.47%, the $E_{\text{pit}}$ rises from 0.178 V to 0.295 V. Figure 2 shows the polarization curves of 0Sn 430LX in 1 M NaCl solution with different additions of Sn$^{2+}$. As the Sn$^{2+}$ concentration increases from 0.0003 M to 0.01 M, the $E_{\text{pit}}$ rises from 0.211 V to 0.471 V. The amount of Cl$^{-}$ is different in each test, but it should be a small effect considering that $E_{\text{pit}}$ follows a $-\log[\text{Cl}^{-}]$ relationship. It can be considered according to the results that Sn shows its performance of inhibiting pitting corrosion whether as ions or alloy elements.

Figure 3 compares the $E_{\text{pit}}$ shown in figures 1 and 2 more clearly. $E_{\text{pit}}$ of 0.10Sn 430LX is similar to that of 0Sn 430LX in 0.0003 M Sn$^{2+}$ solution and the $E_{\text{pit}}$ of 0.47Sn 430LX is similar to that of 0Sn 430LX in 0.003 M Sn$^{2+}$ solution, which proves the similarity of the two experimental methods of tin-containing one and the solution simulation one.

Assuming Sn$^{2+}$ can simulate Sn in the stainless steel, figure 3 reflects the correlation between Sn$^{2+}$ concentrations and compositions of alloyed Sn. To simulate the Sn content in the actual tin-containing stainless steel, the Sn$^{2+}$ concentration used in the experiment will be selected with reference to figure 3.

Table 2 shows the pH-time relationship of solutions with different concentrations of SnCl$2$ solution, which is related to the hydrolysis of Sn$^{2+}$, the hydrolysis equation is shown as equation (1). According to the amount of H$^+$ generated by hydrolysis, Sn$^{2+}$ concentration remaining in the solution can be calculated by equation (2) and the amount of hydrolyzed Sn$^{2+}$ is lower than 15%. Therefore, the solution simulation method is feasible in the potentiodynamic polarization experiment for stainless steel 430LX.

\[ \text{Sn}^{2+} + 2\text{H}_2\text{O} \rightarrow \text{Sn(OH)}_2^+ + 2\text{H}^+ \]  
\[ M(\text{Sn}^{2+}) = M(\text{SnCl}_2) - 0.5M(\text{H}^+) \]

### 3.2. Effect of Sn$^{2+}$ content on the corrosion behavior of ferritic stainless steel

To reveal the effect of Sn$^{2+}$, potentiodynamic polarization tests and CPT tests are carried out under different Sn$^{2+}$ concentrations.

Potentiodynamic polarization experiments in figure 3 have proved that Sn$^{2+}$ has the ability to inhibit pitting corrosion. However, the result of CPT tests shown by figure 4 exhibits a different correlation between the concentration of Sn$^{2+}$ and pitting corrosion behavior. When the Sn concentration increases from 0 to 0.01 M, the CPT decreases from 33 ℃ to 20 ℃, which means that Sn$^{2+}$ can promote the occurrence of pitting.

The trend of CPT is also given in figure 4, where it is compared with the trend of $E_{\text{pit}}$. Looking at figure 2 alone, it can be found that in the Sn$^{2+}$ solution environment, the higher the Sn$^{2+}$ concentration, the higher the
Epit and the stronger the pitting resistance. In the result of CPT tests, the higher the Sn$^{2+}$ concentration, the lower the CPT and the weaker the pitting resistance, which is completely contrary to the Epit results.

According to the results shown in figure 4, Sn has shown different corrosion effects on different experiments, which indicates that the corrosion inhibition of Sn only functions under certain conditions. The most significant difference may lie in the potential, therefore, the influence of potential on the inhibitory effect of Sn becomes a key goal of in-depth study, which will be shown in the next section.

3.3. The effect of potential on the inhibitory behavior of Sn$^{2+}$

In order to study the principle that the aforementioned three kinds of experiments lead to different results, a series of potentiostatic polarization experiments are performed prior to the three experiments. CPT tests after a potentiostatic polarization experiment at $-0.45$ V for 600 s in different concentration of SnCl$_2$ solution are shown in figure 5. The CPT increases from 33 °C to 56 °C as the concentration of Sn$^{2+}$ increases from 0 M to 0.01 M.

All the tests are compared with CPT tests without potentiostatic polarization in figure 5. Tests with potentiostatic polarization (black plot) show higher pitting temperature than those without potentiostatic polarization (red plot). When the concentration of Sn$^{2+}$ increases, the CPT with potentiostatic polarization becomes higher, which is similar to the trend of potentiodynamic polarization tests but contrary to the CPT tests without potentiostatic polarization (see figure 4).
In order to further prove the influence of potential, the same potentiostatic polarization experiments at $-0.45 \text{ V}$ for 600 s are applied prior to potentiodynamic polarization tests in SnCl$_2$ solutions with different concentrations. According to figure 6(A), the $E_{\text{pit}}$ increases from 0.422 V to 0.7 V as the concentration of Sn$^{2+}$ increases from 0.0003 M to 0.01 M. Compare these results with figures 2, 6(B) is obtained, which shows that the potentiostatic polarization in Sn$^{2+}$ solution can increase the pitting potential.

The polarization curves starting from a more positive potential, $-0.25 \text{ V}$, are also measured, as shown in figure 7(A). It is shown that the $E_{\text{pit}}$ decreases when the concentration of Sn$^{2+}$ increases. Comparing the results in figure 7(A) with the results in figures 2, 7(B) shows the opposite trend between experiments starting from $-0.25 \text{ V}$ and $-0.5 \text{ V}$, which means without getting through the low potential, SnCl$_2$ wouldn’t demonstrate protection against corrosion.

According to the above experiments from figure 1 to figure 7, in potentiodynamic polarization tests, the potential experienced the whole range from $-0.6 \text{ V}$ to pitting potential, but in CPT tests, the potential is kept at 0.25 V and OCP, respectively. Besides, the polarization curves in figure 7(A) start from $-0.25 \text{ V}$. Therefore, it can be inferred that Sn$^{2+}$ may activate its inhibitory effect at a potential higher than OCP but lower than $-0.25 \text{ V}$, or lower than OCP. The inhibitory effect will persist until pitting.

To obtain a more accurate potential range, more CPT tests are performed. All the results (average of three experiments) are shown in table 3. Every data reflects the CPT measured after a 600 s potentiostatic polarization experiments at different potentials (versus SCE.).

| [SnCl$_2$] (mol l$^{-1}$) | None | $-0.55 \text{ V}$ | $-0.5 \text{ V}$ | $-0.45 \text{ V}$ | $-0.4 \text{ V}$ | $-0.35 \text{ V}$ |
|--------------------------|------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 0                        | 34   | 29              | 33              | 33              | 33              | 33              |
| 0.0003                   | 29   | 26              | 46              | 43              | 42              | 29              |
| 0.001                    | 26   | 22              | 47              | 47              | 45              | 25              |
| 0.003                    | 23   | 20              | 54              | 52              | 50              | 24              |
| 0.01                     | 21   | 18              | 19              | 56              | 57              | 20              |
| 0.03                     | 19   | 16              | 17              | 16              | 19              | 17              |

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To obtain a more accurate potential range, more CPT tests are performed. All the results (average of three experiments) are shown in table 3. Every data reflects the CPT measured after a 600 s potentiostatic polarization at a certain potential and Sn$^{2+}$ concentration. At a certain potential, if a CPT value in higher concentration of Sn$^{2+}$ is greater than that in lower concentration, it can be considered that there is pitting inhibition of Sn$^{2+}$ under this condition. According to this rule, Sn$^{2+}$ can only show its corrosion resistance between $-0.5 \text{ V}$ and $-0.4 \text{ V}$.

### 3.4. Composition analysis of Sn at different potentials

Through all the tests in table 3, the range that Sn element shows its pitting resistance properties has been basically determined. On this basis, it is necessary to analyze the underlying mechanism of this range. Therefore, the surface products of the sample are analyzed to determine the existing form of Sn. Figure 8 shows the XRD patterns of 0Sn 430LX specimens after polarized at 0 V or $-0.45 \text{ V}$ for 600 s in 1 M NaCl solution with 0.003 M Sn. The only difference between the two graphs is the peak of SnO$_2$, which proves that SnO$_2$ forms at $-0.45 \text{ V}$. 

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**Table 3.** The results (℃) of CPT test in Sn$^{2+}$ solutions with different concentrations after a 600 s potentiostatic polarization experiments at different potentials (versus SCE.).

![Figure 7.](image_url)

**Figure 7.** (A) The polarization curves of 430LX starting from $-0.25 \text{ V}$. (B) The $E_{\text{pit}}$ of 430LX measured by polarization curves starting from $-0.5 \text{ V}$ and $-0.25 \text{ V}$. 

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To further verify the existence of SnO$_2$, XPS tests are shown in figure 9. Figure 9(A) is a 430LX specimen which has been subjected to potentiostatic polarization experiment at 0 V for 600 s in 1 M NaCl solution with 0.003 M Sn. Figure 9(B) is a 430LX sample which has been subjected to potentiostatic polarization experiment at $-0.45$ V for 600 s. Obviously, figure 9(A) fails to show the existence of Sn, while figure 9(B) shows a clear distribution of Sn compounds.

According to figures 8 and 9, it can be judged that the main way for Sn to inhibit corrosion is to form a SnO$_2$ film. Therefore, the range of the inhibitory effect of Sn$^{2+}$ is equivalent to the formation range of SnO$_2$ film. In this way, the complex problem of the role of Sn$^{2+}$ is transformed into the problem of the formation of SnO$_2$ film.

A previous study has proved that SnO$_2$ would also form on the surface of the 430LX samples with Sn element alloyed after potentiostatic polarization test [23]. The similar XRD results between Cheng’s study and figure 9 proves once again that Sn, whether as an alloying element or as ions in solution, has a similar effect on the corrosion process of ferritic stainless steel.

### 3.5. Discussion

As all the results above show, Sn$^{2+}$ could affect ferritic stainless steel 430LX in SnCl$_2$ solution in different ways at different potentials. All the results can be well interpreted with the under-potential deposition (UPD) theory, which mainly refers to the phenomenon that one metal cations (Me$^{z+}$) adsorbed on another metal matrix (Me') at a potential positive to its equilibrium potential $E_{eq(Me^{z+}/Me')}$ This phenomenon is caused by the strong interaction between the deposited metal and the substrate, and the deposited layer is strictly a single-layer metal [24]. The potential interval of UPD, $\Delta E_{UPD}$, conforms to the Kolb–Gerischer linear relationship, which can be calculated by equation (3).

$$\Delta E_{UPD} = E_{a,UPD} - E_{eq(Me^{z+}/Me')} \approx 0.5(\Phi_{Me} - \Phi_{Me'})$$

In equation (3), $E_{a,UPD}$ is the critical UPD potential, it means that when the potential is higher than $E_{eq(Sn^{2+}/Sn)}$ and lower than $E_{a,UPD}$ under-potential deposition may occur. $\Phi_{Me}$ is the work fuction of metal Me.
Figure 9. The XPS results of the 430LX sample after potentiostatic polarization in 1 M NaCl containing 0.003 M Sn\(^{2+}\) solution at (A) 0 V and (B) −0.45 V.

Figure 10. The calculated \(\frac{E_{eq}(\text{Sn}^{2+}/\text{Sn})}{\text{Sn}}\) based on the Sn-UPD theory. The red dot indicates that the CPT is elevated if 430LX is polarized at this point.
In this circumstance, Me and Me’ mean Sn and 430LX, respectively. \( \Phi_{\text{Sn}} \) is 4.42 eV, \( \Phi_{\text{Fe}} \) is 4.66 eV, and \( \Phi_{\text{Cr}} \) is 4.50 eV. Based on the mole fraction of Fe (\( X_{\text{Fe}} = 0.826 \)) and Cr (\( X_{\text{Cr}} = 0.174 \)), \( \Phi_{430\text{LX}} \) can be estimated as 4.63 eV. Therefore, \( \Delta E_{\text{UPD}} = 0.105 \) V [25]. Finally, \( E_{\text{A,UPD}} \) can be calculated by equation (4), and the result is shown as the upper line in figure 10 and the dashed line in figure 11.

\[
E_{\text{A,UPD}} = E_{\text{aq(Sn}^{2+}/\text{Sn})} + 0.105\text{V}
\]

All the data from table 3 are plotted in figure 10 where each CPT test is a point. The red dot indicates that Sn\(^{2+}\) exhibits the inhibitory effect. This result basically corresponds to the UPD range. All the experiments that verify the protection effect of Sn have gone through a potential between \( E_{\text{eq Sn}^{2+}/\text{Sn}} \) and \( E_{\text{aq(Sn}^{2+}/\text{Sn})} + 0.105 \) V.

To theoretically reveal the existence of SnO\(_2\), a simple Pourbaix diagram of Sn is shown as figure 11. All solid lines are calculated by the Nernst equation, and the dashed lines are calculated based on the Nernst equation and the under-potential deposition theory. The figure shows the existing form of Sn element at a certain potential and pH. The area below the dotted line is the area where under-potential deposition may occur and the under-potential deposition range is the pink area in figure 11.

According to the experiments above, the appearance of the corrosion resistance of Sn\(^{2+}\) requires stainless steel to experience a certain potential in the Sn\(^{2+}\) solution and the corrosion resistance will not disappear as the
continuous rise of potential. Coincidentally, all the experiments passed the UPD range (pink region in figure 11) show the corrosion resistance of Sn at high potential. Therefore, it is reasonable to believe that UPD may change the deposition method of SnO2 and also form a SnO2 passive film that resists corrosion.

As the potential gradually increases, the morphology of the Sn element in the solution gradually changes. The effect of UPD in this process and its influence on the formation of SnO2 passive film at different pH range is shown in figure 12.

In figure 12, the three schematic diagrams describe the change process of Sn element during the potential rise process indicated in the three pH ranges from right to left in figure 11. It should be noted that figure 11 is established with [Sn^{2+}] = 0.001 M. As the change of the concentration of Sn^{2+}, the corresponding pH ranges are not exactly the same as those in figure 11.

Figure 12(A) shows the situation at high pH. At low potentials (Sn stable region), Sn deposits unevenly on the surface of stainless steel [26]. As the potential rises, the deposited Sn on the surface is directly oxidized to SnO2. In this case, the oxidation product is not uniform, and thus not protective.

Figure 12(B) shows the situation at middle pH. When the potential exceeds the equilibrium potential of Sn/Sn^{2+}, UPD occurs (pink region in figure 11) and a monolayer Sn forms on the surface of the specimen. As the potential continues to rise, this monolayer then oxidizes into SnO2. According to the Pourbaix diagram, Sn^{2+} in the solution may deposit on the surface, forming a uniform and compact SnO2 film when the potential rises. As a result, a passive film of SnO2 forms, increasing the pitting resistance of 430LX.

Figure 12(C) shows the situation at low pH. In the UPD potential range, on the surface of the stainless steel, a single layer of Sn will also adsorb. But before the Sn element begins to transform into SnO2, the potential has exceeded the under-potential deposition range, and the adsorption layer is dissolved. Therefore, no dense and uniform SnO2 passive film forms eventually.

According to the pH measured in table 2, 0.0003 M to 0.01 M SnCl2 will lead to a middle pH solution and 0.03 M SnCl2 will lead to a low pH solution. Therefore, 0.03 M SnCl2 cannot show the corrosion inhibition. It can be found that the corrosion protection effect revealed by figure 10 corresponds well to figures 11 and 12. All experimental results above can be perfectly explained by the UPD theory.

In general, the necessary condition for the uniform growth of SnO2 passive film in this experimental environment is to undergo an UPD process, and the UPD film of Sn is directly converted to SnO2, which seems to be a relatively restrict condition. But in fact, due to the influence of the hydrolysis process of Sn itself, the possibility of a tin-containing environment to meet this condition is very high. In Zhang’s research [11, 12], when the Sn content of tin-containing stainless steel is too high, the uniform corrosion resistance still rises, but the pitting corrosion resistance drops significantly. UPD theory can also explain this phenomenon. Too low pH will cause SnO2 to fail to form a passive film at high potential, which is shown in figure 12(C) [12, 13]. The UPD theory is used to reasonably explain the previous study on tin-containing stainless steel. But of course, its reliability and more details need to be further verified by subsequent studies.

4. Conclusions

In this work, Sn^{2+} solution simulation method is proved to be feasible for studying the pitting resistance of Sn-containing ferritic stainless steel. 0.003 M Sn^{2+} can be used to simulate 0.47% Sn tin-containing stainless steel, 0.0003 M Sn^{2+} can be used to simulate 0.10% Sn tin-containing stainless steel. Sn^{2+} can inhibit pitting corrosion only when the test experiences a potential between −0.4 V and −0.5 V. At the same time, the concentration of Sn^{2+} needs to be less than 0.03 M. UPD theory can explain the mechanism that Sn^{2+} only produces pitting resistance at the specific potential and pH: Sn^{2+} forms a monolayer in the under-potential deposition range, and then transforms into a SnO2 passive film with pitting resistance.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.
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