

Article

The Corrosion Resistance of Tartaric-Sulfuric Acid Anodic Films on the 2024 Al Alloy Sealed Using Different Methods

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Abstract: Tartaric-sulfuric acid anodic (TSA) films were prepared on the surface of the 2024 Al alloy. These films were sealed with cerium salts at 25 °C and 65 °C, hot water, and dichromate. The morphology and corrosion resistance of the anodic films were investigated using a field emission scanning electron microscope/energy-dispersive spectrometer, an electrochemical workstation, an acidic spot test, and an immersion test. The results indicated that the surface of the TSA film sealed with cerium salt at 65 °C had a slightly lower cerium content compared to the TSA film sealed at 25 °C. It was found that increasing the sealing temperature of cerium salt could enhance the corrosion resistance of the TSA film. After immersion in a 3.5 wt.% NaCl solution for 336 h, no obvious corrosion pits were observed on the surface of the TSA film sealed at 65 °C, whereas many larger corrosion pits appeared on the surface of the TSA film sealed at 25 °C. The improved corrosion resistance of the TSA film sealed at 65 °C could be attributed to the synergistic effect of cerium oxide deposition and the hydration reaction. The corrosion resistance of the TSA film sealed at 65 °C was significantly better than that of the film sealed with hot water, but it was still lower than that of the TSA film sealed with dichromate.

Keywords: tartaric-sulfuric acid anodic film; 2024 Al; cerium salt sealing; corrosion resistance



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1. Introduction

The 2024 Al alloy is widely used in construction and aerospace applications due to its excellent mechanical properties [1]. It has excellent mechanical properties due to its complex microstructure [2,3]. However, alloying can deteriorate the corrosion resistance of the alloy, although it can improve its mechanical properties. For the 2024 Al alloy, the existence of the Cu-rich CuAl₂ phases and Cu-poor regions [4–7] enhances the local electrochemical activity in the alloy [8–12], resulting in severe localized corrosion. Ramirez et al. [13] also found that localized corrosion pits are generally formed in the vicinity of Cu-rich intermetallic compounds. Therefore, aluminum alloys need to be protected to enhance their corrosion resistance and thus increase their service life. Among all the protection methods, anodizing is widely used because of its simple process, low cost, and excellent protection.

Currently, the most widely used anodizing process for aluminum alloys is sulfuric acid anodizing (SAA) [14]. This process offers advantages such as easy operation and the formation of a thick film. However, it can also increase the probability of corrosion fatigue in the workpiece [15]. Additionally, the SAA process consumes a significant amount of sulfuric acid, which can have a considerable impact on the environment. Therefore, it is necessary to develop an anodizing process that provides excellent corrosion resistance while minimizing its environmental impact. A new process, known as tartaric-sulfuric acid anodizing (TSA), was developed by Airbus in France [16,17]. This process significantly reduces the amount of sulfuric acid used compared to the SAA process. Furthermore, Curioni et al. [18] found that the addition of tartaric acid could reduce the dissolution rate of the anodic film in an

acidic environment, thereby significantly enhancing the corrosion resistance of aluminum alloys. Boisier et al. [19] found that the pores of the TSA film were smaller than those of the SAA film, which led to the former showing superior corrosion resistance.

In order to further enhance the corrosion resistance of the anodic film on aluminum alloys, it is commonly sealed. There are many sealing methods, and hot water sealing (HWS) [20,21] is one of the most widely used methods, which involves the use of boiling water to seal the anodic film. HWS can cause the pore wall of the porous layer to swell due to the formation of hydrated alumina, γ -AlO(OH) [19,21–25]. The swelling of the pore wall is attributed to the fact that hydrated alumina typically has a larger volume than aluminum oxides, resulting in pore blockage. However, this method has disadvantages, such as high energy consumption and low efficiency. Dichromate sealing is an effective method. Hydroxy aluminum dichromate (AlOHCrO₄) or hydroxy aluminum chromate ((AlO)₂CrO₄) [21], produced by the reaction of dichromate with aluminum oxide, can inhibit the corrosion of the anodic film. However, Cr⁶⁺ is extremely hazardous to the environment and human health. The current research trend is to find environmentally friendly sealing methods [26–29]. Cerium salts are effective corrosion inhibitors [30] and have been widely used to improve the corrosion resistance of aluminum alloys [31–36]. Moreover, cerium is abundant in nature and is environmentally friendly. The application of cerium in anodic film sealing has attracted much attention [37–42]. Terada et al. [41] found that adding cerium salt to hot water could enhance the corrosion resistance of the TSA film on the 2024 Al alloy. Cerium ions not only formed a cerium conversion layer on the surface of the anodic film but also generated Ce(OH)₄ or CeO₂ precipitates in the micropores of the porous layer [23], which played a significant role in the corrosion protection of the anodic film [43]. In previous studies, it was found that increasing the temperature of the cerium salt sealing solution was beneficial for enhancing the corrosion resistance of the anodic film [13,37]. In the present study, the TSA films on the 2024 Al alloy were sealed with cerium salts at 25 °C and 65 °C, hot water, and dichromate. This research focused on examining the corrosion resistance and morphology of the sealed films.

2. Materials and Methods

2.1. Sample Pretreatment

The material used was the 2024 Al alloy plate, and its nominal chemical composition is listed in Table 1. The plate was first cut into samples with dimensions of 40 mm × 25 mm × 2 mm. Subsequently, the samples were ground step by step using 240#–1000# silicon carbide sandpapers. Before anodizing, the samples underwent the following treatments [40,44]: ultrasonic cleaning (acetone, 10 min; anhydrous ethanol, 20 min) using an ultrasonic cleaner (KQ3200B, Kunshan, China), followed by an alkaline wash (50 g/L NaOH, 60 °C, 3 min), and then desmutting (30% (v/v) HNO₃, 25 °C, 1 min). The samples were rinsed with deionized water after each step.

Table 1. Element composition of 2024 Al alloy.

Element	Fe	Si	Mn	Ni	Cu	Ti	Zn	Mg	Al
Content (wt.%)	0.45	0.50	0.70	0.09	4.70	0.13	0.25	1.75	Bal.

2.2. Anodizing and Sealing

The electrolyte for anodizing consisted of 40 g/L H₂SO₄ and 80 g/L C₄H₆O₆. During the anodizing process, the anode material was a 2024 Al alloy plate, and the cathode material was a lead plate. Anodizing was conducted at a constant voltage of 14 V for 25 min using a DC-regulated power supply, while the electrolyte was magnetically stirred at a temperature of 37 ± 1 °C. After anodizing, the samples were rinsed with deionized water and then thoroughly dried with cold air.

Cerium salt, hot water, and dichromate were used to seal the anodized samples, and H_2O_2 was added to the cerium salt solution within two minutes before sealing. The composition of the sealing solution as well as the sealing conditions are listed in Table 2.

Table 2. Sealing solutions and conditions.

Sealing Methods	Solution Composition	Time (min)	Temperature ($^{\circ}\text{C}$)	pH
Ce 25	40 g/L $\text{Ce}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$ + 3 g/L H_2O_2 (30%)	120	25 ± 1	4~5
Ce 65	40 g/L $\text{Ce}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$ + 3 g/L H_2O_2 (30%)	120	65 ± 1	4~5
Hot water	Deionized water	40	99 ± 1	6.5~7.5
Dichromate	50 g/L $\text{K}_2\text{Cr}_2\text{O}_7$	15	93 ± 1	5~6

2.3. Morphological Observation

The morphology and composition of the anodized samples were analyzed using a Hitachi S-4800 (Hitachi, Tokyo, Japan) field emission scanning electron microscope (FESEM) with an accompanying energy-dispersive spectrometer (EDS, Oxford, UK) [45]. The secondary electron (SE) mode was used to observe the surface of the sample, while the backscattered electron (BSE) mode was utilized to examine the cross-section. The cross-section for FESEM testing was prepared as follows: the sample was cut to the appropriate size using a hacksaw, embedded in epoxy resin, and then ground and polished using emery paper and diamond paste. Platinum was sputtered onto the surface of the samples using a Hitachi E-1045 ion sputter before observation.

2.4. Corrosion Resistance Test

The acidic spot test was conducted on the sealed samples using an acidic spot solution composed of 3 g of $\text{K}_2\text{Cr}_2\text{O}_7$, 25 mL of HCl ($\rho = 1.18 \text{ g/mL}$), and 75 mL of deionized water at room temperature. A drop of the solution was placed on the surface of the anodic film, and the time (t) was recorded when the droplet changed color from orange to green. The corrosion resistance of the anodic film was evaluated in terms of t . The longer the t , the better the corrosion resistance of the anodic film.

The corrosion resistance of the anodic film in the 3.5 wt.% NaCl solution was evaluated using electrochemical techniques. The test equipment used was an electrochemical workstation (CHI604E, Chenhua, Shanghai, China) [45], with a saturated calomel electrode (SCE) as the reference electrode, a graphite electrode as the auxiliary electrode, and an anodized sample (16.39 cm^2) as the working electrode. Before taking measurements, the open-circuit potential (OCP) of the samples should be stable. The scanning rate for potentiodynamic polarization was 0.5 mV/s , and the potential scanning range was $-1.0 \text{ V} \sim -0.25 \text{ V}$. The frequency range of electrochemical impedance spectroscopy (EIS) was $10^5 \text{ Hz} \sim 10^{-2} \text{ Hz}$, and a sinusoidal perturbation voltage of 10 mV was applied. In the present paper, EIS of anodized samples immersed in a 3.5 wt.% NaCl solution for 336 h was continuously monitored to evaluate the change in the corrosion resistance of the anodic film.

3. Results and Discussion

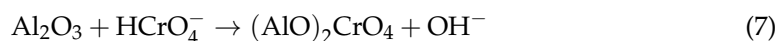
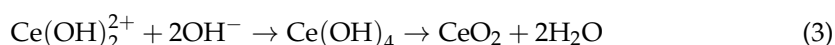
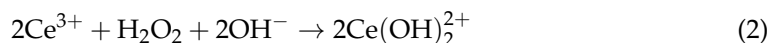
3.1. Morphology and Composition

The surface morphologies and composition of the TSA films sealed using different methods are shown in Figure 1. It can be seen that many spherical particles formed on the surface of the TSA film after sealing with Ce 25 (Figure 1a), which is consistent with the findings of Yu et al. [46]. After sealing with Ce 65, the surface of the TSA film was slightly rough (Figure 1c), relative to the case of Ce 25, which is associated with cerium oxide deposition and the hydration reaction of aluminum oxide [19]. Petal-like structures formed on the surface of the TSA film that was sealed with hot water (Figure 1e), which resulted from the precipitation of aluminum salt, as shown in reaction (1) [19]. As for

dichromate sealing, the surface of the TSA film was almost the same as the unsealed surface (Figure 1g,i).



According to the results of the EDS analysis, it is evident that the TSA films sealed with Ce 25 and Ce 65 contain elements such as O, Al, S, and Ce. However, the Ce content is lower for the film sealed with Ce 65 (Figure 1b,d). This is because an increase in temperature accelerates the decomposition of H_2O_2 , which reduces the amount of H_2O_2 available for the deposition of cerium oxide, resulting in a decrease in cerium content. The effect of H_2O_2 is demonstrated by its ability to hydrolyze to produce OH^- , which increases the pH value at the reaction site [37]. This contributes to the production of more $\text{Ce}(\text{OH})_4$ (reaction (2) and (3)) with a solubility product lower than that of $\text{Ce}(\text{OH})_3$ (reaction (4) and (5)) [38,47,48]. Hot water-sealed and -unsealed TSA films contain only Al, O, and S elements (Figure 1f,j). Element Cr was detected in the TSA film sealed with dichromate (Figure 1h) because chromate can react with aluminum oxide at high temperatures to form hydroxy aluminum dichromate (reaction (6)) and hydroxy aluminum chromate (reaction (7)) [49], which adhere to the surface and pores of the anodic film. The presence of element S in all samples indicates that the sulfate radical also participates in the anodizing reaction, which probably produces $\text{Al}_2\text{O}_3 \cdot \text{Al}(\text{OH})_x(\text{SO}_4)_y$ [44].



The cross-sectional morphologies of the TSA films sealed by different methods are shown in Figure 2. The darker part is the TSA film, and the thickness of the film is approximately 3 μm , which is consistent with the results reported [13]. The EDS line scanning results of the cross-section of the TSA film sealed with Ce 25 and Ce 65 are shown in Figure 3, the scanning route is from the surface to the substrate. It can be seen that the thickness of the TSA film is approximately 3 μm (Figure 3a), and Ce oxides precipitate in the porous layer (Figure 3a,b) [37]. Figure 3b also clearly shows that after sealing with Ce 65, the content of cerium in the TSA film is slightly lower than that of the TSA film sealed with Ce 25. On the one hand, higher temperatures not only promote cerium oxide deposition but also accelerate H_2O_2 decomposition, leading to a reduction in the amount of cerium oxide deposited in the film [50]. On the other hand, hydration reactions may also occur to a greater or lesser extent at higher temperatures, resulting in the swelling of the pore walls and the narrowing of the pores in the porous layer. In narrower pores, it is difficult for the sealing solution to diffuse, resulting in a lower amount of cerium oxide being deposited.

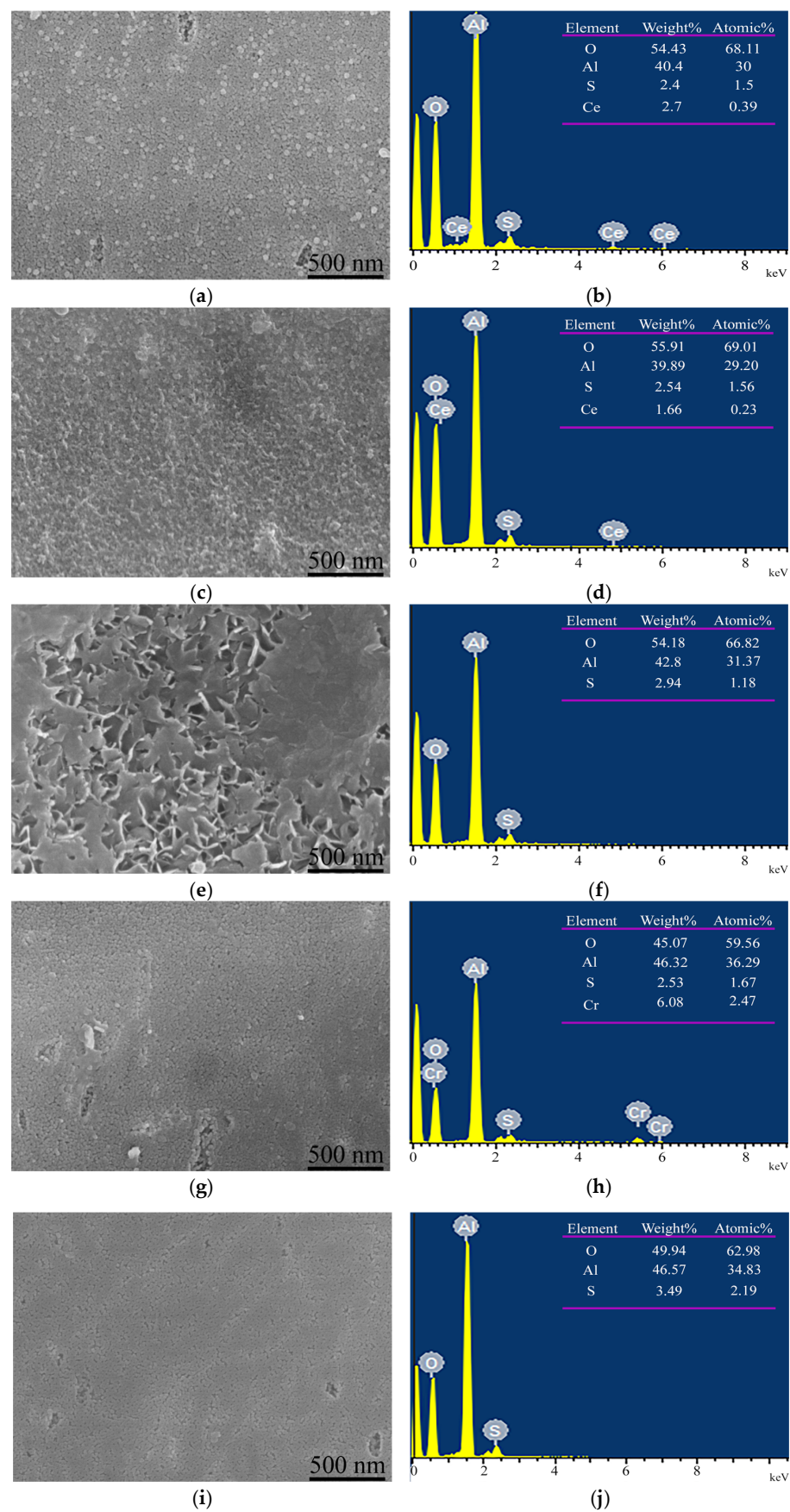


Figure 1. Surface FESEM images (50,000 $\times$) and EDS analysis results of TSA films sealed with (a,b) Ce 25, (c,d) Ce 65, (e,f) hot water, and (g,h) dichromate or left (i,j) unsealed.

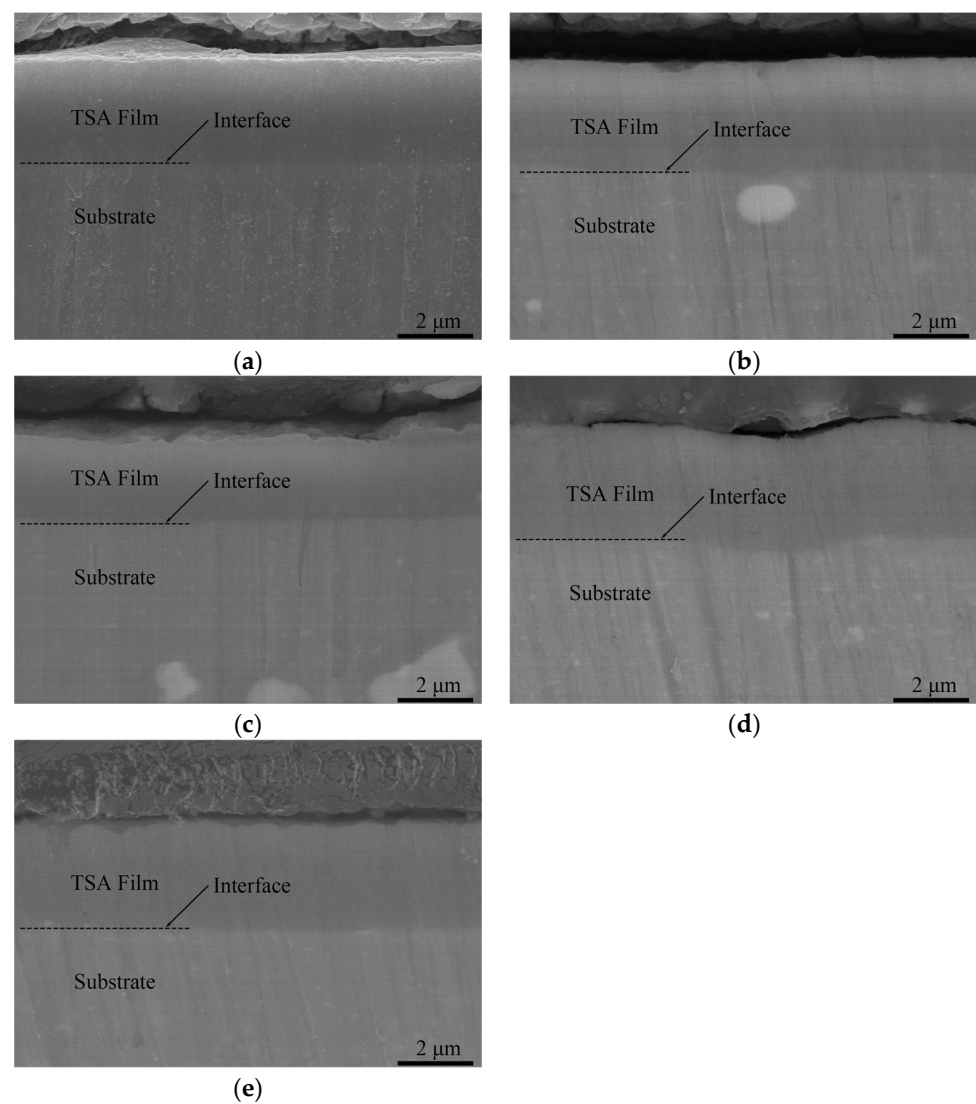


Figure 2. Cross-section FESEM images (10,000 $\times$) of TSA films sealed with (a) Ce 25, (b) Ce 65, (c) hot water, and (d) dichromate or left (e) unsealed.

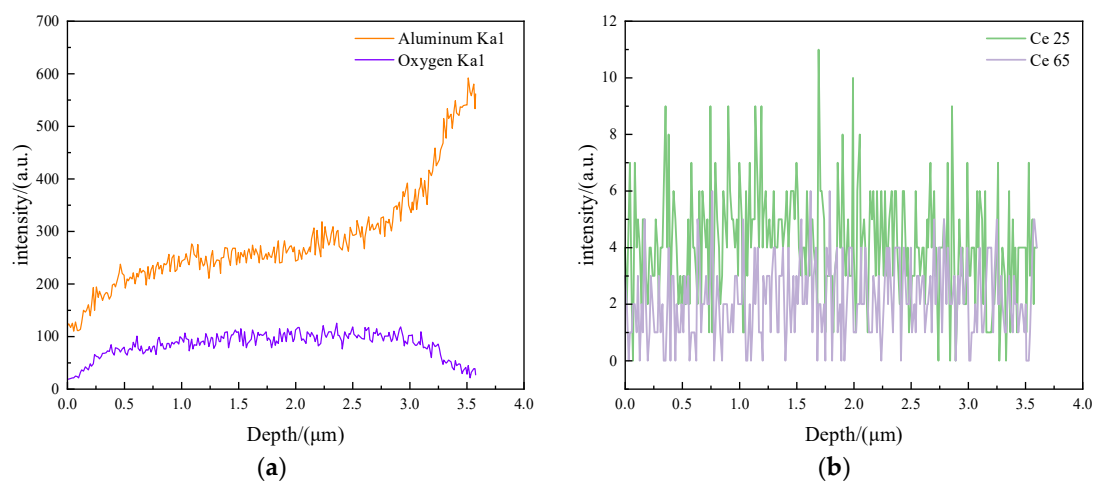


Figure 3. EDS line scanning results of (a) Al, O, and (b) Ce elements on the cross-section of the TSA film sealed with Ce 25 and Ce 65, where the line scanning route is from the film surface to the substrate.

3.2. Corrosion Resistance

The time, t , used to change the acidic spot droplet from orange to green in the acidic spot test, is listed in Table 3. It can be seen that the t of the TSA film sealed with Ce 25 and Ce 65 is 21.02 min and 35.38 min, respectively. The longer t is, the better the corrosion resistance of the anodic film. Therefore, the corrosion resistance of the TSA film sealed with Ce 65 is significantly improved compared to Ce 25 [13]. In comparison, it was found that among the four sealing methods listed in Table 3, the corrosion resistance of the TSA film sealed with Ce 65 was significantly better than that of the TSA films sealed with hot water and Ce 25 but weaker than that of the TSA film sealed with dichromate.

Table 3. The color change time vs. sealing methods in acidic spot test.

Sealing Methods	Ce 25	Ce 65	Hot Water	Dichromate	Unsealed
Time (min)	21.02	35.38	30.51	39.49	12.31

Figure 4 shows the EIS of TSA films sealed using different methods after immersion in a 3.5 wt.% NaCl solution for 1 h. The EIS plot displays the impedance modulus $|Z|$ against frequency f . In this graph, the high-frequency range reflects the resistance and capacitance of the porous layer of the anodic film, and the low-frequency range reflects the resistance and capacitance of the barrier layer. The EIS of the TSA film can be fitted using the equivalent circuit shown in Figure 5, and the fitting results are listed in Table 4. Here, R_s represents the solution resistance; R_p and R_b represent the resistances of the porous layer and the barrier layer of the anodic film, respectively; and CPE_p and CPE_b represent the constant phase angle elements of the porous layer and the barrier layer, respectively. In addition, Y stands for admittance, and n represents the dispersion coefficient. It can be seen that the R_p values of the TSA films sealed with Ce 25 and Ce 65 were $0.45 \text{ M}\Omega\cdot\text{cm}^2$ and $1.71 \text{ M}\Omega\cdot\text{cm}^2$, respectively, indicating that higher-temperature sealing is favorable for increasing the R_p [13]. The TSA film sealed with dichromate had the largest R_p , indicating that the porous layer is the most resistant to aggressive Cl^- and offers the best corrosion resistance. The larger the impedance modulus value at a low-frequency region, the better the corrosion resistance. Therefore, the sealed film exhibited better corrosion resistance than the unsealed film.

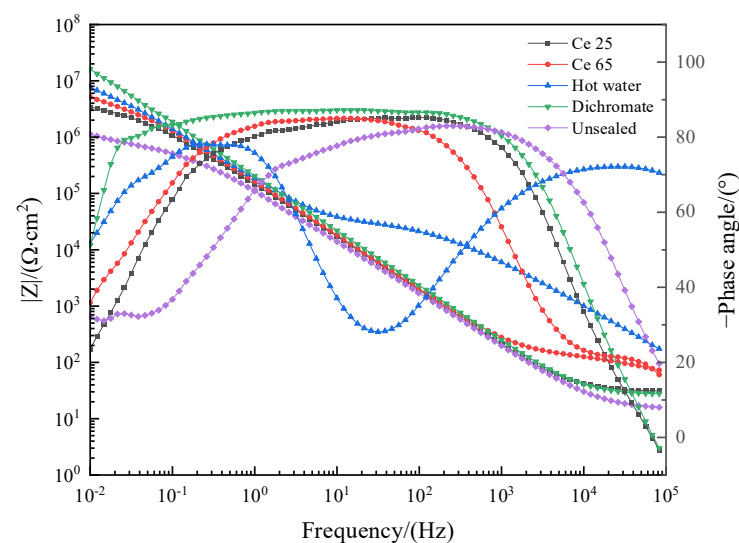


Figure 4. EIS of the TSA films sealed using different methods in 3.5 wt.% NaCl solution.

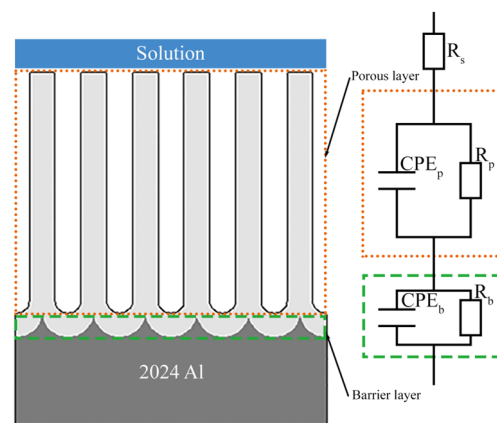


Figure 5. Equivalent circuit for EIS fitting of the TSA films.

Table 4. Fitting results of the EIS for TSA films sealed using different methods.

Sealing Methods	R_p ($M\Omega \cdot cm^2$)	CPE_p		R_b ($M\Omega \cdot cm^2$)	CPE_b	
		Y ($\mu S \cdot s^n \cdot cm^{-2}$)	n		Y ($\mu S \cdot s^n \cdot cm^{-2}$)	n
Ce 25	0.450	1.76	0.961	3.85	3.50	0.941
Ce 65	1.71	1.71	0.942	5.50	2.87	0.969
Hot water	0.0314	0.115	0.823	10.1	0.943	0.916
Dichromate	7.40	0.809	0.974	23.5	0.0628	0.998
Unsealed	0.402	1.42	0.915	1.11	10.5	0.902

To evaluate the differences in the corrosion resistance of anodic films sealed using different methods, the EIS of anodic films immersed in a 3.5 wt.% NaCl solution was continuously monitored for 336 h, as shown in Figure 6. As depicted in the figure, in the low-frequency range, the $|Z|$ values of TSA films sealed with Ce 25 and Ce 65 decrease with increasing immersion time, but the decrease is more significant in the former. In the mid-frequency range, the phase angle and capacitive arc width of the films sealed with Ce 25 and Ce 65 are both reduced with increasing immersion time, but the former reduction is more obvious (Figure 6a,b). In the high-frequency range, the phase angle and $|Z|$ values of the TSA film sealed with Ce 25 increase up to 120 h and then decrease with increasing immersion time. On the contrary, the phase angle and $|Z|$ values of the TSA film sealed with Ce 65 show an increasing trend all the time. The phase angle and $|Z|$ values of TSA film sealed with dichromate show a similar trend to TSA film sealed with Ce 65, and the increase is more significant (Figure 6d). During immersion, the barrier layer of the TSA film sealed with hot water gradually loses its capacitance and becomes more resistive with increasing immersion time (Figure 6c) [4]. In the low-frequency region, its phase angle decreases significantly, and the time constant gradually shifts to higher-frequency regions [4]. The EIS results indicate that the film sealed with Ce 65 provides better protection than Ce 25 and hot water, but it is still lower than that sealed with dichromate.

Figure 7 shows the curves of polarization resistance versus immersion time for TSA films sealed using different methods. During the immersion process, the polarization resistance of the TSA film sealed with Ce 65 was consistently larger than that of the TSA film sealed with Ce 25, revealing that the former has stronger corrosion resistance since the higher polarization resistance represents the stronger corrosion resistance. Although the polarization resistance of the TSA film sealed with hot water was greater than that of the film sealed with Ce 65 in the early stage of immersion (~40 h), it decreased much more than that of the TSA film sealed with Ce 65. Therefore, the corrosion resistance of the film sealed with Ce 65 is better than that of the film sealed with hot water. After 366 h of immersion, the polarization resistances of the films sealed with Ce 25, Ce 65, hot water, and dichromate were $0.65 M\Omega \cdot cm^2$, $3.88 M\Omega \cdot cm^2$, $1.44 M\Omega \cdot cm^2$, and $29.12 M\Omega \cdot cm^2$, respectively. Thus,

dichromate sealing can provide the best corrosion resistance, followed by Ce 65 sealing, while Ce 25 sealing provides the worst corrosion resistance.

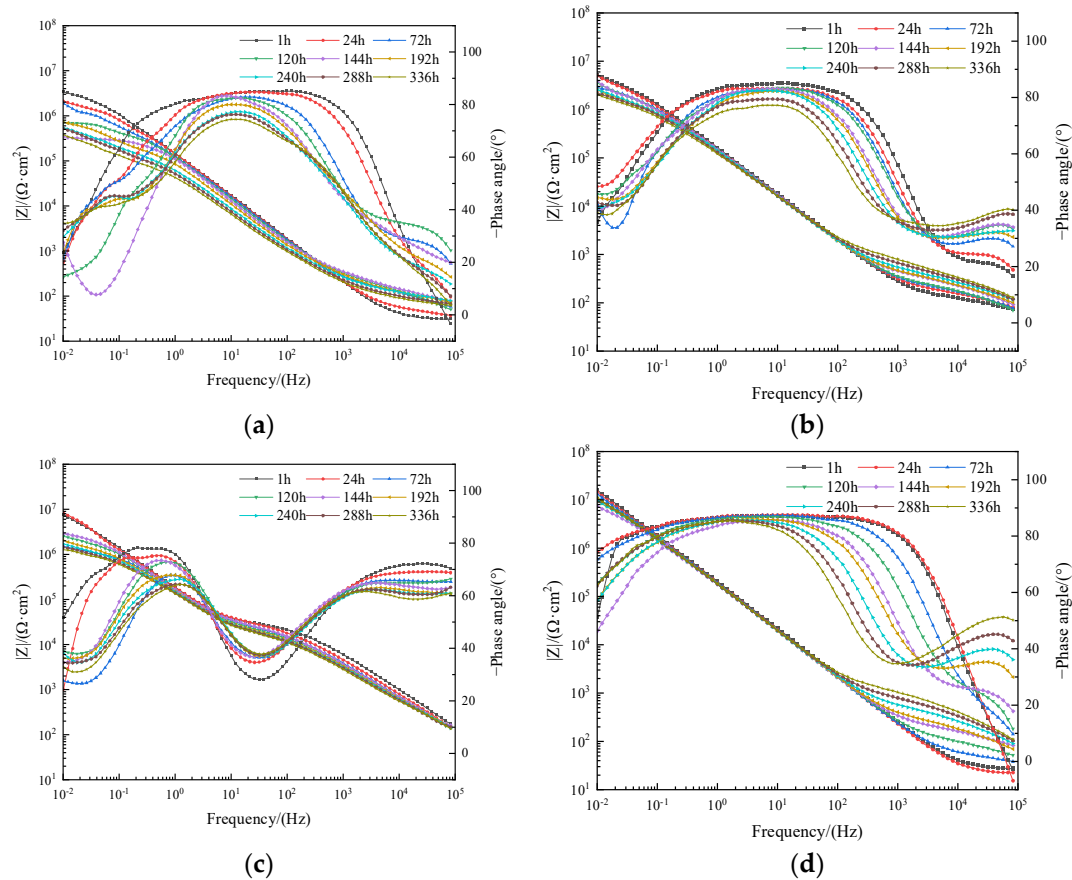


Figure 6. EIS change of the films sealed with (a) Ce 25, (b) Ce 65, (c) hot water, and (d) dichromate as a function of immersion times in a 3.5 wt.% NaCl solution.

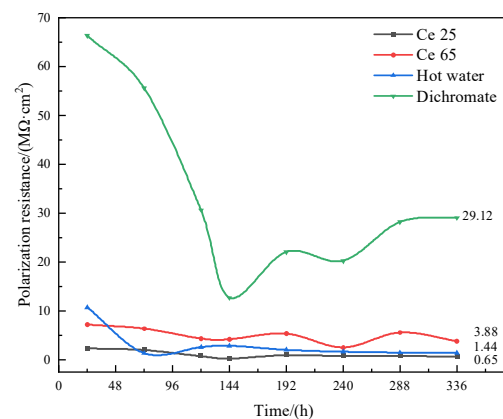


Figure 7. The changes in polarization resistance of the films with immersion times.

Figure 8 shows the polarization curves of the TSA films after immersion in a 3.5 wt.% NaCl solution for 1 h (Figure 8a) and 336 h (Figure 8b), respectively. The corresponding fitting results are listed in Table 5. After immersion for 1 h, the corrosion current density (I_{corr}) of the film sealed with dichromate is 5.16×10^{-10} A/cm², I_{corr} for the film sealed with hot water is 3.51×10^{-9} A/cm², and I_{corr} for films sealed with Ce 25 and Ce 65 are 4.25×10^{-9} A/cm² and 4.06×10^{-9} A/cm², respectively. This shows that dichromate sealing can result in the smallest I_{corr} , whereas there is almost no distinction for the other

three methods. When the immersion times increase from 1 h to 336 h, the corrosion potential (E_{corr}) of the films sealed with Ce 25 and hot water both decrease by ~ 0.2 V, and the E_{corr} of the film sealed with dichromate decreases by ~ 0.1 V. Interestingly, the E_{corr} of the film sealed with Ce 65 stays almost unchanged, and it is about 0.19 V ~ 0.25 V greater/more positive relative to the other films. As for the I_{corr} , the film sealed with Ce 65 is 5.03×10^{-8} A/cm², which is the smallest, except for that of the film sealed with dichromate. In general, the smaller the I_{corr} and the more positive the E_{corr} , the better the corrosion resistance. Therefore, the corrosion resistance of the TSA film sealed with Ce 65 is much better compared with films sealed with Ce 25 and hot water. The more positive the pitting potential (E_{pit}), the stronger the resistance to film breakdown. At 1 h, the E_{pit} values of the films sealed with Ce 65, hot water, and chromate are very close, which are much more positive than that of Ce 25 sealed film. However, after immersion for 336 h, the E_{pit} values of the films sealed with Ce 25 and hot water decrease by 0.2 V, and the E_{pit} value of the film sealed with Ce 65 only decreases about 0.05 V, while the E_{pit} value of the film sealed with chromate increases about 0.07 V. This indicates that Ce 25 and hot water-sealed films were more easily broken down. In contrast, the films sealed with chromate and Ce 65 are more difficult to pit.

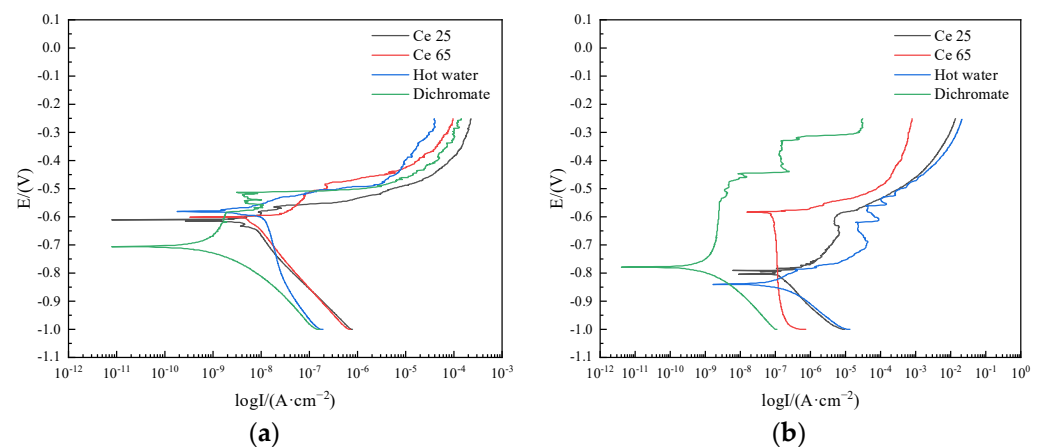


Figure 8. Potentiodynamic polarization curves for the TSA films immersed in 3.5 wt.% NaCl for (a) 1 h and (b) 336 h, respectively.

Table 5. Fitting results of the polarization curves in Figure 8.

Sealing Methods		Ce 25	Ce 65	Hot Water	Dichromate
E_{corr} (V)	1 h	−0.603	−0.601	−0.581	−0.705
	336 h	−0.802	−0.593	−0.840	−0.784
I_{corr} (A/cm ²)	1 h	4.25×10^{-9}	4.06×10^{-9}	3.51×10^{-9}	5.16×10^{-10}
	336 h	1.14×10^{-7}	5.03×10^{-8}	5.27×10^{-8}	6.17×10^{-10}
E_{pit} (V)	1 h	−0.581	−0.527	−0.519	−0.513
	336 h	−0.781	−0.576	−0.775	−0.446

The macroscopic morphology of the TSA films after immersion in a 3.5 wt.% NaCl solution for 336 h is shown in Figure 9. Macroscopically, there appear to be corrosion pits on the surfaces of the films sealed with Ce 25 and hot water (Figure 9a,c), showing that the films are thoroughly damaged near the pits. However, the number of pits is relatively fewer for the latter. No obvious corrosion pits were observed on the surfaces of the TSA films sealed with Ce 65 and dichromate (Figure 9b,d). The microscopic morphology of the TSA films after immersion in a 3.5 wt.% NaCl solution for 336 h is shown in Figure 10. Microscopically, cracks appear on the surface of all TSA films. Except for the large pits (Figure 10a,c), corrosive media can also penetrate to the substrate through cracks, causing substrate corrosion. In addition, the cracks on the surface of the film sealed with Ce 65 are

slightly wider compared to the film sealed with dichromate (Figure 10b,d). This shows that the TSA film sealed with Ce 65 possesses better corrosion resistance than the films sealed with hot water and Ce 25, although it is still lower than the film sealed with dichromate.

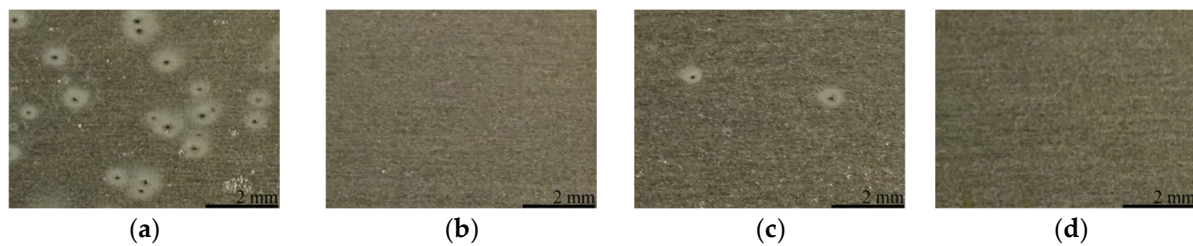


Figure 9. Macroscopic morphology (5×) of TSA films sealed using different methods after 336 h of immersion: (a) Ce 25; (b) Ce 65; (c) hot water; (d) dichromate.

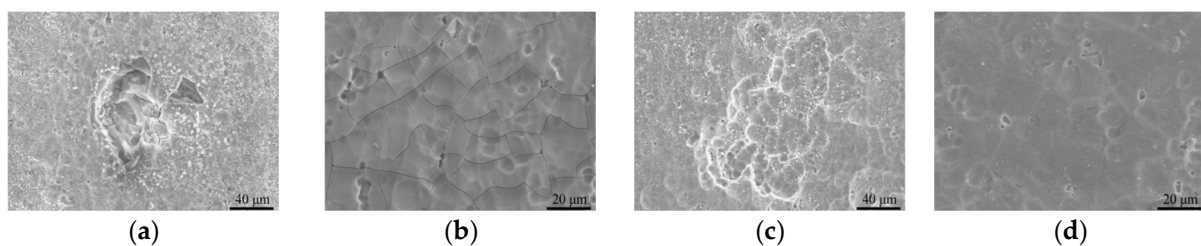


Figure 10. Microscopic morphology of TSA films sealed using different methods after 336 h of immersion: (a) Ce 25 (500×); (b) Ce 65 (1000×); (c) hot water (500×); (d) dichromate (1000×).

4. Conclusions

- (1) The surface morphologies of the TSA films sealed with Ce 25 and Ce 65, hot water, and dichromate were different. The Ce content on the film sealed with Ce 65 was slightly lower compared to the film sealed with Ce 25.
- (2) The experimental results of the acidic spot test indicated that the corrosion resistance of the films, from strongest to weakest, was as follows: sealed by dichromate, Ce 65, hot water, and Ce 25.
- (3) After immersion for 366 h, the polarization resistances of the films sealed with Ce 25, Ce 65, hot water, and dichromate were $0.65 \text{ M}\Omega\cdot\text{cm}^2$, $3.88 \text{ M}\Omega\cdot\text{cm}^2$, $1.44 \text{ M}\Omega\cdot\text{cm}^2$, and $29.12 \text{ M}\Omega\cdot\text{cm}^2$, respectively. The E_{corr} of the film sealed with Ce 65 was almost unchanged, and it was about 0.19 V~0.25 V greater/more positive relative to the other films. As for the I_{corr} , the film sealed with Ce 65 obtained a $5.03 \times 10^{-8} \text{ A/cm}^2$ value, which was the smallest, except for that of the film sealed with dichromate.
- (4) No obvious corrosion pits were observed on the surfaces of the TSA films sealed with Ce 65 and dichromate, whereas more corrosion pits appeared on the surfaces sealed with Ce 25 and hot water.
- (5) The TSA film sealed with Ce 65 exhibited superior corrosion resistance compared to the films sealed with hot water and Ce 25, although it was still inferior to the film sealed with dichromate. The enhanced corrosion resistance of the TSA film sealed with Ce 65 could be attributed to the combined effect of cerium oxide deposition and the hydration reaction.

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