Exfoliation Corrosion of Extruded AA2024-T4 in the Industrial and Coastal-Industrial Environments

Shuangqing Sun,* Shenghui Chen,* Yunfei Ma,* Qifei Zheng,** and Songqing Hu‡,*

ABSTRACT

Exfoliation of extruded AA2024-T4 (UNS A92024) in the industrial and coastal-industrial environments was investigated by the field test and laboratory-accelerated test. Results show that the exfoliation corrosion was influenced by the alloy structure and the type of the atmospheric environment, especially the concentration of SO$_4^{\text{2-}}$ in the environment. In the field test, AA2024-T4 suffered slighter exfoliation in both environments than that in the coastal environments. The side wall with a thinner coarse-grain structure of extruded AA2024-T4 suffered more severe exfoliation than the bottom with a thicker coarse-grain structure after a 20-year exposure. Energy-dispersive spectroscopy (EDS) results show that the corrosion products of extruded AA2024-T4 exposed in both environments contained a small amount of S in addition to a large amount of Al and O. In the laboratory-accelerated test, both the critical relative humidity (RH) and induction period for exfoliation in the simulated coastal-industrial environments were higher and longer than those in the sodium sulfate (Na$_2$SO$_4$)-free simulated coastal environment. Exfoliation was hindered due to the existence of SO$_4^{\text{2-}}$ in Cl-containing environments.

KEY WORDS: aluminum alloy, atmospheric environments, exfoliation corrosion, polarization

INTRODUCTION

High-strength aluminum alloys 2024 (AA2024 [UNS A92024]) are widely used in aircraft structures, but they are susceptible to exfoliation in industrial or marine environments.$^1$ Exfoliation is a form of intergranular corrosion in which attack proceeds along multiple intergranular paths parallel to the surface. Layers of uncorroded metal between the paths are split apart and pushed above the original surface by a large body of corrosion products formed along the paths of attack.$^4,5$ Intergranular corrosion to a depth of 120 µm was observed on the AA2024-T4 after 2 years exposure on Txatxarramendi Island (Basque Country). AA2024 developed some intergranular corrosion, with exfoliation, at a severe industrial site (McCook, United States) and marine site (Kure Beach, United States) after 7 years’ exposure.$^7,8$ Exfoliation attack occurred on AA2024 under different heat treatment conditions after 55 months’ to 61 months’ exposure at Brookfield, United States (severe industrial environment).$^9$ Extruded AA2024-T4 suffered more severe exfoliation at the Wanning test site (coastal environment) than that at the Jiangjin test site (industrial environment) after 20 years’ exposure, and the alloy had completely lost its mechanical properties at the Wanning test site.$^{10}$ Stress corrosion cracks were also observed on the AA2024-T3 when the alloy was exposed to a salt lakes environment for 6 years. The depth of the cracks had reached 75% of the original thickness of the sample after 1 year exposure, and those cracks were branched and intergranular.$^{11}$
In addition to the field test, accelerated laboratory tests (ASTM G34 and ASTM G85) are also used to assess the exfoliation susceptibility and predict the service lifetime of high-strength aluminum alloys. However, these standard tests are always incapable to sufficiently quantify the influence of environmental factors. In 2007, Zhao and Frankel developed a new technique—exfoliation of slices in humidity (ESH)—to determine the exfoliation susceptibility and quantify the exfoliation kinetics in aluminum alloys AA7178-T6 (UNS A97178) and AA7178-T7. Exfoliation was not observed below 50% relative humidity (RH), and above this critical humidity the exfoliation increased with increasing humidity. In 2011, Sun, et al., applied the similar ESH method to study the exfoliation kinetics of AA2024-T4. The relationship between the exfoliation kinetics and environmental parameters, including the sea-salt contamination, RH, and temperature, was analyzed. Based on these accelerated test results, the long-term observations of the field test in the coastal atmosphere were further explained.

In this paper, we investigated the surface appearance, cross-sectional corrosion morphology, and corrosion products of extruded AA2024-T4 exposed for 20 years at the Jiangjin test site (industrial environment) and Qingdao test site (coastal-industrial environment). In the laboratory-accelerated test, a technique of electrochemical pretreatment on the specimens was applied before the simulated environment test. The exfoliation kinetics of the pretreated specimens under different simulated environments (varying RH, sodium sulfate [Na₂SO₄], sodium chloride [NaCl], and pH value) were then investigated to account for the varying exfoliation behavior in the industrial and coastal-industrial environments.

**EXPERIMENTAL PROCEDURES**

*Field Test*

Extruded AA2024-T4 was used in the field testing. Chemical composition of the material is given in Table 1. Extruded AA2024-T4 was groove-shaped, and the size of the sample was 200 mm length by 32 mm width by 16 mm height. The thickness of the side wall and the bottom was 2.5 mm and 3.0 mm, respectively. Prior to the field testing, all the samples were degreased with acetone (CH₃COCH₃), rinsed with distilled water, and dehydrated using absolute alcohol. The dried samples for the field testing were mounted on test racks at the test sites in 1984, exposed at an angle of 45° to the horizontal with the skyward surface facing south. The exposure tests were performed at the test sites located at Jiangjin (industrial atmosphere) and Qingdao (coastal-industrial atmosphere). Geographic coordinates of the test sites and essential environmental characteristics during the period from 1984 to 1994 are given in Table 2. Three samples were withdrawn from the test sites after 20 years’ exposure. In parallel with the samples exposed in the field test, some control samples were kept in desiccators with silica gel in the laboratory for the comparative study and the laboratory-accelerated test.

After 20 years’ exposure, the cross section of the wall and bottom of the AA2024-T4 specimens withdrawn from the field test were ground using a 1000 grit silicon carbide (SiC) paper, polished with 6 μm and 1 μm diamond paste. The corrosion morphologies were characterized using scanning electron microscopy (SEM). Qualitative element mapping and standardless semi-quantitative spot analysis of the corrosion product layers were also performed by energy-dispersive x-ray spectroscopy (EDS). The specimens were also chemically etched with Keller’s reagent (1 mL hydrofluoric acid [HF] + 1.5 mL hydrochloric acid [HCl] + 2.5 mL nitric acid [HNO₃] + 95 mL H₂O) for 3 min at room temperature. Afterward, the cross-sectional morphology was observed using an optical microscope.

*Laboratory-Accelerated Test*

The control samples, which have been kept in desiccators for 20 years, were used in the laboratory-accelerated test. Since the microstructure of the material...
rial varies at the different positions in the transverse section, the specimens with the size of 20 mm by 5 mm by 3 mm were taken from the same region along the direction of extrusion at the bottom of the groove-shaped extruded AA2024-T4. Specimens were first given a galvanostatic electrochemical pretreatment at 0.83 mA/cm² for 32 h in a 1 M NaCl solution to initiate the intergranular corrosion.16 Following the pretreatment, the specimens were ultrasonically rinsed with deionized water and placed in a humidity chamber after drying out. The humidity chamber is a sealed beaker containing a saturated salt solution at 40°C. Different saturated salt solutions were used to create a range of constant RH levels (Table 3).17-18 Thereafter, the specimens were periodically immersed in two kinds of experimental solution for 15 min every day to simulate the exfoliation in the coastal-industrial and industrial environments (Table 4). The development of exfoliation was observed by digital photography on the longitudinal section of the specimens.

The exfoliation kinetics can be determined by the exfoliation depth of the pretreated surface with exposure time. In this work, the unattacked width of specimens was measured at 20 evenly distributed positions along the longitudinal direction of the specimen. From these measurements, the exfoliation depth was obtained from the width difference, and the mean value was calculated by Equation (1):

$$\Delta d = \frac{\sum_{j=1}^{20} \Delta d_j}{20}$$  

where the exfoliation depth $d_j = d_0 - d$, $d_0$ is the original width of the pretreated sample, and $d$ is the unattacked width at the positions of $j$.

### RESULTS

#### Field Exposure Testing

**Surface Appearance and Corrosion Products** — The surface appearances of extruded AA2024-T4 after a 20-year exposure at Jiangjin and Qingdao test sites are shown in Figure 1. Extruded AA2024-T4 suffered exfoliation at both test sites. For the sample withdrawn from Jiangjin, flake-like exfoliation occurred on the internal wall of the groove-shaped specimen (Figure 1[a]). In the case of the Qingdao test site, exfoliation attack at the cut edges of the internal wall was observed on the groove-shaped specimen (Figure 1[b]). For the specimens from both test sites, superficial sheets on the internal wall were pushed away by the corrosion products.

Micrographs of extruded AA2024-T4 exposed for 20 years at Jiangjin and Qingdao at the external bottom (the side facing the sky) and internal bottom (the side facing the ground) are shown in Figure 2. At the Jiangjin test site, the external bottom was covered by a thinner layer of black corrosion products (Figure 2[a]) and some white blisters (such as at the spots of “1,” “2,” and “3”) distributed on that face. The internal bottom was covered entirely with a thicker layer of yellow-white corrosion products (Figure 2[b]).

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**TABLE 3**

<table>
<thead>
<tr>
<th>Salt</th>
<th>NaBr</th>
<th>NaNO₂</th>
<th>NaCl</th>
<th>KCl</th>
<th>KNO₃</th>
<th>K₂SO₄</th>
</tr>
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<tbody>
<tr>
<td>RH (%)</td>
<td>53</td>
<td>62</td>
<td>75</td>
<td>82</td>
<td>89</td>
<td>96</td>
</tr>
</tbody>
</table>

**TABLE 4**

<table>
<thead>
<tr>
<th>Atmosphere</th>
<th>Immersing Solution</th>
</tr>
</thead>
</table>
| Coastal-industrial | 0.6 M NaCl + m Na₂SO₄  
                  | (m = 0.15, 0.3, and 0.6 M) |
| Industrial      | 0.6 M Na₂SO₄ + n pH  
                  | (n = 3.0, 4.0, 5.0, 6.0, and 7.0) |

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**FIGURE 1.** Surface appearances of extruded AA2024-T4 exposed for 20 years at the test sites: (a) Jiangjin (industrial atmosphere) and (b) Qingdao (coastal-industrial atmosphere).
Qingdao test site, a thinner layer of yellow corrosion products formed on the external bottom (Figure 2[c]), and some white blisters (such as at the spots of “4,” “5,” and “6”) were also evenly distributed on that face. The internal bottom also presented a thicker layer of yellow-white corrosion products (Figure 2[d]) as in the case of the Jiangjin test site. Overall, at the both test sites, the internal bottom (Figure 2[b and d]) suffered more serious corrosion than the outside bottom (Figures 2[a] and [c]).

**Cross-Sectional Morphology and Corrosion Products** — The cross-sectional morphologies of the side wall and bottom of AA2024-T4 after a 20-year exposure at Jiangjin and Qingdao are shown in Figure 3. At the two test sites, both intergranular corrosion and pitting corrosion were observed on the surface layer of the specimen. For all specimens, at the surface layer (on the left side of each image) there was a coarse-grain structure (recrystallized grain structure). Under this coarse-grain structure (on the right side of each image), the grains in the substrate structure were highly elongated and flattened. Furthermore, the coarse-grain structure of the wall (80 µm to 100 µm in Figures 3[a] and [b]) was thinner than that of the bottom (240 µm to 280 µm in Figures 3[c] and [d]).

Cross-sectional back-scattered electron (BSE) images of extruded AA2024-T4 after 20 years at Jiangjin and Qingdao, and their corresponding EDS elemental mapping, are shown in Figure 4. The BSE images show that all specimens suffered exfoliation corrosion. A large volume of corrosion products that formed between the layers of the elongated grains pried the elongated grains apart. Many microcracks were seen in these corrosion product layers, which allowed the aggressive ions to pass through the corrosion products to attack the substrate. EDS spot analysis shown in Table 5 indicates that corrosion products contained a large amount of Al and O and a small amount of S at both test sites, which reveals that the corrosion products might consist of aluminum oxides and hydroxides, or sulfides. In addition, at both test sites, in the bottom of the specimens (spots 3 and 4), the corrosion products contained much more S element than that in the side wall (spots 1 and 2). The EDS elemental mapping is consistent with that derived from the EDS spot analysis. The difference in the content of S in the corrosion products between the side wall and bottom of the samples might result from the fact that there were more corrosive particles (sulfur dioxide [SO₂] and hydrogen sulfide [H₂S]) deposited on the skyward-facing surface compared with that on the side wall.

**Laboratory-Accelerated Test**

**Simulated Coastal-Industrial Atmosphere** — The electrochemically pretreated specimens were exposed to different RH conditions ranging from 53% to 96% at 40°C over 61 days. During this period of time, they were immersed in different experimental solutions (0.6 M NaCl + 0.15 M Na₂SO₄, 0.6 M NaCl + 0.3 M Na₂SO₄, and 0.6 M NaCl + 0.6 M Na₂SO₄) for 15 min every day to simulate different environments. The longitudinal sections of the exposed samples showing the corrosion development with RH in different experimental solutions are shown in Figure 5. Under all three simulated environments indicated as different experimental solutions, there were always some white corrosion products incorporating salt particles present on the pretreated surface (on the left side of each sample). When RH value reached 75%, a reddish-brown mixture of corrosion products and salt particles began to appear on the pretreated and the longitudinal surfaces under all three simulated environments (Figures 5[a] through [c]). This indicates that the specimens suffered more serious corrosion at those RH values compared with that at 53% and 62% RH. However, when RH reached 89%, the pretreated specimens exhibited the exfoliation with different severities. With a further increase of RH to 96%, much slighter exfoliation was observed on the pretreated surface in all three different simulation environments compared with that under the 89% RH condition (Figures 5[a] through [c]). This indicates...
that in the simulated environments, the critical RH was 89% below which the extruded AA2024-T4 cannot suffer exfoliation, but the higher RH cannot result in the exfoliation.

Figure 6 shows the exfoliation development with exposure time (up to 66 days) of the specimens immersed in the three simulation environment solutions under 89% RH. Overall, in the three simulation environments, exfoliation aggravated with increasing exposure time. The average exfoliation depth of the pretreated specimens as a function of time is shown in Figure 7. In all three simulated environments, there was a long induction period (about 20 days) for the exfoliation initiation at the early stage of exposure. Following the induction period, the exfoliation depth began to increase gradually and proceeded linearly with time for the specimens immersed in 0.6 M NaCl + 0.15 M Na₂SO₄ and 0.6 M NaCl + 0.3 M Na₂SO₄. For the specimen immersed in 0.6 M NaCl + 0.6 M Na₂SO₄, the exfoliation depth exhibited a slower increase over a period of exposure from 31 days to 66 days compared to the samples immersed in the other two solutions.

**Simulated Industrial Atmosphere** — The electrochemically pretreated specimens were exposed to different RH conditions ranging from 53% to 96% for 60 days. During this period of time, to simulate the industrial atmosphere environment, they were immersed in 0.6 M Na₂SO₄ with different pH values ranging from 3 to 6 at 40°C for 15 min every day. The pretreated surfaces of the exposed samples showing the corrosion development with RH under different conditions (pH) are shown in Figure 8. The pretreated specimens did not suffer apparent exfoliation in all the cases. Under the four pH conditions, there were few corrosion products or salt particles on the surface when the RH value was 53% and 62%. With an increase of RH value to 75%, 82%, and 89%, different numbers of the corrosion spots appeared on the pretreated surfaces. When the RH reached 97%, the pretreated surfaces were totally covered by a thin layer of light blue corrosion products, which might have been cupric hydroxide (Cu(OH)₂) or cupric sulfate (CuSO₄). In particular, when the pH of the Na₂SO₄ solution was 3, a large reddish brown pit filled with dendritic corrosion products was observed on the pretreated surfaces.

**DISCUSSION**

**Corrosion of AA2024 in the Atmospheric Environment**

In the atmospheric environment, the humid air or the rain can form the electrolyte film on the metal’s surface. Water first adheres to a polished metal surface at an approximately 55% RH and then forms a thin film. The thickness of the water film increases with increasing RH. The thin water layer can support an electrochemical reaction, but polarization of the cathodic and anodic sites slows the process as the film thickness decreases and virtually stops at about 60%.[21] When the RH reached the deliquescence point of the atmospheric pollutants of NaCl (75% RH at
25°C) or Na$_2$SO$_4$ (89% RH at 25°C), an electrolyte film containing NaCl and/or Na$_2$SO$_4$ forms on the metal surface. As a result of the existence of the above electrolyte film, the electrochemical reaction will occur, which thereby causes the corrosion of the aluminum alloy.

In the atmospheric corrosion process, the thickness of the electrolyte film deposited on the metal’s surface is an important factor. In this present work, the internal bottom suffered more severe corrosion than the external bottom. This is because of the different existing time of the thin electrolyte layer containing air contaminants, i.e., the wetness time for the two sides of the specimen bottom. During the exposure, the external bottom with more sun radiation and better ventilation had the shorter wetness time than the internal bottom, which resulted in the slighter corrosion.

In particular, in the electrolyte film with a low pH value, the intermetallic particle (Al$_2$CuMg) in Al-Cu-Mg alloys can be anodically polarized by the surrounding matrix phase. The particle dealloyed in the anodic polarization process, leaving behind a porous copper-rich particle remnant. As the fine, porous structure coarsens to reduce its surface energy, small metallic Cu clusters become detached from the particle remnant. This is consistent with our laboratory-accelerated test in the simulated industrial atmosphere, in which the specimens were periodically immersed in 0.6 M Na$_2$SO$_4$ solution with different pH values, and then were exposed to different RH conditions. The result shows that reddish brown pits presented on the

<table>
<thead>
<tr>
<th>Atmosphere</th>
<th>Element</th>
<th>Spot 1</th>
<th>Spot 2</th>
<th>Spot 3</th>
<th>Spot 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jiangjin (industrial atmosphere)</td>
<td>O K</td>
<td>67.21</td>
<td>68.82</td>
<td>74.72</td>
<td>70.64</td>
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<tr>
<td></td>
<td>Al K</td>
<td>32.00</td>
<td>30.45</td>
<td>22.04</td>
<td>26.01</td>
</tr>
<tr>
<td></td>
<td>S K</td>
<td>0.79</td>
<td>0.73</td>
<td>3.24</td>
<td>3.35</td>
</tr>
<tr>
<td>Qingdao (coastal-industrial atmosphere)</td>
<td>O K</td>
<td>41.92</td>
<td>43.57</td>
<td>64.67</td>
<td>65.31</td>
</tr>
<tr>
<td></td>
<td>Al K</td>
<td>57.42</td>
<td>55.85</td>
<td>30.31</td>
<td>32.72</td>
</tr>
<tr>
<td></td>
<td>S K</td>
<td>0.66</td>
<td>0.58</td>
<td>5.02</td>
<td>1.97</td>
</tr>
</tbody>
</table>

FIGURE 4. Cross-sectional BSE images of extruded AA2024-T4 exposed for 20 years and corresponding EDS elemental mapping of Al, O and S: (a) and (b) side wall and bottom in Jiangjin (industrial atmosphere); (c) and (d) outside bottom and inside bottom in Qingdao (coastal-industrial atmosphere).
Effect of Alloy Microstructure of Extruded Aluminum Alloy on Exfoliation Corrosion and Pitting Corrosion

Alloy microstructure also has a significant effect on the corrosion initiation and development. The cross-sectional morphologies of AA2024-T4 showed that at the surface layer there was a coarse-grain microstructure, under which the grains were highly elongated and flattened (Figure 3). The generation of coarse-grain structure resulted from the localized recrystallization in the extrusion process of the alloy, which was mainly caused by the localized temperatures increase, coming from the friction of the extruded alloy with the extrusion die. In addition, the high strain-rate deformation at the die entrance, alloy structure, flow stress, etc., can also result in the recrystallization of the alloy and the formation of the coarse grains.\(^{19-20}\)

In the coarse-grain structure mentioned above, there were fewer grain boundaries than that in the elongated grains structure. The existence of a great number of grain boundaries in the elongated grains structure provided more continuous paths for the propagation of exfoliation corrosion. Therefore, the coarse-grain structure with fewer grain boundaries was more resistant to the exfoliation than the elongated grains structure. In the present work, the side wall of the groove-shaped specimen with a thinner coarse-grain structure (80 µm to 100 µm) suffered more severe exfoliation than the bottom with a thicker coarse-grain structure (240 µm to 280) (Figure 1).

Effect of SO\(_4^{2-}\) on Exfoliation

In our previous report,\(^{16}\) at the Wanning test site (coastal atmosphere), exfoliation corrosion of the groove-shaped AA2024-T4 began to appear after...
6 years’ exposure. Furthermore, after 20 years’ exposure, the specimens entirely lost the mechanical properties because of the severe exfoliation corrosion. In this work, at both Jiangjin (industrial atmosphere) and Qingdao (coastal-industrial atmosphere) test sites, there was only slight exfoliation attack occurring on the side wall of groove-shaped AA2024-T4 after 20 years’ exposure. Therefore, it can be proposed that the exfoliation corrosion of extruded AA2024-T4 in the industrial and coastal-industrial atmospheres is smaller than that in the coastal atmosphere. The comparison of atmospheres and exfoliation of extruded AA2024-T4 in different environments is shown in Table 6.

Based on the comparison of environmental parameters between the industrial (coastal-industrial) atmosphere and the coastal atmosphere, the major difference is the concentration of SO₄²⁻ in different environments. The industrial atmosphere has the higher concentration of SO₄²⁻ than the coastal-industrial and coastal atmospheres. In the industrial environment, the main atmospheric pollutant is SO₂ that deposit on the metal surface. If the RH of the environment is high enough, a thin moisture film can form on the metal surface, and SO₃ will dissolve and ionize in the moisture film:

SO₂(aq) + H₂O → H⁺ + HSO₃⁻ (2)

It can then be oxidized in the solution by the hydrogen peroxide (H₂O₂), ozone (O₃), or metal ions supplied by the aerosol particles (such as Fe and Mn) deposited on the surface:

HSO₃⁻ + H₂O₂ → HSO₄⁻ + H₂O (3)

HSO₅⁻ + O₃ → HSO₄⁻ + O₂ (4)

HSO₄⁻ + [O₁] → HSO₄⁻[Fe, Mn] (5)

The sulfur(VI) generally produced by Equations (3) through (5) is in equilibrium with its ionic forms and will generally be present as sulfate (SO₄²⁻):

HSO₄⁻ → H⁺ + SO₄²⁻ (6)

When SO₄²⁻ adsorbs on the aluminum oxide (Al₂O₃) surface, it is readily available to form basic aluminum hydroxyl sulfate:


Aluminum hydroxyl sulfate is stable and highly insoluble. The formation of aluminum hydroxyl sulfate film can hinder the penetration of corrosive ions onto the metal surface and prevent the initiation and the propagation of exfoliation corrosion. This is consistent with our laboratory-accelerated test results. In the present work, 0.6 M Na₂SO₄ solutions with different pH values (ranging from 3 to 6) were used to simulate the industrial atmosphere. Results show that exfoliation did not occur on the pretreated specimens in all solutions (Figure 8). However, it should be noted that extruded AA2024-T4 suffered slight exfoliation in the long-term field testing in the industrial atmosphere at the Jiangjin test site (Figure 1). This inconsistency might be because of the existence of a small amount of chloride ions in the real industrial environment (Table 2). It has been confirmed that the chloride ion plays a crucial role in the intergranular corrosion initiation and propagation of Al-Cu alloys.

In the case of the simulated coastal-industrial atmosphere, 0.6 M NaCl solutions with different concentrations of Na₂SO₄ were used. It has been seen that the critical RH was 89% for the exfoliation of pretreated specimens in the simulated coastal-industrial environment. In addition, there was a 20-day induction period for the exfoliation initiation at 89% RH. However, in our previous work, the critical RH for exfoliation of the pretreated specimens in the simulated coastal environment (NaCl solution) was 75%. The exfoliation induction period was 5 days. The differences in both critical RH and exfoliation induction period suggest that the exfoliation was hindered due to the existence of SO₄²⁻ in Cl⁻-containing environments. The compassion of exfoliation corrosion of alloys in different simulated environments is also shown in Table 6. The difference is also attributed to the existence of SO₄²⁻, which resulted in the formation of the aluminum hydroxyl sulfate film in the SO₄²⁻-containing environments. Kolics, et al. also found that the surface concentration of chloride ions was smaller than that of sulfate ions at the passive films on pure aluminum in 0.1 mol/L sodium perchlorate (NaClO₄) using a radioactive labeling method and x-ray photoelectron
spectroscopy. As a result of the protection of aluminum hydroxyl sulfate on the surface, the penetration of Cl⁻ into the alloy is hindered. This can explain the different extents of exfoliation corrosion occurring in the coastal atmosphere and the coastal-industrial atmosphere in the field test. This also can account for the exfoliation in different severities caused by different concentrations of Na₂SO₄ addition in the 0.6 M NaCl solution in the laboratory-accelerated test (Figure 7). A higher concentration of Na₂SO₄ in the environment is thought to be more effective to inhibit the penetration of Cl⁻ into the metal surface.

CONCLUSIONS

- In the long-term field test, extruded AA2024-T4 suffered exfoliation corrosion after 20 years' exposure in the industrial and coastal-industrial atmospheres. However, the exfoliation corrosion was much smaller than that occurring in the coastal atmosphere.
- Alloy structure of extruded AA2024-T4 influenced the exfoliation. In the industrial and coastal-industrial atmospheres, the side wall with a thinner coarse-grain structure of groove-shaped AA2024-T4 suffered more severe exfoliation than the bottom with a thicker...
coarse-grain structure after 20 years' exposure due to the existence of a large number of grain boundaries. Moreover, the internal bottom of groove-shaped AA2024-T4 suffered more severe corrosion than the external bottom because of the longer wetness time of the surface.

\* In the long-term field test, corrosion products that formed between layers of the elongated grains contained a small amount of S apart from a large amount of Al and O. Furthermore, there was a higher concentration of S found in the corrosion products at the external bottom because of the longer wetness time that in the side wall. 

\* Exfoliation can be hindered by the existence of \( SO_4^{2-} \) in the atmospheric environment. In the laboratory-accelerated test, both the critical RH (89%) and induction period (~20 days) for exfoliation in the simulated coastal-industrial environment were higher and longer than those in the \( Na_2SO_4 \)-free simulated coastal environment (75% and 5 days, respectively). In the simulated industrial environment with a high concentration of \( Na_2SO_4 \), the specimens did not suffer apparent exfoliation.

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