

Article

Not peer-reviewed version

Anti-Corrosion Performance Evaluation of Polymeric Coatings Applied on Aluminum Alloys Exposed to Tropical Climate Influences of Thailand

Chuanying Li , [Wanida Pongsaksawad](#) , [Piya Khamsuk](#) , Jie Wang , [Pranpreeya Wangjina](#) , [Xiaoguang Sun](#) ^{*} , [Ekkarut Vijanit](#) ^{*}

Posted Date: 1 April 2026

doi: 10.20944/preprints202604.0059.v1

Keywords: atmospheric corrosion; anti-corrosion coatings; electrochemical impedance spectroscopy; tropical climate



Preprints.org is a free multidisciplinary platform providing preprint service that is dedicated to making early versions of research outputs permanently available and citable. Preprints posted at Preprints.org appear in Web of Science, Crossref, Google Scholar, Scilit, Europe PMC.

Copyright: This open access article is published under a [Creative Commons CC BY 4.0 license](#), which permit the free download, distribution, and reuse, provided that the author and preprint are cited in any reuse.

Disclaimer/Publisher's Note: The statements, opinions, and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions, or products referred to in the content.

Article

Anti-Corrosion Performance Evaluation of Polymeric Coatings Applied on Aluminum Alloys Exposed to Tropical Climate Influences of Thailand

Chuanying Li ^{1,2}, Wanida Pongsaksawad ³, Piya Khamsuk ³, Jie Wang ², Pranpreeya Wangjina ³, Xiaoguang Sun ^{1,2,*} and Ekkarut Viyanit ^{3,*}

¹ CRRC Qingdao Sifang Co.,Ltd., Qingdao, 266111, China

² Qingdao Aokang Quality Inspection Technology Co., Ltd., Qingdao 266071, China

³ National Metal and Materials Technology Center (MTEC), Science and Technology Development Agency (NSTDA), 111 Thailand Science Park, Paholyothin Road, Klong Luang, Pathum Thani 12120, Thailand

* Correspondence: author's e-mail: sunx_sf@126.com; ekkarut.viy@mtec.or.th

Abstract

The current study was aimed to investigate anti-corrosion performance of multi-layer polymeric coatings applied on 6005A and 6082 aluminum alloys under influences of monsoon tropical climate in Thailand. The coated samples representing the material used for a vehicle body of high-speed train were exposed to actual atmosphere of urban (Bangkok City) and marine (Songkhla City) environments. The maximum duration of the continuous exposure test was 18 months. After completion of exposure test, the physical deterioration characteristics of coatings was examined with the aid of scanning electron microscopy (SEM). Electrochemical impedance spectroscopy (EIS) was conducted in 3.5 wt.% NaCl solution at 25°C to evaluate the anti-corrosion coating performance after different exposure periods in atmospheric environments. Based on EIS results, the low-frequency impedance of the exposed coatings was higher than $10^9 \Omega \cdot \text{cm}^2$, meaning that the anti-corrosion coating could sufficiently protect the alloys against atmospheric corrosion attacks. However, the gradual degradation of anti-corrosion coating was also noted, particularly, when exposed at marine-coastal environment. The quantitative estimation results indicated that the anti-corrosion coating used in the current research could last for approximately 8 and 11 years when exposed in marine-coastal and urban environments, respectively.

Keywords: atmospheric corrosion; anti-corrosion coatings; electrochemical impedance spectroscopy; tropical climate

1. Introduction

Weight reduction of high-speed rail (HSR) vehicles has raised a demand for light-weight materials usage in manufacturing [1]. Based on techno-economic advantages as compared with other light-weight materials, aluminum alloys, e.g. 5000-, 6000- and 7000-series, have been logically selected for manufacturing various engineering components of HSR vehicles, including the frame structures and body skins [2–4]. In addition to superior corrosion resistance, those aluminum alloys also provide outstanding fabricability. Regarding the HSR service conditions under climatic atmosphere, wet-dry-cycle atmospheric corrosion plays a vital role in causing premature failure of vehicle's body and structure made of metals, including the aluminum alloys [5–7]. Therefore, corrosion protection is crucially applied to maintain service life of those components and structures.

In atmospheric corrosion, an electrochemical reaction takes place due to the formation of electrolyte thin layer on metal surface. From a corrosion point of view, oxygen reduction is a

predominant factor to control the reaction rate of electron acceptance under an atmospheric corrosion process. Basically, oxygen migration from the surrounding atmosphere is strongly dependent on the thickness of electrolyte adlayer [8,9]. Oxygen migration is retarded by increased thickness of adlayer, resulting in deceleration of atmospheric corrosion attack. As the electrolyte layer thickness was below 50 μm , the electronic current generated through oxygen reduction increased, meaning that a corrosion reaction was accelerated [9].

A number and duration of wet-dry cycles can also accelerate atmospheric corrosion [8]. Climate contaminants such as chloride (Cl^-) and sulfur dioxide (SO_2) are quite crucial to accelerate atmospheric corrosion of aluminum alloys because of the formation of less compact and more soluble corrosion products [10,11].

In recent years, atmospheric corrosion behaviors of aluminum alloys were extensively studied. Cui et al. [12] conducted atmospheric corrosion study on 1050A, 5A02, and 6A02 aluminum alloys in tropical marine environment of China (Hainan province). It reported that wet-dry cycles caused meta-stable pit initiation and growth in different manners depending on a type of aluminum alloys. In case of 1050A alloy, meta-stable shallow pits were initiated during the first month of exposure, then became connected after 6-month exposure. 5A02 alloy indicated higher atmospheric corrosion resistance than 6A02 alloy. Pit initiation sites of 5A02 alloy were mainly found in the matrix in the vicinity of Al-Fe-Mn intermetallic particle. The formation of Al_2CuMg anodic-type intermetallic particle along the grain boundaries has been found to increase the intergranular susceptibility of 2A12 aluminum alloy exposed to atmospheric environment [13]. More noble intermetallic phases with respect to the matrix can remarkably accelerate corrosion attacks in the certain areas of aluminium alloy matrix [14]. L. Wang et al. conducted atmospheric corrosion study of 5083, 6063 and 7020 aluminium alloys with 1-year exposure in Bangkok, Thailand [15]. It was revealed that 6063 alloy had the highest corrosion resistance followed by 5083 and 7020 alloys, respectively. Decreased corrosion resistance of those aluminum alloys was attributed to the formation of cathodic-type intermetallic phases, i.e. Fe-Si(Mn)-Al or Fe-Si-Al, which accelerated pitting corrosion of the aluminum alloy matrix. Other cathodic-type intermetallic phases such as AlCu_2Mg and Al_3Fe were also found in some aluminum alloys [16].

Smith et al. conducted atmospheric corrosion exposure test in Australia and reported that exfoliation corrosion was a major cause of metal loss only for 2090 aluminum alloy but not for 7075 aluminum alloy. Corrosion rates of 2090 and 7075 alloys decreased significantly as compared with the exposure test results in the first year. After 4-year exposure, the maximum corrosion rates of 4.9 and 0.92 $\mu\text{m}/\text{year}$ were obtained for 2090 and 7075 alloys, respectively. Sun et al. [18] investigated atmospheric corrosion of alclad and extruded 2024 and 7075 alloys. Their investigation results revealed that the corrosion rate of alclad alloys was much lower than that of extruded alloys. Weight loss of approximately 50 g/m^2 was obtained for extruded 2024 alloy after 10-year exposure in Jiangjin, China.

Regarding the corrosion protection of aluminum alloys during atmospheric exposure applications, the anti-corrosion coatings technique is widely adopted. In aerospace, the coating for protection of aluminum alloys exposed to harsh environment is typically based on a three-layer system consisting of a conversion coating, primer, and topcoat [19]. Epoxy-based primer is well known for corrosion protection due to its advantage dealing with leaching out soluble pigment into the materials defects and inhibition of corrosion progress. Although a topcoat layer can slow down the penetration of water and corrosive ions toward the substrate, those ions can gradually migrate through the coating over time and cause blisters or separation of the coatings. In automotive manufacturing, the three-layer coating system (e-coat + primer + topcoat) with a total dry film thickness of larger than 120 μm was frequently recommended for corrosion protection of vehicles made of aluminum alloys [20].

Due a lack of technical information necessary for establishing a predictive maintenance program of HSR vehicles intendedly employed for mass transit in Thailand, the current study was aimed to

investigate the performance of anti-corrosion coatings applied on 6005A and 6082 aluminum alloys under actual influences of monsoon tropical climate of Thailand.

2. Materials and Experimental Methods

2.1. Material and Test Samples

Anti-corrosion polymeric coatings consisting of epoxy primer and acrylic polyurethane topcoat were applied on 6005A and 6082 aluminum alloys rectangular coupons (70mm X 150mm X 6mm) using manual air spraying to obtain the desired specimens for atmospheric corrosion exposure test. The total thickness of coating dry film was approximately 160 μm (80 μm for each layer) after curing at 30°C for around 16 hrs as schematically shown in **Figure 1**.

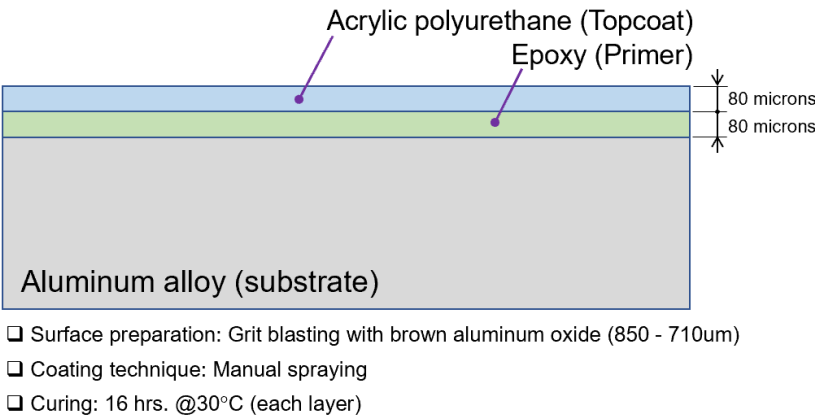


Figure 1. Configuration and technical details of anti-corrosion coating for aluminum alloys.

2.2. Atmospheric Exposure Test and Environmental Data Acquisition

Atmospheric exposure test sites were in Bangkok and Songkhla which represent urban and marine-coastal environments as reported in **Table 1**. Urban environment and its corrosivity level based on carbon steel is categorized into C2 according to ISO 9223 [21]. Due to geography of the marine-coastal environment test site, its corrosivity is categorized as CX based on carbon steel classification. The maximum period of 18 months was designed for the atmospheric exposure test. Prior to conducting exposure test, the polymer-coated samples were rinsed by de-ionized water for removal of surface contaminants followed by sudden dry-off using compressed air. As the assigned exposure test period was completed, the exposed samples were carefully withdrawn from the test sites for subsequent materials characterization and testing.

Table 1. Exposure test sites for atmospheric corrosion study of aluminum alloys.

Province	Env. characteristic	Corrosivity category based on carbon steel	GPS details
Bangkok (BKK)	Urban	C2	13°45' (N), 100°31'(E)
Songkhla (SKA)	Marine-coastal	CX	10°44' (N), 100°37' (E)

Relevant environmental factors, which can dominate atmospheric corrosion attacks, were monitored and recorded using commercial sensors throughout a period of exposure test at each test site. Ambient temperature (T), relative humidity (RH), and cumulative rainfall (RF) were mainly evaluated as the key climatic factors to influencing degradation characteristics of the exposed samples. In addition, chloride (Cl-) and sulfur dioxide (SO₂) depositions were collected using respective dry gauze and PbO₂ cylinder methods in accordance with JIS Z 2382 standard in order to determine the influences of climatic contaminants on degradation progress of the polymeric coatings and corrosion behaviors of the aluminum alloys substrate [22].

2.3. Evaluation of Anti-Corrosion Coating Performance

Electrochemical impedance spectroscopy (EIS) measurement was conducted using a potentiostat/galvanostat unit (Gamry 1010E) for determination of anti-corrosion performance of the polymeric coatings experienced environmentally induced degradation at different exposure test conditions. A sinusoidal potential perturbation was applied at an amplitude of 10 mV from open circuit potential (OCP) within a frequency range between 100 kHz and 10 mHz. EIS measurement was carried out in naturally aerated 3.5 wt.% NaCl solution at 25 °C by using a conventional three-electrode corrosion cell arrangement. The test sample acting as a working electrode with an exposed area of 12.56 cm² to electrolyte was configured. The reference and counter electrodes were Ag/AgCl and graphite, respectively. EIS data were captured during 7-day immersion test. Analysis and simulation of EIS impedance spectra were then carried out using pyZwx V. 1.03 software [23].

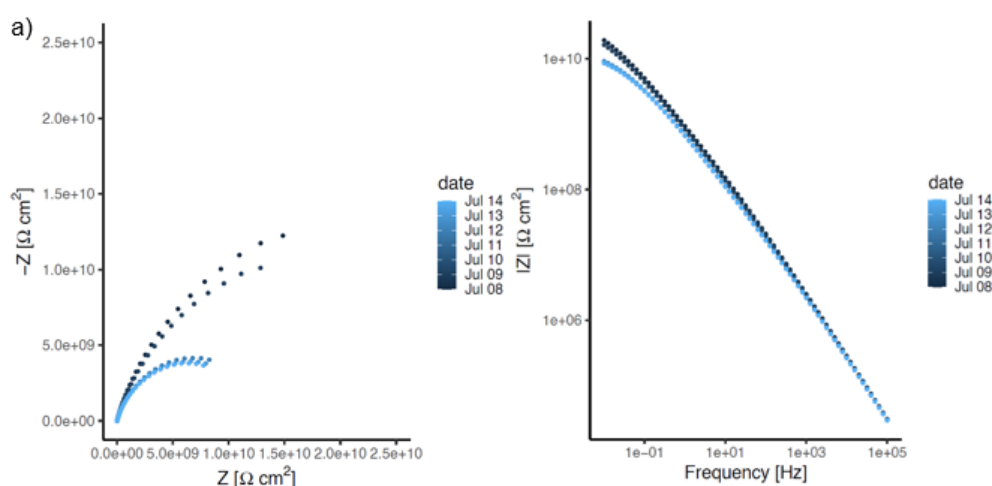
2.4. Polymeric-Coating Degradation Simulation by Salt Spray Test

Comparing with the actual exposure test, which is resource consuming, accelerated salt spray test was carried out at 25 °C for 1000 hrs. following ISO 9227 standard. The concentration of sprayed solution made of sodium chloride in deionized water was 50 g/l ($\pm$ 5 g/l). After salt spray test completion, the anti-corrosion coatings performance of 1000-hour salt sprayed samples were evaluated using EIS measurement whose testing protocol was the same as described in Section 2.3.

3. Results and Discussion

3.1. Anti-Corrosion Coating Performance in Actual Climatic Atmosphere

To evaluate the performance of anti-corrosion coatings applied on 6005A and 6082 alloys, EIS measurement was systematically carried out. The Nyquist and Bode plots of the unexposed samples are shown in Figure 2. Nyquist plots reveal incomplete semicircles due to capacitive behavior of the coatings. The size of such incomplete semicircles tends to decrease with increased immersion time, indicating moisture penetration throughout the coatings. From Bode plots, it reveals that the impedance modulus was continuously decreased with a slope of -1 as frequency increased. However, the impedance modulus at frequency of 100 mHz ($|Z|_{0.1\text{Hz}}$) obtained from all test conditions is significantly greater than 10⁶ $\Omega\cdot\text{cm}^2$, meaning that the coatings is still protective.



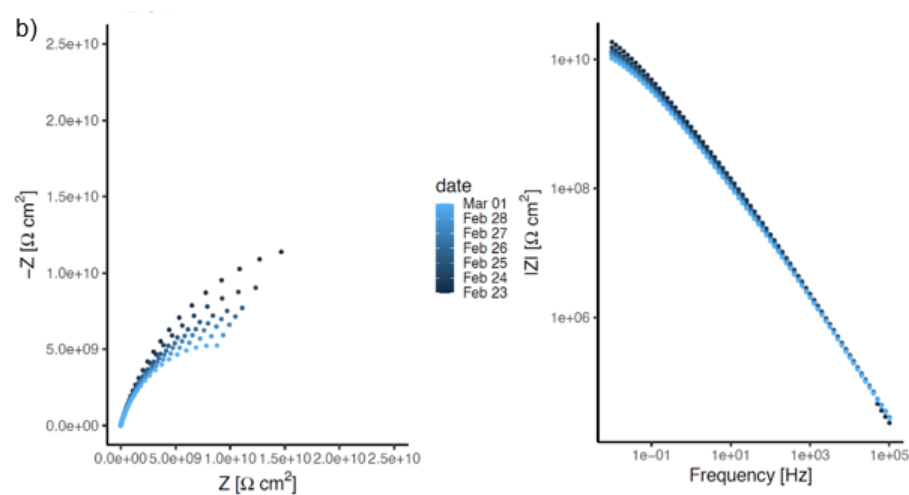


Figure 2. Nyquist and Bode plots obtained from EIS measurement of the unexposed samples: a) s of polymer-coated 6050A (a) and 6082 (b) aluminum alloys.

Figures 3 and 4 show Nyquist plots obtained from EIS tests on polymer-coated 6050A and 6082 alloys, respectively, which were exposed to actual urban and marine-coastal environments for 6 months. All the 6-month exposed samples reveal incomplete semi-circle arcs, implying that the protective coatings still performed and were not significantly deteriorated by climatic environment for 6-month exposure. Based on the EIS results, it clearly shows that the protective property of anti-corrosion coatings was reduced by marine-coastal climatic environment rather than urban climatic environment.

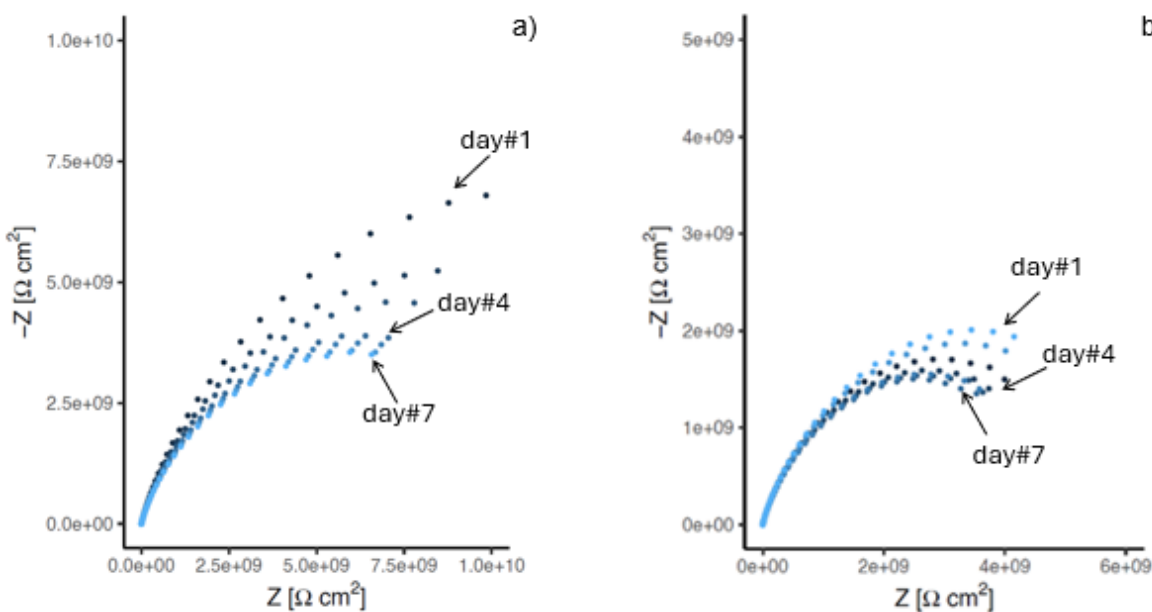


Figure 3. Nyquist plots obtained from EIS tests conducted with the 6-month exposed samples of polymer-coated 6050A alloy in the urban (a) and marine-coastal (b) environments.

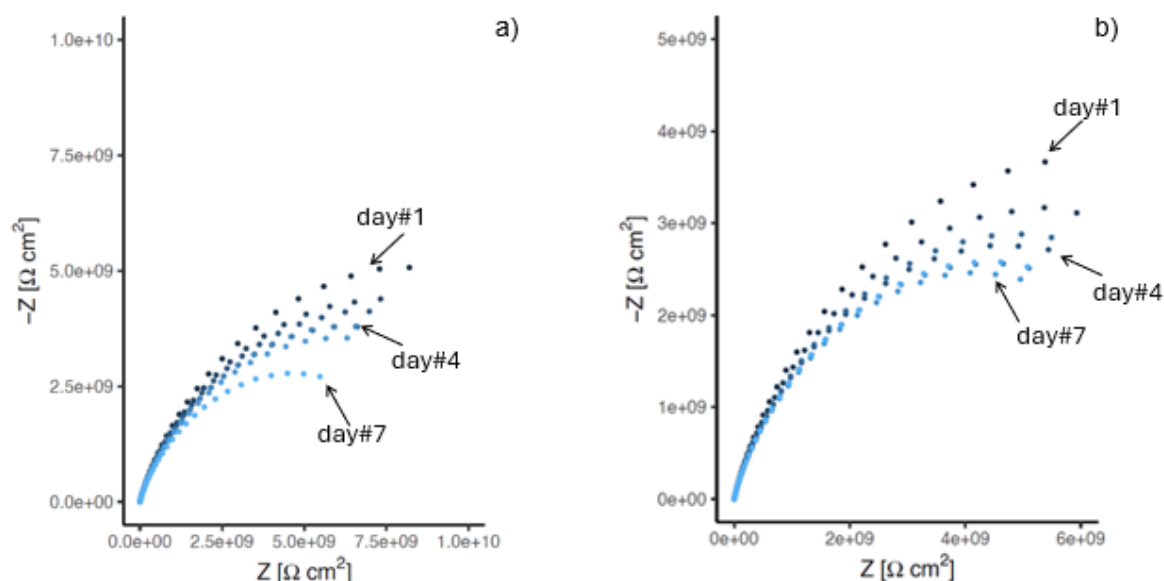


Figure 4. Nyquist plots obtained from EIS tests conducted with the 6-month exposed samples of polymer-coated 6082 alloy in the urban (a) and marine-coastal (b) environments.

To gain an insight into the protective property of anti-corrosion coatings, Bode plots in forms of phase shift and impedance modulus as a function of frequency domain are shown in **Figure 5**. The polymer-coated samples were exposed to urban and marine-coastal climatic environments with varied durations (18 months maximum). In principle, 0-degree phase shift represents a resistive response, while 90-degree phase shift indicates a capacitive response of the anti-corrosion coatings. As frequency increased, the impedance modulus decreased, whereas the phase angle was shifted from low to high. A drop of phase angle at low frequency indicated a resistive response of the anti-corrosion coatings. At low frequency (10 mHz), the impedance modulus of approximately $10^{10} \Omega \cdot \text{cm}^2$ with a phase angle of around 20° was obtained. At high frequency (100 kHz), the impedance modulus became as low as $10^5 \Omega \cdot \text{cm}^2$, and the phase angle was around 90° . A change in impedance modulus and phase angle was considered minimal as the immersion time increased. The polymer-coated 6082 alloy with 12-month exposure at urban environment only revealed the greatest decrease in impedance by almost an order of magnitude as compared during 7-day immersion test. However, it is interesting to note that the polymer-coated aluminum alloys with 18-month exposure at urban environment revealed their slightly increased impedance, and phase angle slightly shifted towards capacitive behaviors at low frequency when increasing immersion time during EIS measurement increased. This phenomenon might be due to inconsistency of the coatings which were manually applied.

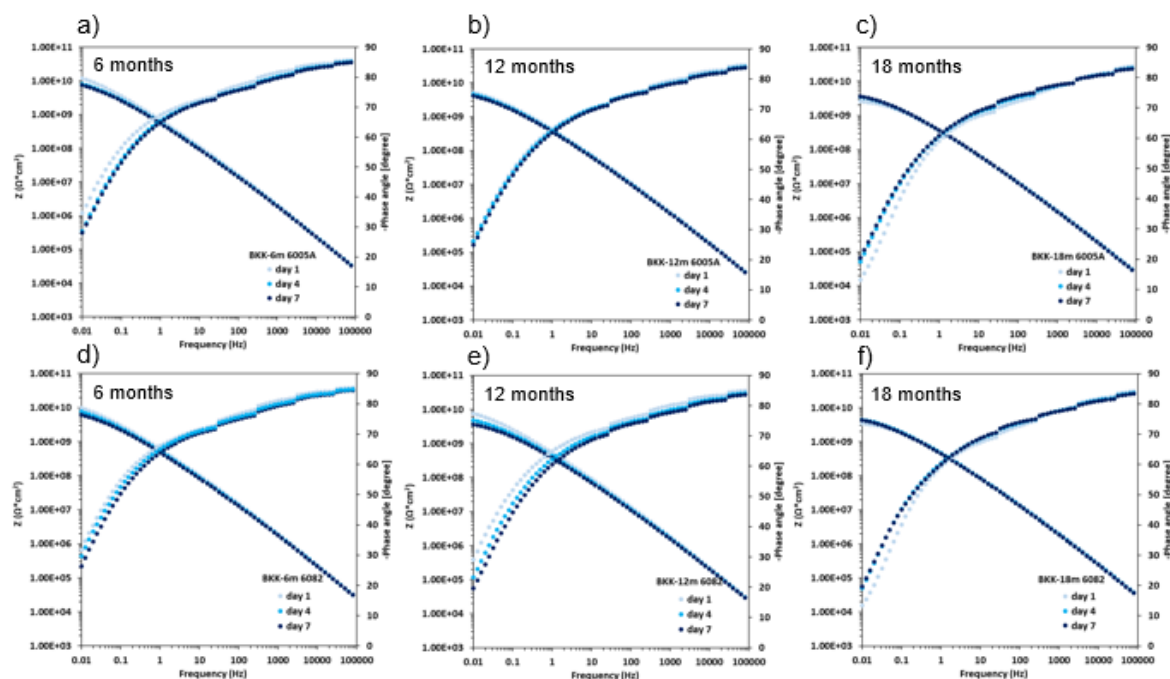


Figure 5. Bode (impedance and phase angle) plots obtained from 7-day EIS measurement of polymer-coated 6005A and 6082 aluminum alloys with 6-, 12-, and 18-month exposure periods in the urban environment (a – c and d - e for belonging to polymer-coated 6005A and 6082 aluminum alloys, respectively).

The degradation behaviors of the anti-corrosion coatings affected by exposure duration together with climatic environment was evaluated from EIS low-frequency impedance response during 7-day immersion test in 3.5% NaCl solution at 25 °C. The impedance response in a low-frequency region typically reflected the coating performance in terms of corrosion resistance, which gradually decreased as field exposure time elapsed for all the polymer-coated alloys. As shown in **Figure 6**, it was seen that the prolonged exposure time in climatic environment resulted in less capacitive response obtained, implying that more electrolyte remarkably migrated through the anti-corrosion coatings deteriorated by atmospheric environment [25]. The degradation of coating barrier property should be attributed to the penetration of corrosive species as well as UV radiation [26]. Regarding the climate factors, it seemed that marine-coastal environment could relatively impact on the remarkable degradation of anti-corrosion coating property with respect to urban environment, in particular, when the exposure time in climatic environment was greater than 12 months. In overall, it is worth to note that anti-corrosion coatings used in the current research could reveal their excellent performance to protect 6005A and 6082 alloys against atmospheric corrosion attacks in tropical climate of Thailand.

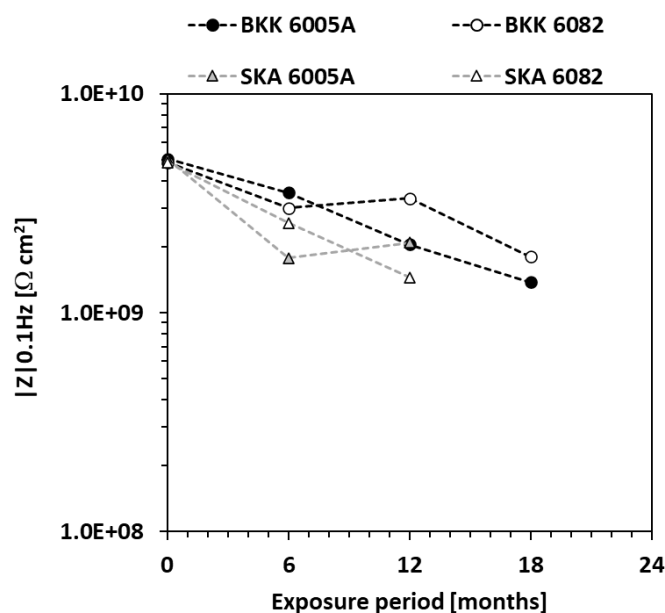


Figure 6. Low-frequency impedance, $|Z|_{0.1\text{ Hz}}$, obtained from EIS tests with the polymer-coated samples under unexposed and exposed conditions for 6, 12 and 18 months in the urban (BKK) and marine-coastal (SKA) environments (7-day immersion).

Equivalent electrical circuit (EEC) was used to simulate EIS spectra data for explanation of physical behaviors of the anti-corrosion coatings applied on 6005A and 6082 alloys. A generic model of EEC for polymer-coated metal was selected to fit the EIS impedance spectra as shown in **Figure 7** [25–29]. For more accurate fitting results with eliminating non-ideal capacitance, a constant phase element (CPE) was employed in relation to capacitive elements [25,27]. In the circuit, R_s represents electrolyte solution resistance. R_c and CPE_1 represent the coating resistance and capacitive element, respectively, which are normally influenced by the existence of defects and porosity in the coatings. R_{ct} and CPE_2 represent the charge transfer resistance and double-layer capacitive element, which are normally used to evaluate electrochemical corrosion phenomena at the metal substrate/coating interface. Based on a CPE impedance equation, n (CPE-power) is varied between 0 and 1 ($0 \leq n \leq 1$). CPE behaves as pure capacitance if n value is 1. The fitted parameters obtained from simulation are summarized in **Table 2**.

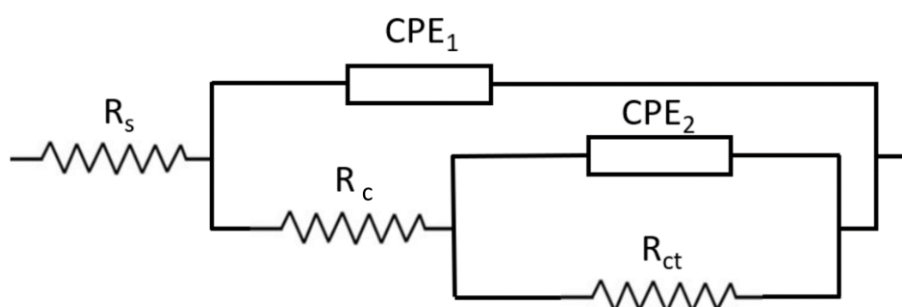


Figure 7. Equivalent electrical circuit model proposed to describe physical characteristics of the anti-corrosion coating on aluminum alloys.

Table 2. Equivalent electrical circuit parameters (M1: polymer-coated 6005A alloy and M2: polymer-coated 6082 alloy).

Sample	R_c [$\Omega\text{ cm}^2$]	R_{ct} [$\Omega\text{ cm}^2$]	CPE_1 F/cm ² /S ⁿ¹	n_1	CPE_2 F/cm ² /S ⁿ²	n_2
M1BKK6m	2.25E+07	2.36E+10	1.15E-10	0.94619	2.63E-10	0.62873
M1BKK12m	2.62E+06	8.24E+09	1.43E-10	0.94724	5.06E-10	0.62409
M1BKK18m	4.22E+05	3.05E+09	7.15E-11	0.97779	6.47E-10	0.68209
M2BKK6m	9.04E+06	1.82E+10	1.16E-10	0.94881	3.22E-10	0.62283
M2BKK12m	3.19E+05	1.03E+09	1.52E-09	0.94796	4.80E-09	0.62517
M2BKK18m	2.48E+05	4.02E+09	4.89E-11	1	5.10E-10	0.68063
M1SKA6m	2.30E+06	5.99E+09	1.24E-10	0.94474	5.21E-10	0.62091
M1SKA12m	6.73E+06	8.99E+09	1.71E-10	0.9247	4.16E-10	0.60702
M2SKA6m	4.13E+06	1.30E+10	1.19E-10	0.94532	3.78E-10	0.63093
M2SKA12m	2.54E+05	4.20E+09	1.00E-10	0.96498	6.51E-10	0.65148

It clearly shows that R_c and R_{ct} tended to decrease with prolonged exposure period in actual climatic environment. R_c decreased by almost two orders of magnitude when the anti-corrosion coating was exposed to climatic environment for 18 months. The most resistant coating was observed from the polymer-coated alloys exposed in urban climatic environment, followed by those exposed in marine-coastal climatic environment. R_{ct} was much higher than R_c , meaning that corrosion promoters, e.g., moisture, oxygen, corrosive species, etc., were not available at the aluminum substrate/coating interface. Based on the impedance spectra and R-values, it was evident that the anti-corrosion coatings serve as a remarkable barrier protecting the substrate alloys underneath against atmospheric corrosion attacks. Low coating capacitance (CPE_1) with a value of approximately 1.0E-10 F/cm²/Sⁿ¹ and n_1 value of almost 1 implied that a small amount of water uptake took place in the anti-corrosion coatings. Double-layer capacitance (CPE_2) with a value of approximately 1.0E-10 F/cm²/Sⁿ² and n_2 value of around 0.6 indicated that some small areas of the substrate were exposed to environment due to exceptionally protective coatings.

3.2. Service Life Prediction of Anti-Corrosion Coatings

According to technical requirements of predictive maintenance scheduling for HSR vehicle structure and body, the performance of polymer-coated aluminum alloys in relation to service life was estimated from the time-dependent plot of low-frequency impedance at 100 mHz ($|Z|_{0.1\text{Hz}}$). $|Z|_{0.1\text{Hz}}$ basically represents the total impedance of solution, coating, and substrate/coating interface which can determine the protective property of anti-corrosion coatings [29]. Based the proposed criteria, the failure of anti-corrosion coatings is remarkable as its $|Z|_{0.1\text{Hz}}$ is lower than 10⁶ $\Omega\text{ cm}^2$. Average $|Z|_{0.1\text{Hz}}$ values of the polymer-coated 6005A and 6082 alloys exposed at urban and marine-coastal climatic environments were calculated and plotted against the exposure period as shown in **Figure 8**. The average value was applied here because the $|Z|_{0.1\text{Hz}}$ values were in the same order of magnitude. It was found that $|Z|_{0.1\text{Hz}}$ decreased exponentially with time. If the decaying function for the anti-corrosion coatings remained the same throughout their service life, projected time to reach $|Z|_{0.1\text{Hz}}$ of 10⁶ $\Omega\text{-cm}^2$ would be 11 years for the polymer-coated aluminum alloys exposed at urban climatic environment and 8 years for those exposed at costal-marine climatic environment. Thus, the anti-corrosion coatings played a crucial role in extending the service life of 6000-series aluminum alloy applied in HSR vehicles manufacturing.

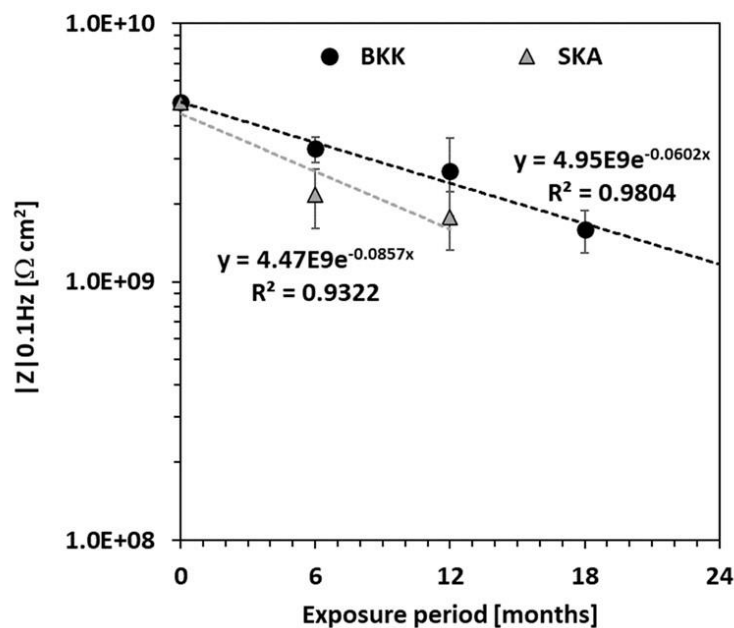


Figure 8. Average low frequency impedance of coatings as a function of time under unexposed and exposed conditions for 6, 12 and 18 months in the urban (BKK) and marine-coastal (SKA) environments (7-day immersion).

3.3. Degradation Simulation of Polymeric-Coated Alloys Using Salt-Spray Test

Comparing between the actual exposure test and accelerated salt spray test, it can be seen the salt spray test could potentially be employed to simulate the atmospheric corrosion behaviors of polymer-coated aluminum alloys under the most severe condition. As the EIS measurement of 1000-hour salt sprayed samples carried out, Nyquist plots of polymer-coated 6005A and 6082 alloys immersed in the electrolyte test solution with a varied duration are shown in **Figure 9**. Incomplete semi-circle arcs were revealed for both polymer-coated samples. The radius of semi-circles tended to decrease as the immersion period increased, allowing more electrolyte penetrating through the anti-corrosion coatings. The performance of anti-corrosion coatings on 6005A alloy was slightly better than that on 6082 alloy. As compared between the actual exposure test and accelerated salt spray test, $|Z|_{0.1\text{Hz}}$ values of the polymer-coated samples undergone 1000-hour salt spray test and 6-, 12-, and 18-month exposure test in urban and marine-coastal environment are shown in **Figure 10**. Due to relatively high severity of salt spray test, it reveals that 1000-hour salt spray test could represent a degradation behavior of polymer-coated alloys when exposed in urban and coastal-marine environments for 18 and 12 months, respectively.

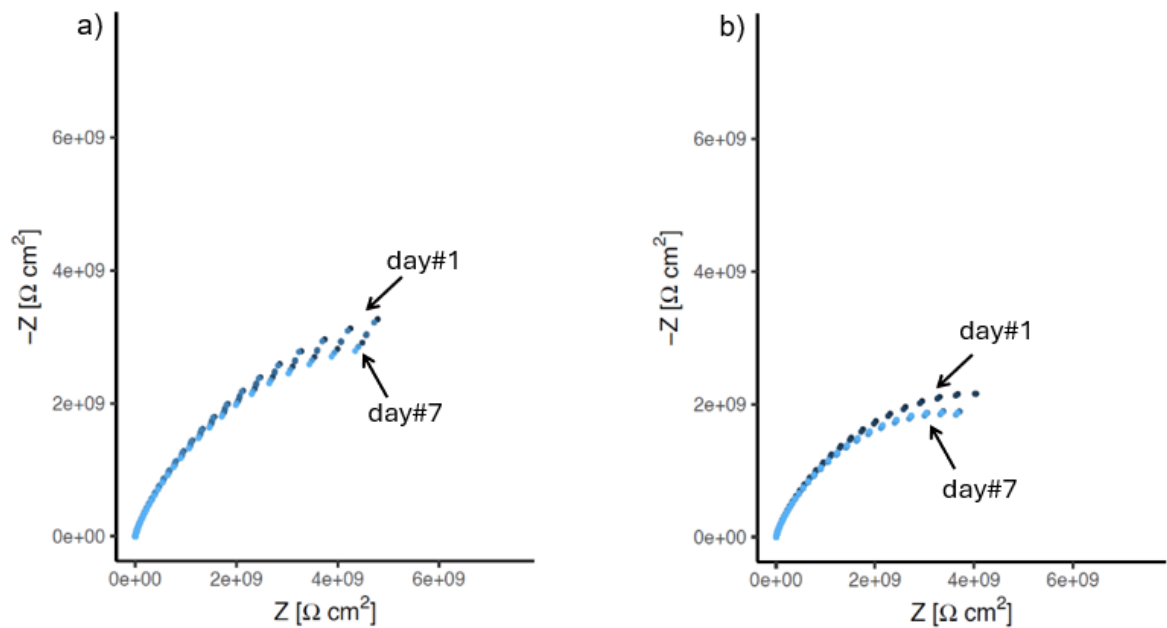


Figure 9. Nyquist plots obtained from EIS test conducted on polymer-coated 6005A (a) and 6082 alloy samples experienced 1,000-hour salt spray test.

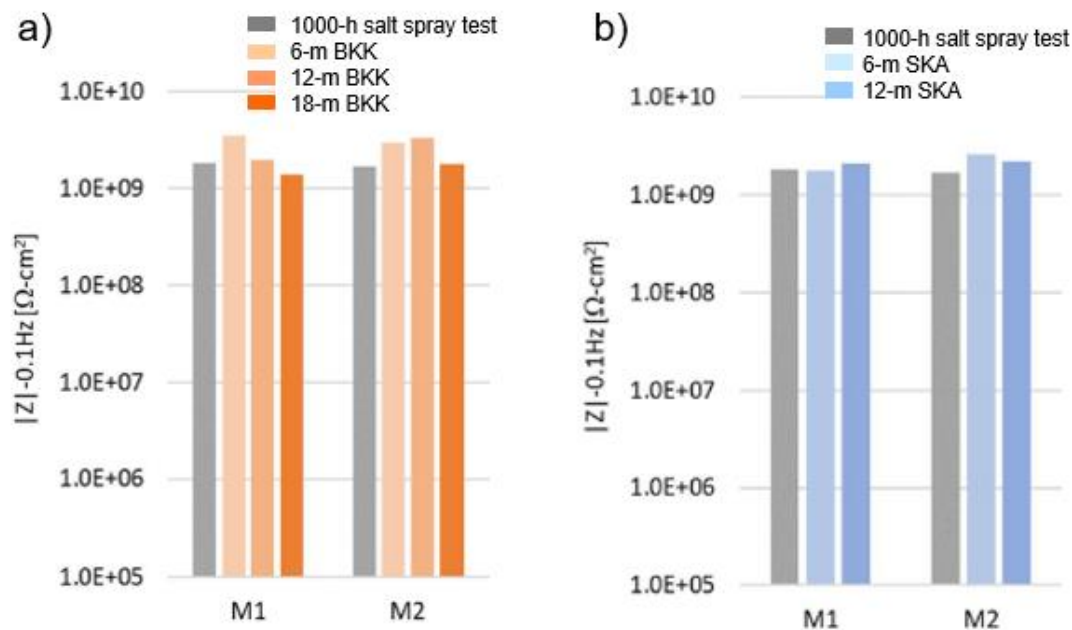


Figure 10. Low-frequency impedance ($|Z|_{0.1\text{Hz}}$) obtained during 7-day EIS test of polymer-coated 6005A and 6082 alloys experienced the exposure test in urban (a) and marine-coastal environment after exposure test .

4. Discussion

From systematic investigation in the current research, marine-coastal environment was more severe than urban environment to cause degradation of anti-corrosion coatings applied on the 6000-series aluminum alloys. Based on corrosion protection perspectives, it was found that the commercial coating system consisting of epoxy primer (~ 80 μm thickness) and acrylic polyurethane topcoat (~ 80 μm thickness) could provide excellent barrier property for the aluminum alloys against atmospheric corrosion attacks. EIS test results revealed that the low-frequency impedance, determined corrosion resistance property of the coatings, was around $10^{10} \Omega\cdot\text{cm}^2$ classified into a very high corrosion resistance category (impedance > $10^7 \Omega\cdot\text{cm}^2$) [28,29]. A slight degradation of the

coating represented by decreased impedance was observed as the exposure period to atmospheric environment elapsed. It was evident by CPE₂ that there were migration paths for electrolyte and other corrosion promoters introduced during either coating application or atmospheric exposure or both to exist in the coating layer, which then allowed the aluminum substrate's surface to be in direct contact with atmospheric environment. This suggested that the coating degradation/aging might be concerned when long-term exposure in tropical climate required. Based on the service life prediction, the anti-corrosion coating on the aluminum alloys could last for approximately 11 years long before repainting when exposed to service conditions in urban environment. Marine-coastal environment played a key role in reducing the service life of the anti-corrosion coatings by around 27% with respect to urban environment. To reduce the resources required for long-term exposure test in actual environment, salt spray test was potentially employed to simulate the degradation characteristics of anti-corrosion coatings.

5. Conclusions

Anti-corrosion performance of polymer-coated aluminum alloys was evaluated by long-term actual exposure test under tropical climate of Thailand with the maximum period of 18 months. From EIS measurement of the exposed test samples, it turned out that the anti-corrosion polymer coating revealed its sufficient performance to protect the 6000-series aluminum alloys against atmospheric corrosion under tropical climate influences. However, the gradual degradation of coating was noticed as the exposure period to atmospheric environment elapsed. It was predicted that the polymer coatings could last for approximately 11 years when exposed at urban environment. Exposure to marine-coastal environment caused a reduction of the coating service life by around 27% as compared with urban environment. Salt spray test served as an alternative to long-term actual exposure test for evaluation the anti-corrosion performance of polymer coatings applied to 6000-series aluminum alloys.

Acknowledgments: This work was supported by the Key R&D Program of Shandong Province (2025KJHZ030), China. The authors were also grateful for in-kind supports provided by National Science and Technology Development Agency (NSTDA), Thailand.

References

1. https://en.wikipedia.org/wiki/Bangkok%E2%80%93Nong_Khai_high-speed_railway
2. X. Sun Xiaohui Han, Chaofang Dong and Xiaogang Li. Applications of aluminum alloys in rail transportation. IntechOpen. doi: <http://dx.doi.org/10.5772/intechopen.96442>
3. J.E. Hatch. Aluminium: Properties and physical metallurgy, American Society of Metals, Metals Park, OH, 1984. pp. 2–24.
4. Alloying: Understanding the basic, J.R. Davis, ASM International, 2001 ISBN: 978-0-87170-744-4, p 351-416. doi:10.1361/autb2001p351
5. Z. Dan, S. Takigawa, I. Muto, and N. Hara. Applicability of constant dew point corrosion tests for evaluating atmospheric corrosion of aluminium alloys. Corros. Sci. 53 (2011) 2006–2014. doi: 10.1016/j.corsci.2011.02.027
6. B.B. Wang, Z.Y. Wang, W. Han, and W. Ke. Atmospheric corrosion of aluminium alloy 2024-T3 exposed to salt lake environment in Western China. Corros. Sci. 59 (2012) 63–70. doi: 10.1016/j.corsci.2012.02.015.
7. Z. Dan, I. Muto and N. Hara. Effects of environmental factors on atmospheric corrosion of aluminium and its alloys under constant dew point conditions. Corros. Sci. 57 (2012) 22–29. doi: 10.1016/j.corsci.2011.12.038.
8. J. Alcántara, D. Fuente, B. Chico, J. Simancas, I. Díaz, and M. Morcillo. Marine atmospheric corrosion of carbon steel: A review, Materials. 10 (2017). <https://doi.org/10.3390/ma10040406>.

9. Y.L. Cheng, Z. Zhang, F.H. Cao, J.F. Li, J.Q. Zhang, J.M. Wang, and C.N. Cao. A study of the corrosion of aluminum alloy 2024-T3 under thin electrolyte layers. *Corros. Sci.* 46 (2004) 1649-1667. doi: 10.1016/j.corsci.2003.10.005.
10. C. Leygraf, I. O. Wallinder, J. Tidbald and T. Graedel. *Atmospheric Corrosion*, 2nd Ed., John Wiley & Sons (2016) 272 - 281
11. R. Vera, D. Delgado, and B. M. Rosales. Effect of atmospheric pollutants on the corrosion of high power electrical conductors: Part 1. Aluminium and AA6201 alloy. *Corros. Sci.* 48 (2006) 2882–2900. doi:10.1016/j.corsci.2005.11.012.
12. Z. Cui, F. Ge, X. Li, M. Zhu, K. Xiao, C. Dong, X. Wang, Mechanistic studies of atmospheric corrosion behavior of Al and Al-based alloys in a tropical marine environment, *J. Wuhan Univ. Technol.-Mater Sci Ed.* 32 (2017) 633–639. <https://doi.org/10.1007/s11595-017-1645-3>.
13. Z. Cui, X. Li, H. Zhang, K. Xiao, C. Dong, Z. Liu, L. Wang, Atmospheric Corrosion Behavior of 2A12 Aluminum Alloy in a Tropical Marine Environment, *Adv. Mater. Sci. Eng.* (2015) 163025. <http://dx.doi.org/10.1155/2015/163205>.
14. A. Boag, A.E. Hughes, A.M. Glenn, T.H. Muster, D. McCulloch, Corrosion of AA2024-T3 Part I: Localised corrosion of isolated IM particles, *Corros. Sci.* 53 (2011) 17–26. <https://doi.org/10.1016/j.corsci.2010.09.009>.
15. L. Wang, C. Dong, D. Zhang, X. Sun, T. Chowwanonthapunya, C. Man, K. XIAO, and X. Li . Effect of alloying elements on initial corrosion behavior of aluminum alloy in Bangkok, Thailand, *Acta Met. Sin.* 56 (2019) 119–128. <https://doi.org/10.11900/0412.1961.2019.00217>.
16. N.L. Sukiman, X. Zhou, N. Birbilis, A.E. Hughes, J. M. C. Mol, S. J. Garcia, X. Zhou and G. E. Thompson. Durability and corrosion of aluminium and its alloys: Overview, property space, techniques and developments, *Al alloys - New trends fabr. appl.* (2012). <https://doi.org/10.5772/53752>.
17. B.S. Smith, E.J. Duxbury, B.T. Moore, Atmospheric corrosivity of defence bases in northern and eastern Australia, (n.d.) 41.
18. S. Sun, Q. Zheng, D. Li, and J. Wen. Long-term atmospheric corrosion behaviour of aluminium alloys 2024 and 7075 in urban, coastal and industrial environments. *Corros. Sci.* 51 (2009) 719–727. <https://doi.org/10.1016/j.corsci.2009.01.016>.
19. J. Yue and Y. Cao. Corrosion prevention by applied coatings on aluminum alloys in corrosive environments. *Int. J. Electrochem. Sci.*, 10 (2015) 5222 - 5237.
20. Z. Xu, G. Anyasodor, and Y. Qin. Painting of aluminium panels – state of the art and development issues, *MATEC Web of Conferences* 21 (2015) 05012, doi:10.1051/mateconf/20152105012
21. ISO 9223:2012. Corrosion of metals and alloys-Corrosivity of atmospheres-Clasification, determination and estimation, 2nd ed.; International Organization for Standardization: Geneva, Switzerland, 2012
22. JIS Z 2382:1998, Determination of pollution for evaluation of corrosivity of atmospheres, (2018). https://www.techstreet.com/standards/jis-z-2382-1998?product_id=1233125#jumps (accessed February 2, 2018).
23. K. Kobayashi and T. S. Suzuki, *Electrochem. "Free analysis and visualization programs for electrochemical impedance spectroscopy coded in Python"* 89, (2021) 218-222. doi: 10.5796/electrochemistry.21-00010
24. P.S. Liss, A.D. Hatton, G. Malin, P.D. Nightingale and S.M Turner. Marine sulphur emissions. *Philosophical Transactions: Biological Sciences* 352(1997), 159–169. <http://www.jstor.org/stable/56558>
25. J.M. Hu, J.Q. Zhang, and C.N. Cao. Determination of water uptake and diffusion of C-ion in epoxy primer on aluminum alloys in NaCl solution by electrochemical impedance spectroscopy. *Progress in Organic Coatings* 46 (2003): 273-279. doi:10.1016/S0300-9440(03)00010-9.
26. T. Zhang, Y. He, X. Du, and S. Zhang. Aging and corrosion behavior of epoxy primer coated aluminum alloys in UVA, UVA-neutral and UVA-acidic alternating-immersion environments. *Engineering Failure Analysis* 130 (2021): 105759. <https://doi.org/10.1016/j.engfailanal.2021.105759>
27. J.B. Bajat, V.B. Mišković-Stanković, Z. Kačarević-Popović, Corrosion stability of epoxy coatings on aluminum pretreated by vinyltriethoxysilane, *Corros. Sci.* 50 (2008) 2078–2084. <https://doi.org/10.1016/j.corsci.2008.04.018>.

28. O. Dagdag, O. Hamed, H. Erramli, A. El Harfi, Anticorrosive Performance Approach Combining an Epoxy Polyaminoamide–Zinc Phosphate Coatings Applied on Sulfo-tartaric Anodized Aluminum Alloy 5086, *J. Bio- Tribo-Corros.* 4 (2018) 52. <https://doi.org/10.1007/s40735-018-0168-6>.
29. J.M. Sanchez-Amaya, R.M. Osuna, M. Bethencourt, F.J. Botana, Monitoring the degradation of a high solids epoxy coating by means of EIS and EN, *Prog. Org. Coat.* 60 (2007) 248–254. <https://doi.org/10.1016/j.porgcoat.2007.07.020>.
30. Z. Pei, X. Cheng, X. Yang, Q. Li, C. Xia, D. Zhang, and X. Li. Understanding environmental impacts on initial atmospheric corrosion based on corrosion monitoring sensors. *Journal of Materials Science & Technology* 64 (2021), 214–221. doi: 10.1016/j.jmst.2020.01.023.
31. M. Gao, Z. Sun, W. Yan, Z. Tang, and Y. Zhang. Influence of solid particles deposition on the initial atmospheric corrosion of 7B04 aluminum alloy. *Materials Today Communications* 31 (2022) 103562. doi: 10.1016/j.mtcomm.2022.103562.
32. M. Natesan, G. Venkatachari, N. Palaniswamy, Kinetics of atmospheric corrosion of mild steel, zinc, galvanized iron and aluminium at 10 exposure stations in India, *Corros. Sci.* 48 (2006) 3584–3608. doi:10.1016/j.corsci.2006.02.006
33. Q. Zhao, C. Guo, K. Niu, J. Zhao, Y. Huang, and X. Li. Long-term corrosion behavior of the 7A85 aluminum alloy in an industrial-marine atmospheric environment. *Journal of Materials Research and Technology* 12 (2021) 1350–1359. doi: 10.1016/j.jmrt.2021.03.085.
34. S. Zhang, T. Zhang, Y. He, D. Liu, J. Wang, X. Du, and B. Ma. Long-term atmospheric corrosion of aluminum alloy 2024-T4 in coastal environment: Surface and sectional corrosion behavior.” *Journal of Alloys and Compounds* 789 (2019), 460–471. <https://doi.org/10.1016/j.jallcom.2019.03.028>.
35. Y. Ji, Y. Xu, B. Zhang, Y. Behnamian, D. Xia, and W. Hu. Review of micro-scale and atomic-scale corrosion mechanisms of second phases in aluminum alloys. *Transactions of Nonferrous Metals Society of China* 31(2021): 3205–3227. doi: 10.1016/S1003-6326(21)65727-8.
36. C. Peng, G. Cao, T. Gu, C. Wang, Z. Wang, and C. Sun. The corrosion behavior of the 6061 Al alloy in simulated Nansha marine atmosphere. *Journal of Materials Research and Technology* 19 (2022), 709–721. <https://doi.org/10.1016/j.jmrt.2022.05.066>.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.