Materials Research Express

PAPER

Comparative investigations on the electrochemical behaviors among Al and aluminum alloys

Yonghong Deng 1, Jian Liu 1, Yang Qiao 1 and Jintao Niu 3

1 Sichuan Institute of Industrial Big-data Applications, Chengdu 611730, People’s Republic of China
2 School of Automobile and Transportation, Chengdu Technological University, Chengdu 611730, People’s Republic of China
3 School of Mechanical Engineering, University of Jinan, Jinan 250022, People’s Republic of China

E-mail: me_niuji@ujn.edu.cn

Keywords: electrochemical behavior, aluminum alloy, potentiostatic polarization measurement, polarization current density

Abstract

Al and aluminum alloys are widely used in the transportation industry and aerospace field owing to their low density. They are always utilized as the sheathing materials, whose corrosion resistances need special attention. In the study, the electrochemical impedance spectroscopy (EIS) measurements and potentiodynamic polarization tests are performed on pure Al, aluminum alloys 2A97, 6061, 7050 and 2024. The corrosion behaviors of the five materials are respectively characterized by the resultant indicators, such as the corrosion potential \( E_{cor} \), the corrosion current density \( I_{cor} \), the corroded surface morphology and the frequency characteristics. The materials sequences that determined respectively by these indicators are compared with each other. The conflicts among these sequences are found. Then potentiostatic polarization measurements are carried out on the five materials. The instantaneous characteristic of the corrosion potential and polarization current density of each material during its corrosion process is revealed. Because of the characteristic, it is concluded that the potentiostatic polarization measurement and resultant polarization current density are more suitable to characterize the corrosion behaviors of Al and aluminum alloys. The investigation could provide help in the exploitation of new aluminum alloys with the better corrosion property.

1. Introduction

The low strength of pure Al is an obstacle to its widespread industrial application. The addition of alloying elements to Al constituting aluminum alloys enhances the mechanical properties of Al, and changes its anticorrosion resistance due to the existence of constituents with different potentials [1, 2].

Till now, some proven methods and corresponding indicators have been applied in characterizing and comparing the corrosion properties of Al and aluminum alloys [3–8]. In summary, four indicators including the corrosion potential \( E_{cor} \), the corrosion current density \( I_{cor} \), the corroded surface morphology and the frequency characteristics are frequently utilized. The four indicators are respectively obtained from potentiodynamic polarization tests, immersion tests and electrochemical impedance spectroscopy (EIS) measurements.

However, it has to be acknowledged that the indicators \( E_{cor}, I_{cor} \) and the frequency characteristics are respectively from the viewpoints of the thermodynamics, kinetics and frequency domain of corrosion. When it comes to comparing simultaneously corrosion properties of specific materials with these indicators, contradictory conclusions may be reached. There are many cases in the existed investigations. Especially, more than two materials [9] or two surface conditions of a material [10] are involved in the comparison. After potentiodynamic polarization and EIS measurements for Al, Al-1Li and Al-2Li, Wang et al [9] found that with increasing Li element content, the \( E_{cor} \) values decreased while corrosion reactions resistances that reflected by their EIS tests increased. The former suggested that alloy Al-2Li possessed the largest corrosion susceptibility, while the indicator from EIS measurements implied the alloy owned the best corrosion property. The results of potentiodynamic polarization measurements for ground-polished surfaces of aluminum alloy 2A97 with different surface roughness showed that their \( E_{cor} \) and \( I_{cor} \) values contradictorily changed [10]. More specifically,
with the increase of the surface roughness values, the $E_c$ values of alloy 2A97 monotonically reduced while their $I_c$ values were not monotonically increased. Therefore, the contradictory sequences of materials and surface conditions were obtained when their corrosion performances were characterized with the existed corrosion parameters, such as $E_c$, $I_c$ and frequency characteristics.

As for the corroded surface morphology, it is generally characterized by the density and depths of the corrosion pits on the corroded surfaces. However, the corrosion of Al and aluminum alloys is nonuniform, which means that corrosion pits distribute locally on their surfaces. Therefore, the conclusion that drawn based on the surface corrosion morphology characteristic could be inconsistent with that concluded with the indicators $E_c$, $I_c$ and the frequency characteristics. Take a comparison in the existed study as an example. After EIS tests and immersions tests of aluminum alloys AA2098-T351 and AA2024-T3, the lower impedance from EIS tests for alloy AA2098-T351 was found while the deeper corrosion pit on corroded surfaces for alloy AA2024-T3 was observed [11]. Undoubtedly, a conflict appeared.

The existed indicators mentioned above only characterize the corrosion properties when materials are tested, and are hard to characterize the continuous variations of the anti-corrosion behaviors with time. This is supposed to account for the conflicts that exist among the materials sequences determined by these indicators. In the investigation, the corrosion behaviors of pure Al, aluminum alloys 2024, 2A97, 6061 and 7050 were firstly characterized with the existed indicators $E_c$, $I_c$, the frequency characteristics and the corroded surface morphology. Then the sequences of these five materials that determined by every indicator were compared with each other. The conflicts among the sequences were found. Lastly, the continuous variations of anticorrosion behaviors of the five materials with time were studied through the potentiostatic polarization measurements. The instantaneous characteristic of electrochemical behaviors of materials was elaborated. Based on the characteristic, the proposal that the potentiostatic polarization measurement and the resultant polarization current density were more suitable to characterize and compare corrosion performances of Al and aluminum alloys was put forward.

### 2. Materials and methods

#### 2.1. Materials

Pure Al, aluminum alloys 2024, 6061, 7050 and 2A97 were chosen as the research objects in the study. The conditions of these four alloys and their chemical compositions were presented in Table 1. Alloy 2024 was solution heat treated at 540 °C for 2 h, followed by water quenching and natural aging at room temperature. Alloy 6061 was solution heat treated at 540 °C for 2 h, followed by water quenching and aged at 120 °C for 12 h. After annealing at 480 °C for 6 h, alloy 7050 was aged at 120 °C for 6 h and followed by aged at 177 °C for 8 h and then was cooled down to the room temperature in the furnace. After homogenizing at 520 °C for 24 h, alloy 2A97 bulk was hot rolled at 475 °C with the rolling reduction 2.24 mm. For the simplification, the corresponding condition of each alloy was consciously omitted hereafter.

#### 2.2. Samples preparation

Six cubic samples with dimensions of 4 mm $\times$ 4 mm $\times$ 6 mm were obtained from every material bulk using the electric discharge machining. More specifically, totally thirty samples from the five materials were prepared for the further operations. After being mounted with cold epoxy, all surfaces except the one with dimensions of 4 mm $\times$ 4 mm of every sample were sealed, and the exposed one was the to-be-tested surface.

Before electrochemical measurements, there were two more steps. Firstly, all the exposed surfaces of the thirty samples were ground and subsequently polished to 1.15 μm surface finish to eliminate the effects of the non-material factors upon the corrosion behaviors of the five materials. Secondly, after ultrasonic cleaning in ethanol for 5 min and drying, the back surface of the ground-polished one of every sample was connected with a copper wire utilizing modified acrylate adhesive. The adhesive was also used to seal the not-to-be tested surfaces, only leaving the ground-polished surface exposed.

---

| Alloy | Condition | Cu | Li | Mn | Mg | Zn | Zr | Si | Al |
|------|-----------|----|----|----|----|----|----|----|----|
| 2024 | T4        | 4.82 | / | 0.52 | 1.54 | 0.11 | / | 0.25 | Balance |
| 6061 | T6        | 0.16 | / | 0.12 | 0.90 | 0.11 | / | 0.65 | Balance |
| 7050 | T7451     | 2.38 | / | 0.08 | 2.37 | 6.56 | 0.12 | 0.06 | Balance |
| 2A97 | Hot rolled | 3.82 | 1.53 | 0.30 | 0.48 | 0.51 | 0.16 | / | Balance |
2.3. Electrochemical measurements

The EIS tests and potentiodynamic polarization tests were performed to obtain the frequency characteristics, $E_c$ and $I_c$, and the corroded surface morphology of samples of these five materials. The potentiostatic polarization measurements were conducted on parallel samples to study their continuous variations of electrochemical behaviors with time.

All the mentioned above electrochemical measurements were carried out with an electrochemical workstation CS310 (Corrtest Instruments Co., Ltd.) based on the three-electrode system at 30 °C. During these measurements, the naturally aerated 3.5 wt% sodium chloride solution was the electrolyte solution; the exposed ground-polished surfaces of samples of these five materials, the saturated calomel electrode (SCE) and two symmetrically arranged pieces of platinum foils acted respectively as the working, reference and counter electrode. Prior to measurements, every sample was immersed in the electrolyte solution for 45 min to stabilize its open circuit potential (OCP).

An EIS test with no harm to surface was firstly performed to every sample. A 10 mV AC stimulus signal was applied on each sample at its OCP within the frequency range between 100000 and 0.01 Hz. A potentiodynamic polarization test that its potential ranged from $-50$ to 800 mV relative to the OCP of every sample with 1 mV s$^{-1}$ scan rate was followed. The sample surface was corroded during the potentiodynamic polarization test. The corroded surface morphology was observed using a laser confocal microscope (Keyence Co., Ltd.). A parallel sample was measured with a potentiostatic polarization test. Every sample underwent a stimulus with 0.05 V polarization potential ($E_a$) above its OCP for 8 h. For the repeatability of these measurements, a new sample corresponded to the fresh 300 ml electrolyte solution.

3. Results and discussion

3.1. Analysis of potentiodynamic polarization measurements

The representative potentiodynamic polarization curves for samples of pure Al, aluminum alloys 2024, 6061, 7050 and 2A97 are depicted in figure 1. There are both similarity and difference among the five curves. The similarity lies in that among the anodic branches of the five curves, there is no passivation region for the four alloys and only a transient passivation region that corresponds to a narrow potential window for pure Al. The feature of no or a transient passivation region means that the anodic protection method is unsuitable for protecting Al and aluminum alloys from corrosion in chloride-containing media [12]. The difference consists in the corrosion parameters that determined by the curves for the five materials. The corrosion parameters (i.e., $E_c$ and $I_c$) are gained on the basis of the Tafel extrapolation method, and they are presented in table 2.

The numbers presented in brackets in table 2 are the orders of the five materials. With the numbers increasing, the corrosion property of the corresponding material gets worse. The two orders based respectively on $E_c$ and $I_c$ both illustrate that among the five materials, the corrosion performance of alloy 7050 is the worst from the perspectives of the corrosion thermodynamics and kinetics. However, there are conflicts between the two orders. Taking alloy 6061 as an example, a huge contradiction exists in the two orders. The $E_c$ of alloy 6061 is only nobler than that of alloy 7050, which means that the corrosion property of alloy 6061 is the worst among the
four materials except alloy 7050; while the $I_c$ of alloy 6061 is just greater than that of alloy 2024, which indicates that the anticorrosion behavior of alloy 6061 ranks the second among the five materials.

### 3.2. Analysis of EIS tests

The representative Nyquist plots at higher frequency stages for the five materials are depicted in figure 2, in which their impedance spectra show a shape characteristic, namely, a depressed capacitive semicircle constituting an impedance spectrum. The shape characteristic is related with the heterogeneity of the tested surfaces of the five materials, for example the microstructure, composition and surface morphology. The obvious difference among the five spectra consists in their arcs radii, and this means the corrosion properties of the five materials are various. According to the observations in our previous studies $[12, 13]$, the greater the radius is, the better corrosion resistance the corresponding material possesses.

The information regarding the five points with the maximum $(-Z''$) values on the five impedance spectra for the five materials is listed in table 3 $[14, 15]$, such as the $Z'$, $|Z|$ and $f$ when $(-Z'')$ achieving its maximum. On the basis of two variables, namely $(-Z'')_{\text{max}}$ and the corresponding $|Z|$, two identical orders of the five materials that represents the anticorrosion behavior of alloy 6061 ranks the second among the five materials.

**Table 2.** $E_c$ and $I_c$ of the five materials that obtained with the Tafel extrapolation method.

| Material | $E_c/(V/SCE)$ | $I_c/(A \cdot cm^{-2})$ |
|----------|---------------|-------------------------|
| Al       | $-0.73081(2)$ | $1.16E-06(3)$           |
| 2A97     | $-0.67853(1)$ | $1.97E-06(4)$           |
| 6061     | $-0.77397(4)$ | $5.96E-07(2)$           |
| 7050     | $-0.79723(5)$ | $5.88E-06(5)$           |
| 2024     | $-0.73897(3)$ | $4.64E-07(1)$           |

Note: With increasing the numbers in brackets, the corrosion property of the corresponding material gets worse.

**Table 3.** The information of the five points with the maximum $(-Z'')$ values on the five impedance spectra for the five materials.

| Material | $(-Z'')_{\text{max}}/(\Omega \cdot cm^2)$ | $Z'/(\Omega \cdot cm^2)$ | $|Z|/(\Omega \cdot cm^2)$ | $f$/Hz |
|----------|------------------------------------------|--------------------------|--------------------------|--------|
| Al       | $8018.7(3)$                              | $10347$                  | $13091(3)$               | $0.423$|
| 2A97     | $8314.5(2)$                              | $13165$                  | $15570(2)$               | $0.423$|
| 6061     | $14840(1)$                               | $16173$                  | $21950(1)$               | $0.531$|
| 7050     | $762.95(5)$                              | $1196.2$                 | $1418.8(5)$              | $0.852$|
| 2024     | $1413.7(4)$                              | $1643.2$                 | $2167.6(4)$              | $0.852$|

Note: With increasing the numbers in brackets, the corrosion property of the corresponding material gets worse.
Figure 3. Surface corrosion morphology: corroded surface (a) and corroded morphology (b) of pure Al; corroded surface (c) and corroded morphology (d) of alloy 2A97; corroded surface (e) and corroded morphology (f) of alloy 6061; corroded surface (g) and corroded morphology (h) of alloy 7050; corroded surface (m) and corroded morphology (n) of alloy 2024.
As mentioned above, there are conflicts among the orders of the corrosion behaviors of the five materials when they are characterized by the existed indicators, including \( E_c, I_c \), the corroded surface morphology and the frequency characteristics. This highlights the significance of seeking a novel indicator.

As presented in figure 1, there is no passivation region for the four aluminum alloys and only a transient passivation region for pure Al. Therefore, the potentiostatic polarization measurement is creatively utilized to compare the corrosion properties of the five materials. The potentiostatic polarization measurement aims to compare the polarization current densities that flow through the five materials by treating them as resistors under the action of a stimulus potential within a time range. The value of the current density associates with the velocity of being oxidized for atoms within materials, which is the essence of materials corrosion. The greater the current density is, the faster the corrosion occurs, namely the less corrosion resistance the corresponding materials indicate.

| Material | Measurements | Average | Deviation |
|----------|--------------|---------|-----------|
| Al       | 85.651       | 88.436  | 81.226    | 86.185    | 3.672   |
| 2A97     | 82.175       | 59.299  | 77.475    | 72.488    | 9.914   |
| 6061     | 130.897      | 92.037  | 113.145   | 121.221   | 24.300  |
| 7050     | 71.583       | 76.464  | 70.907    | 73.745    | 2.917   |
| 2024     | 100.239      | 77.968  | 71.495    | 88.354    | 16.013  |

Table 4. The measurements in the depth direction on corroded surfaces of the five materials.

The corrosion performances of the five materials are respectively characterized and compared with \( E_c, I_c \), and the frequency characteristics, as presented in tables 2 and 3. Through comparing the orders of the five materials that determined by the three indicators, the following three observations are found. Firstly, the three orders that determined by the three indicators all indicate that the corrosion resistance of alloy 7050 is the worst among the five materials. The \( I_c \) value of alloy 7050 is the largest, while its \( E_c, (−Z')_{\text{max}} \) and \( |Z| \) are the least. Secondly, the three comparisons of the five materials using three indicators just compare the corrosion properties of materials when they are tested. These characterizations are incapable of reflecting the continuous variations of the corrosion resistance of a material with time. Last but not least, there are obvious conflicts among the three orders for the other four materials except alloy 7050. Taking alloys 2024 and 6061 as examples, among the four materials that excludes alloy 7050, the \( (−Z')_{\text{max}} \) and \( |Z| \) values of alloy 2024 are the least while its \( I_c \) value is also the smallest. As for alloy 6061, its \( (−Z')_{\text{max}} \) and \( |Z| \) values are the largest while its \( E_c \) value is the least.

3.3. Analysis of surfaces corrosion morphology

After potentiodynamic polarization measurements, the representative corroded surface morphology of samples of the five materials is observed, as depicted in figure 3. From figure 3, it is clear that the corrosion of pure Al and aluminum alloys is nonuniform. Corrosion pits are developed at some locations resulting from severe corrosion while at other sites, no pit appears and the surface just gets dark in colour. From the visual viewpoint, after undergoing the polarization measurements with the same condition, the corrosion degree of alloy 2A97 is the least among the five materials. On the contrary, the large area of corrosion pits on corroded surfaces of alloys 6061, 7050 and 2024 suggest that they suffered the serious corrosion. The comparisons of the corrosion extent of the five materials indicate that the corrosion property of alloy 2A97 is much better than those of alloys 6061, 7050 and 2024.

Besides the visual comparisons of corrosion degrees of the five materials, namely the bidimensional sizes, the depths of the corrosion pits are also compared. Based on the same principle of selecting horizontal planes, the heights between the lowest and the highest points of random areas on corroded surfaces are measured. The measurements are listed in table 4. The average heights that showed in table 4 illustrate that the corrosion resistances of alloys 2A97 and 7050 are better than those of alloys 2024 and 6061, and pure Al ranks the third. According to what mentioned above, the orders of materials that determined by the corroded surface characteristics, including the surfaces bidimensional sizes and depths, are not enough convincing owing to the following two points. Firstly, there are conflicts between the two orders. As an example, alloy 7050 is one of the three materials that underwent the most severe corrosion based on the bidimensional sizes of corrosion pits while the measurements in depth direction reveal it is one of the two materials that suffered the least corrosion. Secondly, the surfaces corrosion morphology in figure 3 and the deviations that followed the mean measurements in table 4 both highlight that corrosion developed locally on Al and aluminum alloys surfaces. This means that the reliability of comparative results depends heavily on the statistic analysis.

3.4. Analysis of potentiostatic polarization measurements

As mentioned above, there are conflicts among the orders of the corrosion behaviors of the five materials when they are characterized by the existed indicators, including \( E_c, I_c \), the corroded surface morphology and the frequency characteristics. This highlights the significance of seeking a novel indicator.

As presented in figure 1, there is no passivation region for the four aluminum alloys and only a transient passivation region for pure Al. Therefore, the potentiostatic polarization measurement is creatively utilized to compare the corrosion properties of the five materials. The potentiostatic polarization measurement aims to compare the polarization current densities that flow through the five materials by treating them as resistors under the action of a stimulus potential within a time range. The value of the current density associates with the velocity of being oxidized for atoms within materials, which is the essence of materials corrosion. The greater the current density is, the faster the corrosion occurs, namely the less corrosion resistance the corresponding materials indicate.
material possesses. After the measurements with the same condition, the electrochemical responses (i.e., instantaneous corrosion potential and polarization current density) curves are compared with each other, as depicted in figure 4.
In Figure 4, it is clear that with the polarization processes proceeding, the corrosion potential \( E_c \) and the polarization current density \( I_a \) values of the five materials keep changing. The instantaneous characteristic is closely related with the continuous change of the surfaces conditions of the five materials. More specifically, under the effect of 0.05 V \( E_a \), the aluminum oxide on surfaces unceasingly dissolves and generates, meanwhile the insoluble corrosion product continuously generates and finally deposits back on corrosion surfaces \[16\].

After comparing the \( E_c \) responses curves of the five materials, the following two observations are found. Firstly, a common feature exists among the five \( E_c \) curves, and it is that a minimal value appears after the polarization start for each material. It is related with the fact that the thickness and volume of the surface oxide film get respectively thin and decreasing because of corrosion. Secondly, the variation trends of the five \( E_c \) curves are different. The \( E_c \) values for pure Al and alloy 2024 roughly keep decreasing with their polarization processes proceeding while those for alloy 2A97 first reduce and then increase. As for alloys 6061 and 7050, their \( E_c \) values during the polarization processes are even greater than those when the polarization measurements just begin.

The five materials are divided into two categories according to the variation tendencies of their \( I_a \) responses curves. Pure Al, alloys 6061, 7050 and 2024 constitute a group. Among their \( I_a \) curves, the total spans for their \( I_a \) values decreasing are all larger than 4 h. Differing from them, on the \( I_a \) curve of alloy 2A97, there is no stage where its \( I_a \) values clearly decrease.

For the better comparison, the \( I_a \) responses curves of the five materials are all depicted in Figure 5. Figure 5(a) shows the variations of \( I_a \) values of the five materials within 8 h under 0.05 V \( E_a \) action. Besides the various increasing tendencies of \( I_a \) values of the five materials, there are huge differences among their increasing rates, especially at the early polarization stage, as presented in figure 5(b). Figure 5(b) depicts the variations of \( I_a \) values of the five materials within the first 500 s after the measurements start. The increasing rates of \( I_a \) values of alloys 6061 and 2024 are much larger than those of pure Al, alloys 2A97 and 7050.

**Figure 5.** The \( I_a \) response curves for the five materials: (a) during the entire polarization processes; (b) within the first 500 s.
It should be acknowledged that at the moment of the polarizations start, the $I_a$ value of alloy 7050 is the largest among the five values for the five materials. This corresponds to the phenomenon that the corrosion property of alloy 7050 is the worst among the five materials based on the existed indicators $E_v$, $I_a$, $(−Z''_{\text{max}})$ and $|Z|_i$, as presented in tables 2 and 3. The situation that its $I_a$ value is larger than those of the other four materials lasts for nearly 50 s, as shown in the bottom left corner of figure 5(b). With the proceeding of polarization processes, along with the instantaneous characteristic of $I_a$ values, the orders of corrosion properties of the five materials could change. When compared with the other four materials, the corrosion property of alloy 7050 gets better and better. The continuous change with time could be characterized by $I_a$ values rather than indicators $E_v$, $I_a$, the frequency characteristics and the corroded surface morphology. Considering the cumulative feature of the corrosion degree, the integral of $I_a$ over time could be another one novel indicator to compare corrosion behaviors of Al and aluminum alloys, which is our parallel investigation.

4. Conclusions

The EIS tests, potentiodynamic polarization and potentiostatic polarization measurements were carried out for Al and aluminum alloys 2A97, 6061, 7050 and 2024. Based on the observations in the study, the following conclusions were reached.

(1) There were conflicts among the orders of corrosion behaviors of the five materials that determined respectively by the indicators $E_v$, $I_a$, the corroded surface morphology and the frequency characteristics.

(2) The instantaneous characteristic of the corrosion potentials and polarization current densities of materials during their corrosion processes were found. The potentiostatic polarization measurement and resultant polarization current density are respectively the novel method and indicator to characterize the continuous variations of the corrosion resistance with time.

(3) Compared with the other four materials, the corrosion resistance of alloy 7050 was inferior at the early corrosion process, while it turned to be the best with the proceeding of corrosion process.

Acknowledgments

The authors would like to acknowledge the financial support from A Project of Shandong Province Higher Educational Youth Innovation Science and Technology Program (2019KJB021), the National Key Research and Development Program of China (2018YFB1701502) and the Scientific research Fund of SiChuan Provincial Education Department (17CZ0001).

ORCID iDs

Yonghong Deng https://orcid.org/0000-0003-3629-0196
Jintao Niu https://orcid.org/0000-0002-0377-9107

References

[1] Mccafferty E 1999 J. Electrochem. Soc. 146 2863
[2] Mccafferty E 2003 Corros. Sci. 45 301
[3] Duan S W, Wu D T, Liu W Y, Chen J, Wang T and Zou Y 2020 Vacuum 176 109299
[4] Ghosh R, Venugopal A, Narayanan P R, Sharma S C and Venkitakrishnan P V 2017 Trans. Nonferrous Met. Soc. China 27 241
[5] Luo C, Albu S P, Zhou X R, Sun Z H, Zhang X Y, Tang Z H and Thompson G E 2016 J. Alloys Compd. 658 61
[6] Donatus U, Berbel L O and Costa I 2018 Mater. Corros. 69 1375
[7] Zou Y C, Yan H, Hu Z and Ran Q W 2020 Mater. Res. Express 7 026526
[8] Tian W, Hu M N, Chen X H, Zhou H L, Sun Y, Lu Q Q and Wan M Y 2020 Mater. Res. Express 7 036532
[9] Wang H N, Liu C Z, Lu L, Li R S and Lin D 2017 Mater. Corros. 68 58
[10] Niu J T, Liu Z Q, Wang B, Hua Y and Wang G J 2019 Mater. Corros. 70 259
[11] Milagre M X, Donatus U, Machado C S C, Araújo J V S, da Silva R M P, de Viveiros B V G, Asturita A and Costa I 2019 Corros. Eng. Sci. Technol. 54 402
[12] Niu J T, Liu Z Q and Wang G J 2019 IEEE Access 7 134198
[13] Niu J T, Liu Z Q, Wang G J, Huang W M and Xu Y 2020 Mater. Corros. (https://doi.org/10.1002/maco.202011846)
[14] Qiang Y J, Fu S L, Zhang S T, Chen S J and Zou X F 2018 Corros. Sci. 140 111
[15] Qiang Y J, Zhang S T, Tan B C and Chen S J 2018 Corros. Sci. 133 6
[16] Goebel J, Ghidini T and Graham A J 2016 Mater. Sci. Eng. A 673 16