High effective organic corrosion inhibitors for 2024 aluminium alloy

S.V. Lamaka\textsuperscript{a,∗}, M.L. Zheludkevich\textsuperscript{a}, K.A. Yasakau\textsuperscript{a}, M.F. Montemor\textsuperscript{b}, M.G.S. Ferreira\textsuperscript{a,b}

\textsuperscript{a} University of Aveiro, CICECO, Department of Ceramics and Glass Engineering, 3810-193 Aveiro, Portugal
\textsuperscript{b} Instituto Superior Técnico, ICEMS, Department of Chemical Engineering, Av. Rovisco Pais, 1049-001 Lisboa, Portugal

Received 6 January 2007; received in revised form 10 April 2007; accepted 18 May 2007
Available online 31 May 2007

Abstract

The inhibiting effect of several organic compounds on the corrosion of 2024 aluminium alloy in neutral chloride solution was investigated in the present work. The candidates were selected based on the assumption that effective inhibitors should form highly insoluble complexes with components of AA2024. Along with organic complexing agents, the salts of rare-earth elements were included into screening electrochemical impedance spectroscopy (EIS) test for getting comparative data. Results of EIS analysis revealed three most effective organic inhibitors: salicylaldoxime, 8-hydroxyquinoline and quinaldic acid. Their anti-corrosion performance was additionally investigated via dc polarization, as well as localized techniques: scanning electron microscopy coupled with energy dispersive spectroscopy (SEM/EDS), X-ray photoelectron spectroscopy (XPS) and atomic force microscopy coupled with scanning Kelvin probe (SKPFM). Localized measurements at exactly the same microdimensional zones of the alloy before and after immersion into 0.05 M sodium chloride solution allowed tracing the evolution of the Volta potential, chemical composition, surface topography and formation of corrosion products on the surface and intermetallic inclusions during the corrosion tests. The results show that the quinaldic acid, salicylaldoxime and 8-hydroxyquinoline provide anti-corrosion protection for AA2024 forming a thin organic layer of insoluble complexes on the surface of the alloy. Inhibiting action is the consequence of suppression of dissolution of Mg, Al and Cu from the corrosion active intermetallic zones.

© 2007 Elsevier Ltd. All rights reserved.

Keywords: Inhibitor; Aluminium alloy; Salicylaldoxime; 8-Hydroxyquinoline; Quinaldic acid; Scanning Kelvin probe force microscopy

1. Introduction

The aluminium alloy 2024 is widely used in the aerospace industry because of the optimal weight to strength ratio. However this alloy is one of the most susceptible to localized corrosion due to segregation of the intermetallic particles in the grain boundaries. The significant role of intermetallic inclusions in the initiation and behavior of localized corrosion of aluminium alloy is well-known and reported in literature [1–5].

The corrosion mechanism of AA2024 in chloride-containing solution was investigated in detail and reported in several recent papers [1,2,6–9]. Localized pitting corrosion begins in the location of the most predominant intermetallic inclusions which cover almost 3% of the geometrical surface area of the alloy. These intermetallic zones, so called S-phase, present about 60% of all intermetallic inclusions, are composed of Al\textsubscript{2}MgCu and reveal cathodic potential relatively to the alloy matrix. The chemical and electrochemical dissolution of magnesium and aluminium from Al\textsubscript{2}MgCu particles occurs at the initial stages of the corrosion process leading to dealloying of intermetallic zones enriching them in copper. The intermetallic precipitates play the role of active anodes and cathodes at the same time causing deep dealloying. The “swiss-cheese” like porous copper remnants inside the pits and the copper thin film around the pits are formed on the following stages due to the chemical dissolution of copper with consequent electrochemical redeposition. The process of copper redeposition plays an important role in the further development of local corrosion attack due to increase of the effective surface area of the cathodic zones resulting in autocatalytic character of the pitting corrosion. Thus, the suppression of S-phase dealloying and copper redeposition can be an effective strategy of inhibition of localized corrosion on AA2024. The organic compounds which are able to form insoluble complex compounds with components of the S-phase are potential candidates to provide strong inhibiting action. The inhibitors for corrosion of AA2024 known up to date confirm these assumptions.
The salts of rare-earth elements are well-known as corrosion inhibitors of AA2024 [6,10–12]. The main role of Ce$^{3+}$ and La$^{3+}$ in the corrosion protection is formation of highly insoluble deposits on S-phase intermetallic inclusions that prevents local increase of pH, which is responsible for the acceleration of the intermetallics dealeoying [6].

The triazole and thiazole derivatives were firstly investigated as corrosion inhibitors for copper and its alloys [13–15]. Later applicability of these compounds as inhibitors for aluminium-based copper-containing alloys was also studied [16–18]. In our previous work it was shown that thiazole derivatives form deposits on the copper-reach particles decreasing their cathodic and anodic activity [18,19].

Inhibiting effect of 8-hydroxyquinoline on pure aluminium was studied in [20]. The strengthening of passive alumina layer for long immersion time was explained by formation of a complex aluminium chelate on the surface. Inhibitory action of 8-hydroxyquinoline on the copper corrosion process [21] showed formation of protective film composed by Cu(II)–8-hydroxyquinoline complexes on the copper surface. Inhibition of corrosion of pure aluminium by Ce$^{3+}$ and 8-hydroxyquinoline studied by pH and metal ion selective imaging fiber bundles is described in [10].

However investigation of inhibiting action of 8-hydroxyquinoline, salicylaldoxime and quinaldic acid on corrosion of aluminium alloys has not been reported yet.

Scanning Kelvin probe (SKP) is a useful tool for the investigation of the corrosion activity of different metals in microscale [22,23]. It was found that measured Volta potential and the corrosion potential of the probed metal surface under thin electrolyte layer are in a linear dependency what was confirmed by different authors [22,23]. However, in spite of the valuable information about electrochemical activity of metals that SKP can give, its resolution is too low to be applied for investigation of the localized corrosion of aluminium alloys. Development of AFM gave rise to a new technique called scanning Kelvin probe force microscopy that can be used in submicromaser. SKPFM technique has been used by many authors for aluminium alloys [24–27], magnesium alloys [23,28,29] and different metals [30]. Application of SKPFM to the corrosion of aluminium alloy 2024 by Schmutz and Frankel showed a linear relationship of measured Volta potential of different metals in air and a corrosion potential [25,26]. It shows practical usage of such technique for localized investigation of corrosion behavior of alloys. However, the application of SKPFM for studying inhibiting effect of organic compounds on corrosion behavior of AA2024 has not been reported yet.

Volta potential results obtained from the SKPFM measurements are not straightforward comparing to the SKP. Measured Volta potential has a contribution not only from the work function of pure elements but also from other factors. For instance, it was shown that the measuring Volta potential on the intermetallic inclusions or matrix of 2024 aluminium alloy is affected by the presence of surface oxide films or layers of the corrosion products [25,26,31]. On the other hand, Ar sputtering of S-phase particles lowers the Volta potential, while, AES analysis does not show any significant changes in the composition of surface film [27,31]. Such changes of Volta potential can be explained in terms of surface adsorption, charge accumulation, changes in oxide structure and chemical composition [31]. Moreover, contaminations on the surface of the tip [29], conditions of sample preparation [24,31] which change the chemistry of the surface, tip and cantilever geometry [32] and roughness of the surface [30] influence on the Volta potential measurements as well.

The present article reports results of screening comparative investigation of the inhibiting action of 15 new and already known corrosion inhibitors for the 2024 aluminium alloy in neutral chloride solution. The corrosion protection and the mechanism of corrosion suppression of three most effective organic inhibitors salicylaldoxime, 8-hydroxyquinoline and quinaldic acid have been investigated by means of macroscale electrochemical techniques (dc polarization and EIS) and localized microscopic methods (SEM with associated elemental analysis by EDS, XPS and SKPFM).

2. Experimental

2.1. Substrates preparation

The aluminium alloy 2024-T3 with elemental composition shown in Table 1 was used in this work. Two different methods of surface cleaning were applied for substrates preparation. For visual observation and EIS measurements bare metal substrates were cleaned in the alkaline cleaner TURCOTM 4215—50 g/l during 35 min at 65$^{\circ}$C then rinsed with distilled water followed by immersion in 20% solution of nitric acid during 15 min, rinsed again with distilled water and finally air-dried. Samples for dc polarization investigations were polished sequentially with 400, 800 and 1200 grade sand paper in water and rinsed with ethanol. The specimens used for SKPFM, XPS and SEM/EDS measurements were polished sequentially with 400, 800, 1200 and 2500 grade sand paper in water and then with nonaqueous polishing by CafroTM diamond paste down to 0.5 µm and finally cleaned in ethanol or acetone. The polishing procedure was employed for specimens investigated by SKPFM because the roughness of “as-produced” samples does not allow conducting atomic force microscopy measurements. The same polishing procedure was reproduced on samples for XPS analysis in order to keep ability to match the results of both methods. The necessity to retain the procedure of samples prepa-
Table 2
Composition of the solutions for testing the effectiveness of the inhibitors

<table>
<thead>
<tr>
<th>Solution Description</th>
<th>Concentration of the reagent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. NaCl 0.05 M</td>
<td></td>
</tr>
<tr>
<td>2. NaCl 0.05 M + La(NO₃)₃</td>
<td>0.5 g/l</td>
</tr>
<tr>
<td>3. NaCl 0.05 M + Ce(NO₃)₃</td>
<td>0.5 g/l</td>
</tr>
<tr>
<td>4. NaCl 0.05 M + Y(NO₃)₃</td>
<td>0.5 g/l</td>
</tr>
<tr>
<td>5. NaCl 0.05 M + 2-mercaptobenzothiazole</td>
<td>Saturated</td>
</tr>
<tr>
<td>6. NaCl 0.05 M + salicylaldoxime</td>
<td>0.5 g/l</td>
</tr>
<tr>
<td>7. NaCl 0.05 M + dithizone</td>
<td>Saturated</td>
</tr>
<tr>
<td>8. NaCl 0.05 M + 8-hydroxyquinoline</td>
<td>Saturated</td>
</tr>
<tr>
<td>9. NaCl 0.05 M + 5,7-dibromo-8-hydroxyquinoline</td>
<td>Saturated</td>
</tr>
<tr>
<td>10. NaCl 0.05 M + thiourea</td>
<td>0.5 g/l</td>
</tr>
<tr>
<td>11. NaCl 0.05 M + quinaldic acid</td>
<td>Saturated</td>
</tr>
<tr>
<td>12. NaCl 0.05 M + α-benzoïnoxime</td>
<td>Saturated</td>
</tr>
<tr>
<td>13. NaCl 0.05 M + 2-(2-hydroxyphenyl)benzoxazole</td>
<td>Saturated</td>
</tr>
<tr>
<td>14. NaCl 0.05 M + cupferron</td>
<td>0.5 g/l</td>
</tr>
<tr>
<td>15. NaCl 0.05 M + cuprizone</td>
<td>0.5 g/l</td>
</tr>
<tr>
<td>16. NaCl 0.05 M + dithiooxamide</td>
<td>Saturated</td>
</tr>
</tbody>
</table>

ration similar arises from depending of surface properties and consequently the corrosion activity of the alloy on preliminary treatment. The polishing of samples for SEM/EDS investigation was made since the procedure of chemical etching removes the majority of intermetallic inclusions from the surface [33]. The behavior of S-phases intermetallic particles during the immersion tests was one of the points of SEM/EDS investigations. It is necessary to point out that all experiments and conclusions made within one technique compare the behavior of samples with surface prepared in the same way.

2.2. Solutions

Inhibitors and other chemicals were received from Aldrich, Fluka or Alfa Aesar and contain at least 98% of ground substance. The concentration of inhibitors was rather low 0.05 g/l or even lower in the case where saturation of the aqueous solutions was achieved at smaller inhibitor content. All solutions were prepared using 0.05 M NaCl as a blank electrolyte. No pH buffers were used. The list of the tested inhibitors and concentration of the solutions are presented in Table 2.

2.3. Experimental techniques

The EIS technique was used as screening method to estimate the inhibiting action of the organic compounds and to select the most promising ones from the large set of different possible candidates. EIS measurements were carried out in a Faraday cage with a Gamry FAS2 Femtostat coupled with a PCI4 Controller at open circuit potential with applied 10 mV sinusoidal perturbations in the 100 kHz–10 mHz frequency range with 10 steps per decade. A three-electrode cell was used, consisting of a saturated calomel reference electrode, a platinum foil as counter electrode and the exposed AA2024 substrate as working electrode with a surface area of 3.4 cm².

Polarization curves were taken on the bare alloy after different times of exposition in pure 0.05 M NaCl solution or in the same solution doped with the most effective organic inhibitors. Polarization was made with a rate of 1 mV/s using a VoltaLab PGZ 100 potentiostat. The potential was scanned separately in the positive and negative direction starting from the open circuit potential.

To reveal the evolution of the microstructure of the surface and changes of the chemical composition, scanning electron microscopy (SEM/EDS) was employed. SEM images were taken with a Hitachi S-4100 system; beam energy is 25.0 kV.

The identification of the different elements present on the surface was performed by XPS analysis. The analysis of samples surface was made after 5 h of immersion into solutions of different inhibitors (8-hydroxyquinoline, salicylaldoxime or quinaldic acid) with the 0.05 M NaCl blank solution or in pure NaCl solution. Immersion lasted 5 h, as in the case of samples analyzed by SKPFM. After immersion, substrates were rinsed with distilled water for several times.

The X-ray photoelectron spectroscopy measurements were performed using a Microlab 310 F (from Thermo Electron—former VG Scientific). The spectra were taken in CAE mode (20 eV), using an Al (non-monochromate) anode. The accelerating voltage was 15 kV. The quantitative XPS analysis was performed using the Avantage software. The relative atomic concentration (Aᵣ) was calculated using the following relation:

\[ Aᵣ = \frac{\text{normalised peak area} \times 100}{\sum \text{normalised peak areas}} \]

where the subscript \( x \) refers to the quantified specie and the subscript \( i \) refers to the other species detected in the XPS spectra. The normalised peak area was obtained by dividing the intensity of the XPS peak of the species (after background subtraction) by the sensitivity factor of the corresponding specie.

The background subtraction was performed using the Shirley algorithm, which gives a curve S shaped and assumes that the intensity of the background is proportional to the peak area on the higher kinetic energy side of the spectrum. The quantification was performed after peak fit. The peak fit function used was a Gaussian–Lorentzian product function and the algorithm was based on the simplex optimisation as used in the Avantage software.

SKPFM was performed to study the evolution of the Volta potential of the alloy surface after immersion in the electrolyte. For SKPFM measurements the AFM was operating in the interleave mode with two pass scans. The first scan acquired topography of the surface, while during the second scan the tip was lifted up from the surface to a constant distance of 100 nm, the piezoelectric actuator was switched off and an ac voltage of 1000 mV amplitude was applied between the tip and sample to cause electrostatically induced oscillation of the cantilever. Using the nulling technique the Volta potential difference between the sample surface and the tip was measured over the whole surface to obtain the Volta potential map. After SKPFM measurements of the target surface, the Volta potential map was recorded on Ni surface that was previously immersed in DI water for 10 min. Values of the Volta potential were normalised to the nickel surface as a reference. Nickel is known to have stable values of the potential and could be used as a reference surface for
Kelvin probe microscopy [25,26]. For all SKPFM measurements silicon probes covered with Cr–Pt layers were used.

3. Results and discussion

A number of organic compounds were chosen as potential inhibitors for AA2024. As it has been shown in several previous articles [19], the corrosion of AA2024 starts with dissolution of magnesium and aluminium along with dealloying and redeposition of copper of S-phases on the surface of the alloy. Thus, the idea behind this choice was based on assumption that organic compounds which are able to block dissolution of Mg, Al and Cu apparently can provide inhibiting action on development of corrosion process.

This approach is confirmed by the mechanism of inhibiting action of lanthanide salts [6]. It implies formation of dense insoluble layer of lanthanide hydroxides in the local zones where pH increases due to corrosion reaction. However, that mechanism does not include direct interaction of inhibiting agent with corroding metal. Another approach may provide interaction of inhibitor with corroding metals and formation of deposits or adsorptive layers on the surface of alloy or atop the intermetallic inclusions. The main decisive factor on selection of organic compounds was their ability to form insoluble complexes with Mg, Al and Cu at different conditions (pH, concentration). Organic compounds picked up for testing of their inhibiting action are the analytical reagents for gravimetric determination of Mg, Al or Cu in aqueous solutions [34]. Lanthanide salts were also tested as a reference due to well-known inhibiting effect of their cations.

3.1. EIS measurements and visual observation

The screening test using NaCl electrolyte doped with different active agents was performed by means of EIS. Fig. 1a and b demonstrate the Bode plots of AA2024 specimens after 2 weeks of immersion in 0.05 M NaCl solution in the presence of the following inorganic and organic compounds: La(NO₃)₃, Ce(NO₃)₃, Y(NO₃)₃, 2-mercaptopentaothiazole, salicylaldoxime, dithizone, 8-hydroxyquinoline, 5,7-dibromo-8-hydroxyquinoline, thioacetamide, quinaldic acid, α-benzoino- noxime, 2-(2-hydroxyphenyl)benzoxazole, cupferron, cuprizone, dithiooxamide. The composition of the tested electrolytes is detailed in Table 2.

The low-frequency impedance of the corroded metallic electrode can be used as a measure of the corrosion activity. As shown in Fig. 1a and b the minimal value of the low-frequency impedance has AA2024 immersed in the inhibitor-free solution. Thus, all tested reagents reveal a certain inhibiting action conferring different protective efficiency. Salts of rare-earth elements such as Ce and La, well-known [6,10–12,16–19] as corrosion inhibitors for AA2024, as well as thiazole derivative demonstrated high value of the low-frequency impedance, which is related to the corrosion process. Inhibiting effectiveness of several organic compounds under study is comparable or even better: low-frequency impedance is one to two orders of magnitude higher for the specimens immersed in chloride-containing solution of 8-hydroxyquinoline, salicylaldoxime and quinaldic acid than for the alloy immersed in the undoped electrolyte. The screening impedance test was repeated twice. The values of low-frequency impedance for two tests converged within 20%.

The impedance spectrum of the alloy immersed into inhibitor-free NaCl solution (Fig. 1c) reveals two time-constants at 5 Hz and incoherent one at about 0.01 Hz. The higher frequency time-constant can be assigned to the capacitance of the double layer on the surface of the alloy. The low-frequency constant is related to
Fig. 2. The equivalent circuit models used for fitting experimental spectra for specimen immersed (a) in blank NaCl and (b) in inhibitor-containing NaCl solutions.

In the case of AA2024 immersed in the electrolytes doped with the best corrosion inhibitors the two time-constants displayed on spectra have different origin (Fig. 1c). Two high-frequency time-constants are related to the native aluminium oxide layer (at about 8 Hz, which is close to the same value in the case of sample treated with pure NaCl solution) and to the layer of adsorbed inhibitor (at about 300 Hz). The time-constant related with the presence of adsorbed layer is better pronounced in the case of 8-hydroxyquinoline. One wide time-constant revealed by sample immersed in quinaldic acid is composed of the same two components. Fig. 2b shows the equiv-

<table>
<thead>
<tr>
<th>Parameter</th>
<th>QuinAcid + NaCl</th>
<th>8-Hydroquin + NaCl</th>
<th>Salicyl + NaCl</th>
<th>NaCl blank</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_{\text{sol}} ) (( \Omega \text{ cm}^2 ))</td>
<td>24.07</td>
<td>53.05</td>
<td>36.2</td>
<td>43.28</td>
</tr>
<tr>
<td>( R_{\text{ox}} ) (k( \Omega \text{ cm}^2 ))</td>
<td>1446</td>
<td>35.03</td>
<td>554.2</td>
<td>5.318</td>
</tr>
<tr>
<td>( C_{\text{ox}} ) (( \text{mS s}^{-1} \text{cm}^{-2} ))</td>
<td>0.54</td>
<td>2.24</td>
<td>1.84</td>
<td>71.4</td>
</tr>
<tr>
<td>( N_{\text{ox}} )</td>
<td>0.9384</td>
<td>0.8402</td>
<td>0.9398</td>
<td>0.9046</td>
</tr>
<tr>
<td>( R_{\text{inh}} ) (k( \Omega \text{ cm}^2 ))</td>
<td>5.711</td>
<td>6.219</td>
<td>0.661</td>
<td>–</td>
</tr>
<tr>
<td>( C_{\text{inh}} ) (( \text{mS s}^{-1} \text{cm}^{-2} ))</td>
<td>4.305</td>
<td>1.086</td>
<td>3.696</td>
<td>–</td>
</tr>
<tr>
<td>( N_{\text{inh}} )</td>
<td>0.9458</td>
<td>0.9565</td>
<td>0.9101</td>
<td>–</td>
</tr>
<tr>
<td>( R_{\text{polar}} ) (k( \Omega \text{ cm}^2 ))</td>
<td>4035</td>
<td>4035</td>
<td>9740</td>
<td>14.6</td>
</tr>
<tr>
<td>( C_{\text{dl}} ) (( \text{mS s}^{-1} \text{cm}^{-2} ))</td>
<td>55.19</td>
<td>19.7</td>
<td>68.8</td>
<td>1575</td>
</tr>
<tr>
<td>( N_{\text{dl}} )</td>
<td>0.9571</td>
<td>0.9419</td>
<td>0.9484</td>
<td>0.9576</td>
</tr>
<tr>
<td>( W ) (m( \text{S s}^{1/2} \text{cm}^{-2} ))</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>91.6</td>
</tr>
<tr>
<td>( II ) (sec( ^{1/2} ))</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>8.87</td>
</tr>
<tr>
<td>Goodness of fit</td>
<td>8.84E−05</td>
<td>1.82E−03</td>
<td>1.29E−03</td>
<td>2.50e-03</td>
</tr>
</tbody>
</table>
alent circuit used for fitting the impedance spectra obtained for the AA2024 specimens immersed in the inhibitor-containing solution. The $R_{\text{inh}}$ is the resistance of inhibitor layer, $C_{\text{inh}}$ and $N_{\text{inh}}$ the parameters of CPE which characterize the capacitance of the inhibitor layer. The capacitance of inhibitor layers was calculated from the values of CPE using the following equation:

$$C = \text{CPE} \cdot C_{\text{inh}}(\omega_{\text{max}})^{CPE N_{\text{inh}}^{-1}},$$

where $\omega_{\text{max}}$ is the frequency at which the imaginary impedance reaches a maximum for the respective time-constant, $C_{\text{inh}}$ and $N_{\text{inh}}$ are the parameters for CPE that characterizes the capacitance of the inhibitor film [35].

Only the first indications of low-frequency time-constant attributable to the corrosion process appear. The models presented for two different specimens allowed fitting experimental data with high goodness. The obtained parameters of both equivalent circuits for specimens immersed in three most effective inhibitors under study and pure NaCl are shown in Table 3.

Fig. 3a presents the evolution of capacitance, which depends on the film’s thickness and dielectric constant, and resistance of the inhibitor layer during the immersion of AA2024 specimens into inhibitor-containing solutions of NaCl. Both evolution trends are not similar for three tested inhibitors. The capacitance and resistance of the salicylaldoxime and quinaldic acid films are not changing significantly after 50 h of immersion. That can be attributed to the relatively fast formation of stable inhibitor-containing layer on the surface of the alloy. The behavior of specimen immersed into 8-hydroxyquinoline-containing solution is different. Prolonged decrease of capacitance points at continuous increase of thickness of the inhibitor layer. Generally, quinaldic acid, salicylaldoxime and 8-hydroxyquinoline form dense and stable for a long time adsorptive films on the surface of the AA2024.

The condition of native aluminium oxide impacts significantly on the anti-corrosion resistance of the aluminium-based alloys. The evolution of oxide resistance indicates the intensity of corrosion process and presented in Fig. 3b. Constant low value of $R_{\text{ox}}$ is observed for sample immersed in pure NaCl solution. Addition of inhibitors into corroding solution leads to increase the resistance by one to two orders of magnitude. The values of $R_{\text{ox}}$ increases slightly for salicylaldoxime- and quinaldic acid-containing solutions or decrease in the case of 8-hydroxyquinoline-containing NaCl, but remains in the range of $10^5$ to $10^6 \ \Omega \ \text{cm}^2$ which is significantly higher than in the case of inhibitor-free solution.

Visual observation of the surface of the samples (Fig. 4) after 2 weeks of immersion demonstrates that the sample immersed in pure chloride solution has many pits on the surface and seems to be completely corroded. Addition of lanthanide salts or mercapto-benzothiazole decreases the number of pits and reduces the degree of corrosion attack being in agreement with previous works [6,19]. The samples immersed in the electrolyte doped with some new inhibitors seem even better showing low corrosion attack especially in the case of 8-hydroxyquinoline where the surface is visually absolutely intact after such a long immersion test. This result is in a good agreement with impedance data presented in Fig. 1a and c where the most defined response from the adsorbed organic layer was revealed in the case of 8-hydroxyquinoline.

The analysis of the results presented in Figs. 1a and 4 proves that the inhibiting action of 8-hydroxyquinoline, salicylaldoxime and quinaldic acid is comparable or even more effective than in the case of lanthanide salts and mercapto-benzothiazole. These substances revealed superior corrosion suppression and were selected to be tested by means of different techniques to confirm their inhibiting action and get understanding of the mechanism of anti-corrosive effect. The chemical formulas of these most perspective compounds are presented below.

![Chemical formulas](image-url)
3.2. Polarization measurements

Potentiodynamic polarization measurements were carried out in the potential range of −0.8 to 0.6 V versus open circuit potential to characterize the effect of different inhibitors on the anodic and cathodic partial electrode reactions. The dc polarization technique cannot be used in the case of AA2024 as a quantitative technique because of localized character of corrosion attack. The pitting formation potential lies in this case below the corrosion potential and no Tafel slope is observed in the anodic branch. Cathodic polarization also does not follow the Tafel law due to diffusion limitations of oxygen reduction reaction. However potentiodynamic polarization can be utilized for qualitative study of different inhibitors on the cathodic and anodic processes. The separate specimens were employed for the potentiodynamic polarization measurement in the anodic and cathodic direction. The 8-hydroxyquinoline, salicylaldoxime and quinaldic acid display weak acid–base properties. Experimentally determined pH of used solutions is 5.6 for inhibitor-free 0.05 M NaCl; 5.3 for quinaldic acid + 0.05 M NaCl; 5.5 for salicylaldoxime + 0.05 M NaCl and 6.4 for 8-hydroxyquinoline + 0.05 M NaCl. The small difference in pH values was a main reason why no pH buffers were used during measurements.

The polarization curves presented in Fig. 5 were recorded after 1 h (Fig. 5a) and 24 h (Fig. 5b) of immersion at the open circuit potential in blank 0.05 M NaCl or the same solution in the presence of inhibitors. Doping of chloride electrolyte with the inhibitors leads to decrease of the cathodic current. As it was shown earlier [19,36,37] the reduction of oxygen on copper rich intermetallics is likely the main cathodic process on AA2024 at lower cathodic potentials. The decrease of the cathodic current after 1 h of immersion is more pronounced in the more negative
potential range where hydrogen evolution occurs. Increase of immersion time makes the inhibiting action stronger, dropping the cathodic current by more than one order of magnitude. It demonstrates that the interaction of the inhibitors with aluminium alloy including the cathodic particles is, most probably, a slow process which takes several hours. This conclusion is in agreement with results of longer-term EIS measurements, which prove the increase of thickness of 8-hydroxyquinoline film and stability of salicylaldoxime and quinaldic acid layers on the surface of AA2024.

The anodic partial reactions are also influenced by 8-hydroxyquinoline, salicylaldoxime and quinaldic acid. After 1 h there is almost no difference in the anodic currents due to the addition of inhibitor. The difference is much more defined after longer immersion time. The anodic branch of the polarization curve on AA2024 has two breakdown potentials.

Fig. 6. (a) EDS profiles of AA2024 with relative concentration of Mg, Cu and Al before and after 4 days of immersion in 0.05 M NaCl solution. SEM images of analyzed zones before (b) and after (c) immersion. SEM images before (e) and after (f) 4 days of immersion in chloride solution doped with 0.5 g/l of 8-hydroxyquinoline and EDS profiles (d). White lines on SEM images indicate the stripes where EDS profiles were taken.
accompanied with sharp growth of the current. The first breakdown is due to the dissolution of S-phase intermetallics and the second one at more positive potentials is caused by intergranular attack [6,38]. Addition of quinaldic acid decreases the maximal current density at low anodic polarization. However the second breakdown potential is not shifted in this case. Salicylaldoxime and 8-hydroxyquinoline act differently. They decrease the anodic dissolution of the S-phase intermetallic inclusions leading to lower current densities in the potential range between the two breakdown potentials. The second breakdown potential is also shifted towards more positive values, demonstrating inhibition of the intergranular attack as well.

The longer immersion time before polarization leads to formation of denser protection layer on Cu- and Mg-containing S-phase intermetallics. In turn it suppresses the cathodic reduction of oxygen and anodic dissolution of Mg and Al on these intermetallic zones.

Fig. 7. The evolution of percentage content of Al, O and Mg in the matrix and intermetallic zones of AA2024. Measurements were made by SEM/EDS analysis at the same zones on four different samples immersed in solutions of quinaldic acid, salicylaldoxime and 8-hydroxyquinoline with 0.05 M background of NaCl or pure NaCl solution.
3.3. SEM/EDS study

Two types of local SEM/EDS investigations have been made for better understanding of the mechanism of corrosion inhibition. For the first type of studies, EDS profiles of zones with the most prone for corrosion attack S-phase intermetallics were taken before and after 4 days of immersion into 0.05 M NaCl solution. Fig. 6 presents the comparative content of Al, Mg and Cu along the surface of the aluminium samples. Fig. 6a displays changes in the chemical composition of the surface and the upper (about 1 μm broad) layer of specimen immersed in pure chloride-containing solution. Fig. 6d shows the same data for the sample immersed in 8-hydroxyquinoline-containing NaCl solution. Fig. 6b, c, e and f show the SEM images of the zones under investigation. SEM images and EDS profiles were taken at exactly the same zones of alloy. The dissolution of Mg and redeposition of Cu with accumulation of corrosion products such as aluminium hydroxide on the surface of the alloy are evident in the case of pure NaCl solution (Fig. 6a–c). None, or very little changes occurred with the aluminium alloy immersed in NaCl solutions which contain inhibitors. The presence of 8-hydroxyquinoline suppresses the dissolution of Mg and Cu as well as corrosion (Fig. 6d–f). The addition of quinaldic acid and salicylaldoxime in pure sodium chloride solution has an effect identical to that created in the presence of 8-hydroxyquinoline (the figures are not shown). Thus, the inhibiting action of quinaldic acid, salicylaldoxime and 8-hydroxyquinoline is the consequence of suppression of dissolution of Mg, Al and Cu from the intermetallic zones.

The second type of SEM/EDS examination consisted in analysis of identical local zones of the alloy samples after different times of immersion. The evolution with time of aluminium, oxygen and magnesium relative content is shown in Fig. 7a–f. The content of Al and O in matrix and intermetallic zones (Fig. 7a, b, d and e) changed in inverse proportion in pure 0.05 M NaCl solution. Marked reduction of Al and increase of O content is an evidence of accumulation of corrosion products on the surface of the alloy. The presence of inhibitors reduces this process essentially. The content of Mg in the alloy matrix and intermetallic zones is decreased drastically in pure NaCl solution, while the presence of inhibitors leads to considerable reduction of this process (Fig. 7c and f). SEM images of identical zones of the

![Fig. 8. SEM images of identical zones of the alloy surface before and after 14 days of immersion in pure 0.05 M NaCl and solution of quinaldic acid with the same chloride background. (a) Before immersion into quinaldic acid-containing solution; (b) after immersion into quinaldic acid-containing solution; (c) before immersion into NaCl solution; (d) after immersion into NaCl. White crosses indicate the places of point analysis on the intermetallic zones. White rectangulars specify the area of repetitive analysis of the matrix.](image-url)
alloy surface before and after immersion in pure 0.05 M NaCl and solution of quinaldic acid with the same background confirm these conclusions (Fig. 8a–d). The aggregation of corrosion products, which mostly consist of aluminium hydroxide, on the top of the intermetallic zones and matrix is evident for the sample immersed in NaCl solution for 14 days. The alloy surface is free of corrosion product in the case of the sample immersed in quinaldic acid doped NaCl solution. Probably, dark zones around the intermetallics, with lower relative content of Cu, can be assigned to the first weak signs of dissolution of S-phases although the main part of the inclusions and matrix are still intact. Salicylaldoxime and 8-hydroxyquinoline reveal identical corrosion suppression behavior (images are not shown).

3.4. XPS characterization

The analysis of chemical composition of the surface of the samples immersed in the blank NaCl solution or into the same solution with quinaldic acid, salicylaldoxime or 8-hydroxyquinoline was made by XPS analysis. Fig. 9a shows the Al 2p ionization obtained on immersed substrates. The main Al 2p peak, with binding energy of approximately 74.6 eV can be assigned to Al–O bonds due to the presence of Al₂O₃/Al(OH)₃ [39]. The minor Al 2p peak with binding energy of about 71.8 eV is related to the presence of metallic aluminium and it was detected only on the samples immersed in the inhibitor-containing solutions. It is commonly known that the surface of aluminium alloys is always covered with a thin passive aluminium oxide layer. The presence of a small amount of metallic aluminium can be explained by the existence of intermetallic particles which are usually [40] covered with a very thin defective layer of Al₂O₃ or not covered with oxide at all. The presence of metallic aluminium in the samples exposed to the NaCl plus inhibitor solutions, proves that the inhibitors delay electrochemical activation of the intermetallic particles. In the blank NaCl solutions the chemical and electrochemical decomposition of the intermetallics inclusions is faster, changing the chemical composition of the outer layers and promoting corrosion activity of the whole alloy.

The presence of organic inhibitors on the surface of the immersed specimens is proved by Fig. 9b, which depicts the N 1s ionization. This ionization is composed by a main peak, at binding energies of between 400 and 401 eV that can be assigned to the presence of C–N bonds present in the inhibitor molecules. In the case of the salicylaldoxime a small peak was also detected in the higher binding energy side of the N 1s spectrum and can be related with the N–OH bonds.

Fig. 9. (a) Al 2p, (b) N 1s, (c) Cu 2p, and (d) Mg 2p ionizations obtained on the AA2024 specimens immersed for 5 h into blank 0.05 M NaCl solution, or NaCl with different inhibitors.
Copper and magnesium were also detected on the surface of all AA2024 samples. The Cu 2p ionization for all the samples is depicted in Fig. 9c. The relative atomic contents of Cu in the samples are presented as well. The total amount of different forms of Cu is 1.5–2.4 times higher for the specimens immersed in blank NaCl solution.

The Cu 2p envelope for the sample exposed to blank NaCl presented a FWHM (full width at half maximum) of about 6 eV, revealing the contribution of different forms of copper. These can link both Cu(I) and Cu(II), although the shake-up satellites above 938.0 eV and characteristic of Cu(II) could not be detected [41]. Therefore, the composition of the Cu envelop can be related with Cu(I)–Cl complexes and Cu(I)–O species. The FWHM of the Cu 2p ionization decreased for the samples exposed to the NaCl plus inhibitors solutions and for the quinaldic acid and 8-hydroxyquinoline only one Cu peak was observed, which may correspond to the Cu present in the precipitates.

The Mg 2p ionization, showed a very low signal background ratio. However, two peaks can be observed: one at binding energies of approximately 48.0 eV, corresponding to metallic Mg and another at about 51 eV, traceable to the Mg–O bonds arising from inhibitor–Mg\(^2+\) complexes or Mg oxide/hydroxide [42] (Fig. 9d). The peak obtained in the blank NaCl solution is slightly different and seems to present only one contribution, at 49.8 eV probably due to magnesium corrosion products. Relative atomic percentage of Mg is depicted in the figure label. The sample immersed in the blank NaCl solution presents the lowest amount of Mg, which gives an evidence of more intense corrosion processes.

The trends observed in the Cu 2p and Mg 2p ionizations are in a good agreement with the corrosion mechanism proposed for the AA2024 [6] and prove that there is copper redeposition and magnesium dissolution from the intermetallic zones which happen when corrosion process is starting.

The XPS data also proved the presence of adsorbed N-containing layers and the absence of significant corrosion activity signs on the surface of the specimens exposed to the solutions-containing inhibitor, contrasting with features observed in blank NaCl where corrosion activity is more intense.

3.5. SKPFM investigations

Scanning Kelvin probe microscopy was successfully used for the investigation of the corrosion process occurring on aluminium alloy 2024 [25–27,31]. In present work Volta potential measurements were performed to obtain the information on the influence of inhibitors under study on the corrosion behavior of the alloy matrix and intermetallic inclusions. It allowed supplementing the knowledge on evolution of surface composition with versatile information and arrange more complete picture of the inhibition action of quinaldic acid, salicylaldoxime and 8-hydroxyquinoline. The distribution of the Volta potential was

Fig. 10. Topography (a and b) and Volta potential maps (c and d) obtained at the same places of 2024 aluminium alloy before (a and c) and after (b and d) 5 h of immersion in 0.05 M NaCl solution.
measured along the same surface of the alloy specimens before and after immersion in a corrosion media. The difference in Volta potential which is picked up by SKPFM technique can be a result of presence of different elements under tip which have different work function. For instance values of the work functions in vacuum of pure elements which compose the alloy are 4.19 eV for Al; 4.70 eV for Cu; 3.66 eV for Mg [43] and show the work to be done to remove electron from bulk material. However, in air conditions Volta potential will be related not only to the work function and will be affected by the adsorbed layer of water [26] and other compounds presented in air. The presence of oxides, corrosion products, contaminations influence on the Volta potential measurements. Nevertheless, correlation of the Volta potential values with the OCP measurements in water for pure metals makes SKPFM a powerful technique to reveal nobility of the surface [25,26].

Fig. 10 presents topography and Volta potential maps obtained for the same places of the aluminium alloy before and after 5 h of immersion in 0.05 M NaCl solution. Fig. 11 presents the same data for the sample immersed in 0.5 g/l solution of salicylaldoxime with 0.05 M background of NaCl. Fig. 12a and c displays the Volta potential and height profiles taken in the zones marked by the lines in Figs. 10 and 11. The presence of S-phases, which usually have the chemical composition roundly Al2CuMg, on the area analyzed by SKPFM was proven by SEM/EDS analysis. SEM images of zones investigated by means of SKPFM and EDS before and after immersion and analysis are presented in Fig. 13.

On the polished surface of the untreated specimens (Figs. 10a and 12a) perceptible protuberances correspond to intermetallic inclusions (which also shown in Fig. 13a and c) since the hardness of the phases which contain Mg and Cu, are different in comparison with the aluminium matrix. The Volta potential maps (Figs. 10c and 11c) display well-defined peaks in the same intermetallic zones. The increase of Volta potential precisely at the intermetallic zones is the result of higher content of Cu which has nobler Volta potential comparatively to Al and Mg.

After immersion of the aluminium sample in pure NaCl solution, well-defined dissolution of part of the S-phase occurred, forming holes at the edge as shown in topography map (Fig. 10b) and height profile (Fig. 12a). The peaks which appeared simultaneously on height profile evidently correspond to the corrosion products. Broadening of the noble zones in the Volta potential map argues for copper redeposition on those zones and is in agreement with previous works [6,12,44,45]. The increase of potential of the matrix can be explained by the total increase of Cu content on the surface of the alloy resulting from redeposition processes around dissolved S-phases. This is confirmed by data of XPS analysis, which shows the increase of copper content on the surface of alloy immersed in blank NaCl solution (Fig. 9c) compared to lower amount of Cu on the
surface of specimens immersed into inhibitor-containing solutions. The zones with nobler Volta potential coincide with the S-phases zones enriched with Cu according to the EDS profiles for both specimens, which were immersed in blank NaCl solution and salicylaldoxime-containing one (Fig. 12b and d). White lines on SEM images (Fig. 13b and d) correspond to the places where the EDS profiles depicted in Fig. 12b and d were taken.

All mentioned above changes did not happen with the aluminium specimen in the presence of salicylaldoxime. The absence of even minor changes at the height profile testifies the stability of the intermetallic particles in the solution doped with salicylaldoxime. Slight (about 50 mV) shift of the initial Volta potential map to the region of negative potentials can be the effect of adsorption of inhibitor on the surface. Chemisorption with formation of thin monomolecular layer of insoluble complexes on the surface is the most likely process and confirmed by XPS analysis. The 8-hydroxyquinoline and quinaldic acid revealed behavior identical to that for salicylaldoxime, therefore the data are not shown.

The fact that the data of SKPFM are mainly in a good agreement with versatile and comparative results of other methods proves that SKPFM can be applied for investigation of inhibiting action of organic compounds along with other localized methods.

3.6. Discussion and perspectives

The effectiveness of corrosion inhibition for AA2024 mainly determine by the mechanism of action of the explored chemicals on the activity of the S-phases.

One of the possible mechanisms is the formation of hardly insoluble chelate compounds on the whole surface and atop the intermetallic inclusions. It is proven by results of EIS measurements namely by presence of two time-constants on spectra of samples immersed into inhibitor-containing solutions. One is attributed to the native alumina layer, second one to the presence of adsorbed layer of inhibitor or products of its interaction with Al$^{3+}$, Mg$^{2+}$ or Cu$^{2+}$. Data of XPS analysis demonstrate presence of nitrogen on the surface of specimens immersed into inhibitor-containing solutions which can be explained only by presence of absorbed inhibitor or deposited complexes of inhibitor–Me on the surface of alloy.

Analytical data regarding the conditions of formation, composition and properties of complexes of the investigated inhibitors with cations of Mg, Cu and Al fragmentary found in literature [46–48] are presented in Table 4. The 8-hydroxyquinoline forms very low soluble precipitates with all the components of S-phases. Such low values of product solubility and wide pH range of stability of the complexes result on the formation of insoluble Al(C$_9$H$_6$ON)$_3$, Mg(C$_9$H$_6$ON)$_2$ and...
Cu(C₉H₆ON)₂ compounds at the very beginning of the corrosion process when only the first products of corrosion appeared at low concentration. Moreover, the layers of deposited chelates prevent penetration of chloride ions to the surface covered with native aluminium oxide, which remains intact. Although formation of chelate 8-hydroxyquinoline complexes on the surface of aluminium [20] and copper [21] was described, the inhibiting action of 8-hydroxyquinoline on dissolution of magnesium from intermetallic inclusion, which is clear proven in presented work have not been mentioned earlier. Salicylaldoxime and quinaldic acid have never been mentioned before in literature as inhibitors of copper, magnesium or aluminium corrosion process. Although no strict analytical data on numerical values of solubility or stability constants for complexes of Cu with quinaldic acid and salicylaldoxime or Al with salicylaldoxime were found out, there is information on gravimetric [49–52] and conductometric [53] determination of Cu and Al in the form of their quinaldic or salicylaldoxime complexes. Thus, Al and Cu are able to form the insoluble complexes with salicylaldoxime and quinaldic acid as well as 8-hydroxyquinoline. Formation of water insoluble complex layers on the entire metal surface and on the active sites of AA2024 alloy stops the extension of the corrosion and is most probably responsible for effective inhibition of the localized corrosion processes.

Semi-quantitative estimation of Mg, Cu and Al content in the intermetallic zones before and after immersion made by SEM/EDS methods demonstrates that intermetallic inclusions remain nearly intact at the presence of inhibitors into corroding solution while immersion into pure NaCl during only 5 h results into almost complete disappearance of Mg from the composition of S-phase. SEM/EDS analysis of alloy matrix confirm higher content of Cu, Mg and Al on the top layer of the 2024 alloy after immersion into inhibitor-containing solutions compare with sample immersed into pure NaCl solution. Data of XPS analysis emphasize the features of active corrosion process with Mg dissolution and Cu redeposition which occurred with the samples in the absence inhibitors. High resistance of native aluminium oxide layer after 2 weeks of immersion.

Table 4
The properties of insoluble complexes of Cu, Mg and Al with 8-hydroxyquinoline

<table>
<thead>
<tr>
<th>Me</th>
<th>pH</th>
<th>PSᵃ</th>
<th>Compound</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>4.2–9.8</td>
<td>1.03 × 10⁻²⁹</td>
<td>Al(C₉H₆ON)₃</td>
<td>[46]</td>
</tr>
<tr>
<td>Mg</td>
<td>9.4–12.7</td>
<td>6.8 × 10⁻¹⁶</td>
<td>Mg(C₉H₆ON)₂</td>
<td>[47]</td>
</tr>
<tr>
<td>Cu</td>
<td>5.3–14.6</td>
<td>4.2 × 10⁻²⁴</td>
<td>Cu(C₉H₆ON)₂</td>
<td>[48]</td>
</tr>
</tbody>
</table>

ᵃ PS = aₘₑ⁻ᵃₙₐₐ, a is the activity of ion when dissociation of low soluble Kₘₑ⁻ₐₐ ocurrs. Kₘₑ⁻ₐₐ = mKₑ⁻ + nAn.
into inhibitor-containing solution detected by EIS measurements confirm effectiveness of anti-corrosion protection.

The mechanism of inhibiting action of explored chemicals, especially the fact that they prevent dissolution of magnesium from intermetallic inclusions, let us assume that 8-hydroxyquinoline, salicylaldoxime and quinaldic acid can inhibit corrosion of magnesium-based alloys.

The number of investigations aimed at the exploration and development of effective substitution of chromates has considerably increased since the prohibition of the use of chromate-containing anti-corrosion coatings. Undoubtedly, the environmental amiability of newly discovered inhibitors is an issue. According to the MSDS (material safety data sheet) of ChemExper data base [54] carcinogenicity of 8-hydroxyquinoline, salicylaldoxime and quinaldic acid are not listed by ACGIH, IARC, NIOSH, NTP, OSHA in contrast with compounds of Cr(VI) which is a known carcinogen. However, exact toxicological tests should be provided before wide industrial use of investigated inhibitors.

The corrosion inhibitors in the case of the aeronautical applications, where AA2024 is mainly used, cannot be added to the corrosive environment like in some technological cases where the metallic constructions are employed. Another way is to introduce the organic inhibitor into the coating system. The methods of delivery of the inhibitors to the metal surface can strongly influence the effectiveness of the inhibiting action. The different ways of embedding inhibitors into coating systems have been reported in our previous papers [55–57]. It has been shown that impregnation of inhibitor into nano- and micro-porous titanium oxide deposited on aluminium alloy as well as using of inhibitor-loaded nanocontainers result in high effective corrosion protection. Such coating systems are able to provide controllable release of inhibitors under the influence of corrosion agents. Effectiveness of this approach has been verified by the use of benzotriazole. The self-healing effect of benzotriazole-loaded titanium oxide layer coated with sol–gel has been demonstrated [55,56]. Detailed description of the effect of active corrosion protection on aluminium alloy coated with a sol–gel pre-treatment-containing benzotriazole-loaded nanocontainers was also reported [57]. The main concept of prospective application of salicylaldoxime, quinaldic acid and 8-hydroxyquinoline is their embedding as active components into thin hybrid organic–inorganic sol–gel coatings.

4. Conclusions

Three organic inhibitors salicylaldoxime, 8-hydroxyquinoline and quinaldic acid are proposed for highly effective corrosion protection of AA2024.

The results of long-term tests—EIS, dc polarization, SEM observations and EDS investigations point on stable, prolonged inhibiting effect of tested organic compounds and stability of inhibitor solutions in contact with AA2024.

The presence of inhibitors into the corrosive medium leads to significant weakening of the corrosion processes as a result of formation of a thin adsorptive protective layer on the surface of the alloy. The inhibiting action is based on the passivation of active intermetallic zones due to prevention dissolution of Mg and Al as well as dissolution and redeposition of Cu. Moreover, insoluble chelate layer prevents adsorption of aggressive chloride ions on the surface of the alloy.

The presence of inhibitors layer on the surface of immersed specimens is proven by XPS and EIS analysis. Quantitative consideration of results of XPS and EIS analysis allows to conclude that 8-hydroxyquinoline forms thicker layer on the surface than salicylaldoxime and quinaldic acid.

Chemisorption and precipitation of complexes occur on the alloy surface including active S-phases and block the extension of the corrosion processes.

The 8-hydroxyquinoline, salicylaldoxime and quinaldic acid decrease the rate of the anodic reaction. The cathodic process occurring mainly on the intermetallic particles is slowed down as well.

Comparison of the data of EIS tests, namely low-frequency impedance allow to conclude that 8-hydroxyquinoline, salicylaldoxime and quinaldic acid suppress corrosion of AA2024 comparatively or even more effective than mercaptobenzothiazole, Ce and La salts.

For the first time SKPFM was applied for studying of inhibiting action of organic compounds. The data of SKPFM are mainly in a good agreement with results of SEM/EDS, XPS, dc polarization and EIS methods. Thus, SKPFM is applicable for studying the phenomena of inhibiting action of organic compounds along with other localized and electrochemical methods.

The fact that investigated inhibitors prevent dissolution of magnesium from intermetallic inclusions, allows to suppose that 8-hydroxyquinoline, salicylaldoxime and quinaldic acid can inhibit corrosion of magnesium-based alloys.

The 8-hydroxyquinoline, salicylaldoxime and quinaldic acid are promising candidates to be added to the coating systems as active anti-corrosive components for long-term corrosion protection of 2024 aluminium alloy.

Acknowledgements


References