

Aromatic Carboxylic Acids as Corrosion Inhibitors for Aluminium in Alkaline Solution

Ali Reza Madram,* Foroozan Shokri, Mohammad Reza Sovizi, Hamide Kalhor

*Department of Chemistry and Chemical Engineering, Malek Ashtar University of Technology,
Tehran 15875-1774, I.R. Iran*

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Abstract

The corrosion behavior of aluminium in 1 M NaOH solution, in the absence and presence of some aromatic carboxylic acids, was investigated using potentiodynamic polarization techniques, electrochemical impedance spectroscopy (EIS) and scanning electron microscope (SEM). The results among the investigated aromatic carboxylic acids, 4-bromomethyl, 3-bromo and 3-hydroxy benzoic acid were more efficient corrosion inhibitors for aluminium in alkaline medium. The values of different thermodynamic parameters such as adsorption equilibrium constant (K_{ads}) and free energy of adsorption (ΔG_{ads}) were calculated and discussed. The adsorption process of studied inhibitors on aluminium surface obeys the Langmuir adsorption isotherm.

Keywords: aluminium corrosion, aromatic carboxylic acids, inhibitor, electrochemical impedance spectroscopy, potentiodynamic polarization.

Introduction

Aluminium is an attractive fuel for electrochemical power sources. Its principal advantages as an anode material include high power, energy density, and great abundance. Corrosion of aluminium and its alloys has been the subject of numerous studies, due to their wide range of industrial applications, especially in aerospace, surface coating and alkaline batteries [1-3]. Aluminium and its alloys, however, are reactive materials and are prone to corrode. Aluminium relies on the formation of a compact, adherent passive oxide film for its corrosion immunity in various environments. This surface film is amphoteric and dissolves substantially when the metal is exposed to high concentrations of acids or bases [4]. Alkali destroys the protective aluminium film very quickly, because OH^- ions are adsorbed, thus increasing the dissolution rate of aluminium [5]. The corrosion inhibition of aluminium and its alloys is of tremendous technological importance, due to the increased applications of these materials. Many investigators have studied ways to obtain optimum corrosion protection for aluminium in various

* Corresponding author. E-mail address: ar.madram@gmail.com and armadram@mut.ac.ir

media, by either finding new inhibitors or improving the inhibition efficiency. The inhibitor efficiency has been attributed to the adsorption of the inhibitor molecules on the metal surface, forming a protective layer. The extent of adsorption of an inhibitor depends on many factors: (a) the nature of the metal, (b) the mode of adsorption of the inhibitor, and (c) the surface condition [6-8]. The inhibition effect mainly depends on some physicochemical and electronic properties of the organic inhibitor which relate to its functional groups, steric effects, electronic density of donor atoms, and orbital character of donating electrons [9-12]. Several inhibitors have been used to control the corrosion of aluminium. To prevent the corrosion of aluminium in acid medium, inhibitors such as antibacterial drugs [13], imidazoline derivatives [14], Schiff bases [15] and delonix regia extract [16] have been used. In alkaline medium, inhibitors such as polyvinyl alcohol [17], gongronema latifolium extract [18] and 3-hydroxyflavone [19] have been used to prevent corrosion of aluminium. Aromatic carboxylic acid, especially benzoic acids and their substituted compounds were investigated as effective inhibitors for aluminium in acidic and alkaline solutions [20]. Adsorptive characteristics of the benzoic acids have an influence on the corrosion inhibition capacities. The benzene ring attached to the carboxyl group contributes to the inhibitor efficiency, which is further influenced by the substituent in the benzene ring. Thus, the present study was undertaken to compare the inhibitive abilities of some aromatic carboxylic acids shown in Fig. 1 on the corrosion of aluminium in 1 M NaOH solutions by using potentiodynamic polarization and electrochemical impedance spectroscopy (EIS) methods. The surface analysis was carried out using scanning electron microscope (SEM). The adsorption behavior of the inhibitors was analyzed against Langmuir adsorption isotherm theory.

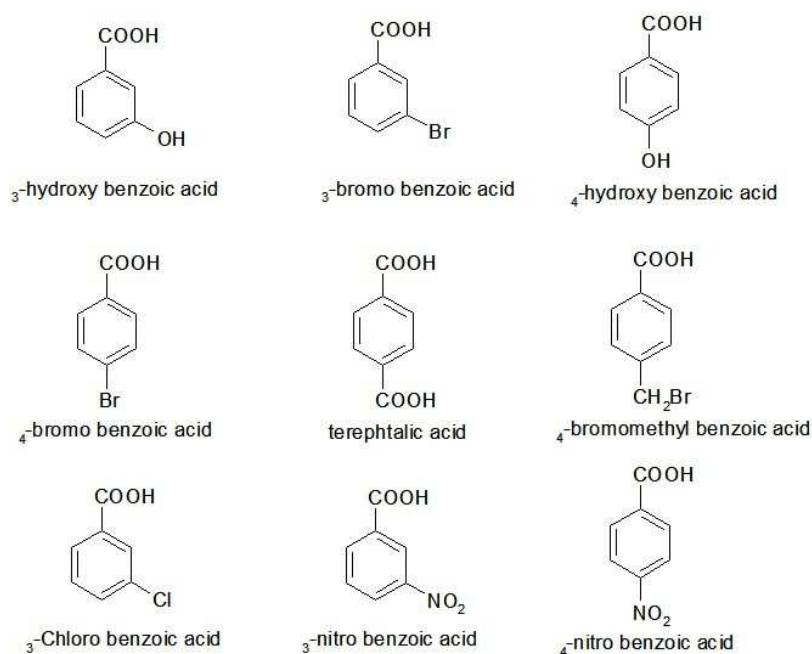


Figure 1. Chemical structure of the investigated aromatic acids.

Experimental

Materials and methods

The working electrode was made of aluminium (Al-1050); surface preparation consisted of abrasion with sandpaper (P 800-2000, Siawat®), followed by degreasing in an ultrasonic bath using ethanol and deionized water, and drying with a stream of air. The investigated aromatic carboxylic acids (Fig. 1) were of analytical grade and used as purchased without further purification.

Electrochemical experiments

The electrochemical experiments were carried out using a traditional three-electrode cell. The working electrode was an aluminium electrode (0.5 cm²). The counter electrode was a platinum foil and the reference electrode was an Hg/HgO electrode. Electrochemical measurements were performed by a Bio Logic (SP-150) instrument. Impedance measurements were performed under the corrosion potential with a sinusoidal potential perturbation of 5 mV in amplitude, and the frequency was from 100 kHz to 10 mHz. The measurements were taken until the electrode reached a steady state.

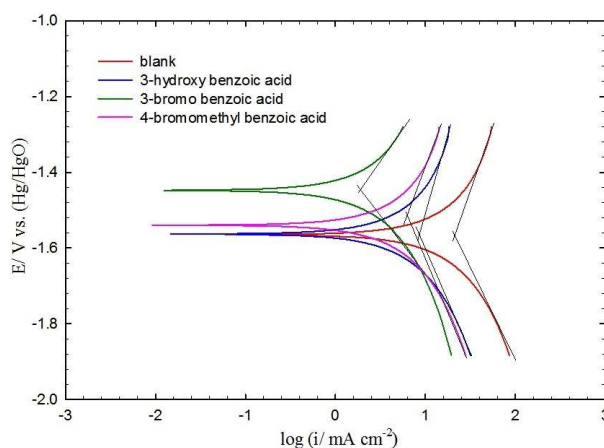


Figure 2. Polarization Tafel curves for aluminium in 1 M NaOH in the absence and presence of 3-bromo, 4-bromomethyl and 3-hydroxy benzoic acid (500 µg/mL) at a sweep rate of 0.5 mV s⁻¹ at 25 °C.

Results and discussion

Polarization measurements

Polarization measurements were performed in the absence (blank solution) and presence of various concentrations (100, 250 and 500 ppm) of the investigated aromatic carboxylic acids in 1 M NaOH at 25 °C. Fig. 2 shows typical Tafel polarization curves for aluminium in 1 M NaOH for blank solution, and in the presence of the more efficient investigated aromatic carboxylic acids (3-bromo, 4-bromomethyl and 3-hydroxy benzoic acid), at a concentration of 500 µg/mL and a sweep rate of 0.5 mV s⁻¹ at 25 °C. The data clearly show that the addition of the derivatives of benzoic acids shifts the corrosion potential (E_{corr}) in the positive direction (especially for the 3-bromo and 4-bromomethyl derivatives) and reduces both the anodic and cathodic current densities. The anodic current was, however,

reduced more significantly than the cathodic current for 3-bromo, 4-bromomethyl and 3-hydroxy derivatives of benzoic acid (Fig. 2).

These results indicate that these three aromatic carboxylic acids act as mixed-type inhibitors. This means that these inhibitors have significant effects on retarding the cathodic hydrogen evolution reaction and inhibiting the anodic dissolution of aluminium in alkaline solution. The Tafel extrapolation method was used to evaluate the corrosion parameters and the values of related electrochemical parameters, i.e. E_{corr} , corrosion current density (i_{corr}), and inhibition efficiency (IE%) were calculated from the related polarization curves, and are presented in Table 1.

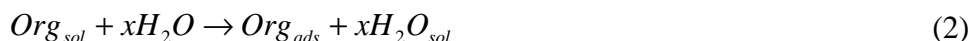
The percentage inhibition efficiency (IE%) was calculated as follows [21]:

$$\text{IE\%} = \frac{(i_{\text{corr}} - i'_{\text{corr}})}{i_{\text{corr}}} \times 100 \quad (1)$$

where i_{corr} and i'_{corr} are the corrosion current densities in the absence and presence of inhibitors, respectively. The values of cathodic (β_c) and anodic (β_a) Tafel constants were calculated from the linear region of the polarization curves.

As presented in Table 1, the corrosion current density was reduced in the presence of all investigated aromatic carboxylic acids, especially in the presence of 3-bromo, 4-bromomethyl and 3-hydroxy benzoic acid. The values of IE% for these inhibitors at a concentration of 500 ppm were 81, 72 and 70%, respectively. Furthermore, the increase of inhibition efficiencies for the aluminium corrosion in 1 M NaOH, with increasing concentrations of organic acids, can be explained on the bases of the inhibitor adsorption.

This behavior can be attributed to the increased surface coverage θ , due to the increase of the number of adsorbed molecules at the metal surface [13]. So, the investigation of the relation between corrosion inhibition and adsorption is of great importance. The adsorption of organic inhibitors at the metal/solution interface takes place through the replacement of water molecules by organic inhibitor molecules, according to the following process [13]:



where $\text{Org}_{(\text{sol})}$ and $\text{Org}_{(\text{ads})}$ are organic molecules in the solution and adsorbed on the metal surface, respectively, and x is the number of water molecules replaced by the organic molecules. Different adsorption isotherms were analyzed in order to obtain more information about the interactions between aromatic carboxylic acids and the aluminium surface. The linear relationship between θ values and concentration of inhibitor, C_{inh} , is to be found in order to obtain the isotherm. The degree of θ is calculated from the polarization data using the following equation [13]:

$$\theta = \frac{i_{\text{corr}} - i'_{\text{corr}}}{i_{\text{corr}}} \quad (3)$$

Table 1. Tafel polarization and EIS parameters for aluminium corrosion in the absence and presence of the investigated inhibitors in 1 M NaOH at 25 °C.

Inhibitor	Concentration (ppm)	Tafel polarization					EIS		
		-E _{corr} (mV)	i _{corr} (μAcm ⁻²)	β _a (Vdec ⁻¹)	β _c (Vdec ⁻¹)	IE%	R _{ct} (Ωcm ²)	C _{dl} ×10 ³ (mFcm ⁻²)	IE%
blank solution	-	1560	33880	341	291	-	1.5	55	-
3-hydroxy benzoic acid	100	1566	10529	361	288	68	6.1	35	58
	250	1557	10449	344	293	69	6.5	32	61
	500	1536	10268	348	290	70	7.0	28	69
4-hydroxy benzoic acid	100	1467	26765	348.9	291	21	2.7	40	14
	250	1461	25980	351.3	291.1	23	3	37	22
	500	1445	24609	328.9	292.2	27	3.3	33	29
3-bromo benzoic acid	100	1404	7090	342.1	182.3	79	9.8	39	76
	250	1403	6881	326.4	289.4	80	10.4	36	81
	500	1387	6584	346.8	302.8	81	10.9	32	81
4-bromo benzoic acid	100	1499	23180	332.8	302.3	32	3.3	36	31
	250	1499	21890	332.8	302.3	35	3.4	35	31
	500	1483	21480	343.8	292.3	37	3.6	34	35
terephthalic acid	100	1569	23904	332.1	295.7	29	3.0	48	22
	250	1569	21853	334.4	295.1	35	3.4	36	31
	500	1551	20986	338.3	293.9	38	4.0	34	42
4-bromomethyl benzoic acid	100	1451	9810	335.2	293.2	71	6.5	41	61
	250	1423	9698	352.1	295.1	71	7.2	37	70
	500	1424	9416	351.7	291.5	72	7.2	35	70
3-nitro benzoic acid	100	1464	17929	342.4	293.5	47	3.1	49	26
	250	1471	17408	379.8	288.9	49	3.4	42	31
	500	1460	16900	346.8	292.0	50	4.0	40	41
4-nitro benzoic acid	100	1474	26212	345.7	292.0	23	3.0	48	22
	250	1456	22959	345.4	292.8	32	3.2	40	27
	500	1452	22087	337.7	294.3	35	3.5	38	33
3-chloro benzoic acid	100	1499	17130	335.6	295.4	49	3.0	45	22
	250	1487	17041	356.7	289.3	50	3.2	40	28
	500	1497	15970	353.1	291.4	53	3.4	37	31

Attempts were made to fit the θ values to various isotherms, including Langmuir, Temkin, Frumkin and Flory-Huggins. The best fit is obtained with the Langmuir isotherm. The Langmuir adsorption isotherm is given by [22]:

$$\frac{C_{\text{inh}}}{\theta} = C_{\text{inh}} + \frac{1}{K_{\text{ads}}} \quad (4)$$

where K_{ads} is the adsorption equilibrium constant. A plot of C_{inh}/θ against C_{inh} for the more efficient investigated inhibitors showed a straight line, indicating that adsorption follows the Langmuir adsorption isotherm, as shown in Fig. 3.

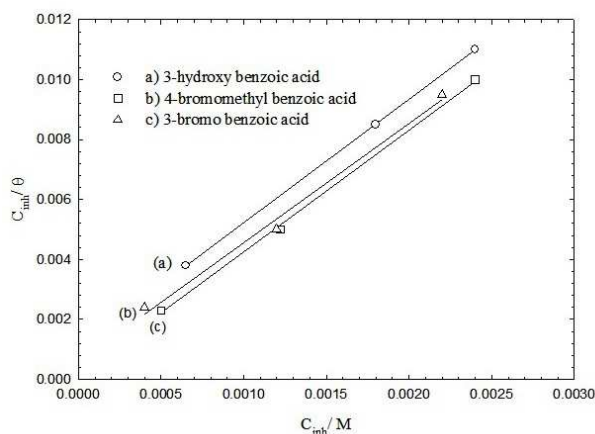


Figure 3. Langmuir adsorption isotherm plot for corrosion of aluminium in 1 M NaOH containing 3-bromo, 4-bromomethyl and 3-hydroxy benzoic acid at 25 °C.

The values of K_{ads} obtained from the Langmuir adsorption isotherm are related to the standard free energy of adsorption (ΔG_{ads}) [23]:

$$\Delta G_{\text{ads}} = -2.303RT \log(55.5K_{\text{ads}}) \quad (5)$$

where R is the universal gas constant, T is the absolute temperature, and the value of 55.5 is the molar concentration of water in the solution. The values of K_{ads} for the more efficient investigated inhibitors, i.e., 3-bromo, 4-bromomethyl and 3-hydroxy benzoic acid, were 1250, 1111 and 1000 $\text{L}\cdot\text{mol}^{-1}$, respectively. The higher value of K_{ads} for 3-bromo benzoic acid indicates stronger adsorption on the aluminium surface. Furthermore, $-\Delta G_{\text{ads}}^{\circ}$ values for 3-bromo, 4-bromomethyl and 3-hydroxy benzoic acid were 27.6, 27.3 and 27.1 $\text{kJ}\cdot\text{mol}^{-1}$, respectively (Table 2). That indicates 3-bromo benzoic acid was more effectively adsorbed on aluminium surface than other investigated carboxylic acids. The negative values for $\Delta G_{\text{ads}}^{\circ}$ are consistent with the condition for spontaneity of the adsorption process and the stability of the adsorbed layer on the aluminium surface.

Table 2. Values of adsorption constant (K_{ads}) and free energy of adsorption ($-\Delta G_{\text{ads}}$) for adsorption of 3-bromo, 4-bromomethyl and 3-hydroxy benzoic acid.

Inhibitor	K_{ads} ($\text{L}\cdot\text{mol}^{-1}$)	$-\Delta G_{\text{ads}}$ ($\text{kJ}\cdot\text{mol}^{-1}$)
3-bromo benzoic acid	1250	27.6
4-bromomethyl benzoic acid	1111	27.3
3-hydroxy benzoic acid	1000	27.1

EIS measurements

The EIS were recorded for aluminium in the absence and presence of investigated aromatic carboxylic acids. The complex plane plots of the EIS measurements, obtained at open-circuit potential after one hour immersion in the absence and presence of 3-bromo, 4-bromomethyl and 3-hydroxy benzoic acid as the best investigated inhibitors, are presented in Fig. 4(a).

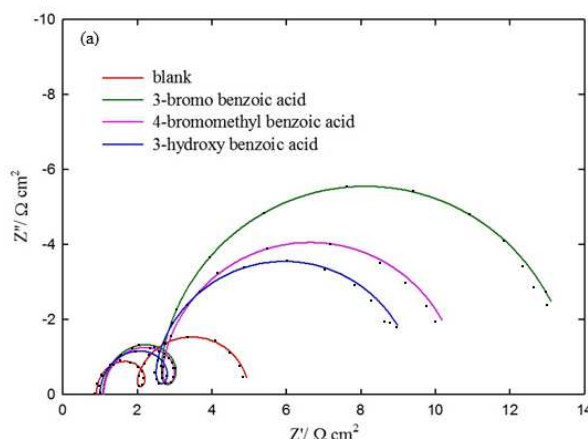


Figure 4 (a). Complex plane plots of the EIS measurements obtained for aluminium in absence and presence of 3-bromo, 4-bromomethyl and 3-hydroxy benzoic acid in 1 M NaOH at 25 °C.

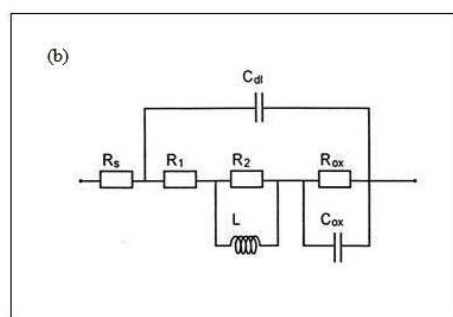


Figure 4 (b). Equivalent circuit used for approximation of the EIS data. Symbols indicate experimental results, and solid lines approximated data obtained using CNLS method.

Furthermore, an equivalent circuit to describe the electrochemical impedance characteristics of aluminium is shown in Fig. 4(b).

It is composed of a Faradaic impedance parallel to a double layer capacitance: C_{dl} . Faradaic impedance consists of R_{ct} ($=R_1+R_2$), indicating the charge transfer resistance at the metal/oxide film interface; L results from the interruption of anodic dissolution of aluminium by the surface charge build-up; R_{ox} is the resistance against charge transport in the oxide film and C_{ox} , due to the dielectric properties of surface oxide film. The R_s component in the circuit is a solution resistance with the value at a high frequency intercept on the real impedance axis [24]. This model circuit shows that the capacitive semicircles occurring at the high and low frequencies in Fig. 4(a) are due to the charge transfer reaction at the metal/surface oxide film, and the dielectric properties of surface oxide film, respectively. It has been reported that aluminium dissolves into the solution in the 3^+ oxidation state through the generation of Al^+ or Al^{+2} intermediate species [24]. Therefore, the charge transfer resistance, R_{ct} , might be represented by the sum of R_1 and R_2 in the equivalent circuit. The inductive loop shown in the medium frequency range might have been caused by the intermediate species generated during metal dissolution. The EIS data obtained in the NaOH solution are shown in Table 1. Inspection of Table 1 reveals that R_{ct} values increase prominently,

while C_{dl} reduces with the concentration of all investigate inhibitors. R_{ct} is associated with the corrosion resistance, so, the higher charge transfer resistance indicates better inhibition performance. The decrease in C_{dl} , compared with that in the blank solution, which can result from a decrease in local dielectric constant and/or an increase in the thickness of the electrical double layer, suggests that the inhibitor molecules function by adsorption at the solid/solution interface [25]. However, the values of the charge transfer and inhibition efficiency were increased in the presence of all inhibitors, especially in the presence of 3-bromo, 4-bromomethyl and 3-hydroxy derivatives of benzoic acid. These results are in good agreement with those obtained from polarization measurements (Fig. 2). The effect of temperature on the rate of dissolution of aluminium in 1 M NaOH containing 100 $\mu\text{g/mL}$ of the 3-bromo benzoic acid, as the most efficient investigated inhibitor, was evaluated by the Tafel polarization and EIS methods over a temperature range from 25 to 80 $^{\circ}\text{C}$ (Table 3).

Table 3. Corrosion parameters and free energy of adsorption for aluminum in 1 M NaOH containing 3-bromo benzoic acid (100 $\mu\text{g/mL}$) at different temperatures.

Temperature ($^{\circ}\text{C}$)	i_{corr} (μAcm^{-2})	$-E_{corr}$ (mV)	R_{ct} ($\Omega \text{ cm}^2$)	$C_{dl} \times 10^3$ (mF cm^{-2})	IE%	$-\Delta G^{\circ}_{ads}$ (kJ mol^{-1})
25	7090 \pm 28	1404 \pm 11	9.8 \pm 0.9	39 \pm 2.0	76	22.9
40	8064 \pm 41	1439 \pm 25	8.4 \pm 1.1	41 \pm 1.0	61	23.9
60	9524 \pm 26	1493 \pm 25	6.9 \pm 0.4	45 \pm 0.6	52	25.7
80	12436 \pm 32	1539 \pm 30	4.2 \pm 1.2	45 \pm 0.9	39	27.8

The results revealed that a higher temperature increased the corrosion rate of Al-1050 for this inhibitor. Additionally, the increase in corrosion rate in the absence of 3-bromo benzoic acid was higher than in its presence at all temperatures, suggesting more aggressiveness of a free alkaline solution. It was proved that benzoic acid is a good corrosion inhibitor, probably because the dimeric structure is formed, and this structure is somehow preferable for adsorption [26]. The results of Table 3 revealed that the ΔG°_{ads} values increased from -22.9 to -27.8 kJ mol^{-1} with increasing temperature from 25 to 80 $^{\circ}\text{C}$; this means adsorption phenomena are affected by dimerization of 3-bromo benzoic acid on aluminium surface.

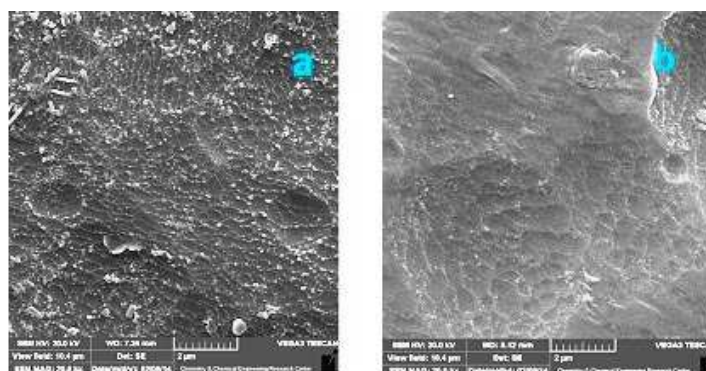


Figure 5. SEM images of aluminium surface in 1 M NaOH solution in the absence (a) and presence (b) of 3-bromo benzoic acid (100 $\mu\text{g/mL}$) at 25 $^{\circ}\text{C}$ after 1 h exposure.

SEM studies

The SEM images of aluminium in 1 M NaOH solution in the absence (a) and presence (b) of 3-bromo benzoic acid (100 µg/mL) at 25 °C after 1 h exposure are given in Fig. 5.

The surface is porous and the large and deep holes appear. However, the appearance of Al surface is different after the addition of 3-bromo benzoic acid as the most investigated inhibitor for the corrosive solution. It can be seen from Fig. 5 that the dissolution rate of aluminium is considerably reduced, and the smooth surfaces appear by the formation of a protective film on the Al surface.

Conclusions

Some aromatic carboxylic acids were studied for the inhibition of aluminium corrosion in alkaline solution. The polarization and EIS measurements showed that 3-bromo, 4-bromomethyl and 3-hydroxy benzoic acid were the more effective inhibitors among all investigated aromatic carboxylic acids on corrosion of aluminium in 1 M NaOH at 25 °C. The IE% values calculated from polarization Tafel curves for these inhibitors at concentration of 100 ppm were: 79, 71 and 68, respectively. These results are in good agreement with those obtained from EIS measurements. Furthermore, the IE % was found to increase with an increase in inhibitors' concentration. The adsorption of these inhibitors on the aluminium surface obeyed the Langmuir adsorption isotherm model. The negative values of ΔG°_{ads} indicate spontaneous adsorption of the inhibitors on the surface of aluminium. The effect of temperature on the rate of dissolution of aluminium in 1 M NaOH containing 100 µg/mL of the 3-bromo benzoic, as the most efficient investigated inhibitor, revealed that higher temperatures increased the corrosion rate of Al-1050 for this inhibitor. Surface morphological studies by SEM analysis were in good agreement with electrochemical measurements.

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References

1. Hori Y, Takao J, Shomon H. Improvements of anode properties of aluminium alloys for aluminium primary cell: heat treatment and corrosion inhibitors, *Electrochim Acta*. 1986;36:555.
2. Wilhelmsen W, Arnesen T, Hasvold O, et al. The electrochemical behavior of Al-In alloys in alkaline electrolytes. *Electrochim Acta*. 1991;36:79-85.
3. Zeinelabedin S, Saleh AO. Characterization of some aluminium alloys for application as anodes in alkaline batteries. *J Appl Electrochem*. 2004;34:331.
4. Ashassi-Sorkhabi H, Shabani B, Aligholipour B, et al. *Appl Surf Sci*. 2006;252:4039.

5. Noor AE. Potential of aqueous extract of Hibiscus Sabdariffa leaves for inhibiting the corrosion of aluminium in alkaline solutions. *J Appl Electrochem.* 2009;39:1465.
6. Zhang DQ, Gao LX, Zhou GD. Inhibition of copper corrosion in aerated hydrochloric acid solution by heterocyclic compounds containing a mercapto group. *Corros Sci.* 2004;46:3031.
7. Elmorsi MA, Hassanein AM. Corrosion inhibition of copper by heterocyclic compounds. *Corros Sci.* 1999;41:2337.
8. Curkovic HO, Stupnisek-Lisac E, Takenouti H. The influence of pH value on the efficiency of imidazole based corrosion inhibitors of copper. *Corros Sci.* 2010;52:398.
9. Lamaka SV, Zheludkevich ML, Yasakau KA, et al. High effective organic corrosion inhibitors for 2024 aluminium alloy. *Electrochim Acta.* 2007;52:7231.
10. Branzoi V, Golgovici F, Branzoi F. Aluminium corrosion in hydrochloric acid solutions and the effect of some organic inhibitors. *Mater Chem Phys.* 2003;78:122.
11. Fleischmann M, Hill IR, Mengoli G, et al. A comparative study of the efficiency of some organic inhibitors for the corrosion of copper in aqueous chloride media using electrochemical and surface enhanced Raman scattering techniques. *Electrochim Acta.* 1985;30:879.
12. Sanja M, Metikoš-Huković M. A nonlinear kinetic model introduced for the corrosion inhibitive properties of some organic inhibitors. *J Appl Electrochem.* 2003;33:1137.
13. Abdallah M. Antibacterial drugs as corrosion inhibitors for corrosion of aluminium in hydrochloric solution. *Corros Sci.* 2004;46:1981.
14. Quraishi MA, Rafique MZA, Khan S, et al. Corrosion inhibition of aluminium in acid solutions by some imidazoline derivatives. *J Appl Electrochem.* 2007;37:1153.
15. Safak S, Duran B, Yurt A, et al. Schiff bases as corrosion inhibitor for aluminium in HCl solution. *Corros Sci.* 2012;54:251.
16. Abiola OK, Oforka NC, Ebenso EE. et al. Inhibitive action of Delonix regia extract for the corrosion of aluminium in acidic medium. *Anti-Corrosion Methods Mater.* 2005;54:219.
17. Umoren SA, Ebens EE, Okafo PC, et al. Effect of halides ions on the corrosion inhibition of aluminium in alkaline medium using polyvinyl alcohol. *J Appl Polym Sci.* 2006;103:2810.
18. Oguzie EE, Onuoha GN, Ejike EN. Effect of Gongronema latifolium extract on aluminium corrosion in acidic and alkaline media. *Pigment Resin Technol.* 2007;36:44.
19. Princey JM, Nagarajan P. Corrosion inhibition of aluminium using 3-Hydroxy flavone in the presence of quarternary ammonium salts in NaOH medium. *J Korean Chem Soc.* 2012;56:201.
20. Moussa MN, El-Tagoury MM, Radi AA, et al. Carboxylic acids as corrosion inhibitors for aluminium in acidic and alkaline solutions. *Anti-Corros Methods Mater.* 1990;37:4.

21. Tao Z, Zhang S, Li W, et al. Adsorption and inhibitory mechanism of 1H-1,2,4-triazol-1-yl-methyl-2-(4-chlorophenoxy) acetate on corrosion of mild steel in acidic solution. *Ind Eng Chem Res.* 2011;50:6082.
22. Obot IB, Obi-Egbedi NO, Umoren SA. Antifungal drugs as corrosion inhibitors for aluminium in 0.1 M HCl. *Corros Sci.* 2009;51:1868.
23. Yurt A, Aykın O. Diphenolic Schiff bases as corrosion inhibitors for aluminium in 0.1 M HCl: Potentiodynamic polarisation and EQCM investigations. *Corros Sci.* 2011;53:3725.
24. Lee KK, Kim KB. Electrochemical impedance characteristics of pure Al and Al-Sn alloys in NaOH solution, *Corros Sci.* 2001;43:561.
25. Lagrenée M, Mernari B, Bouanis M, et al. Study of the mechanism and inhibiting efficiency of 3, 5-bis(4-methylthiophenyl)-4H-1, 2, 4-triazole on mild steel corrosion in acidic media. *Corros Sci.* 2002;44:573.
26. Bilgiç S. The inhibition effects of benzoic acid and salicylic acid on the corrosion of steel in sulfuric acid medium. *Mater Chem Phys.* 2002;76:52.