Arabian Journal of Chemistry (2015) **8**, 527–537

King Saud University

Arabian Journal of Chemistry

www.ksu.edu.sa
www.sciencedirect.com

ORIGINAL ARTICLE

Corrosion inhibition of aluminum with a series of aniline monomeric surfactants and their analog polymers in 0.5 M HCl solution

Part II: 3-(12-sodiumsulfonate dodecyloxy) aniline and its analog polymer

M.M. El-Deeb [a,c,*], **S.M. Sayyah** [a], **S.S. Abd El-Rehim** [b], **S.M. Mohamed** [a]

[a] *Chemistry Department, Faculty of Science, Beni Suef University, 62514 Beni Suef, Egypt*
[b] *Chemistry Department, Faculty of Science, Ain Shams University, Cairo, Egypt*
[c] *Chemistry Department, Faculty of Science, Ha'il University, Ha'il, Saudi Arabia*

Received 18 February 2013; accepted 7 September 2013
Available online 19 September 2013

KEYWORDS

Polymers;
Electrochemical techniques;
Adsorption;
Corrosion;
Contact angle;
Aluminum

Abstract The inhibition effect of 3-(12-sodiumsulfonate dodecyloxy) aniline monomeric surfactant (MC_{12}) and its analog polymer Poly 3-(dodecyloxy sulfonic acid) aniline (PC_{12}) on the corrosion of aluminum in 0.5 M HCl solution was investigated using weight loss and potentiodynamic polarization techniques. The presence of these two compounds in 0.5 M HCl inhibits the corrosion of aluminum without modifying the mechanism of corrosion process. It was found that these inhibitors act as mixed-type inhibitors with anodic predominance as well as the inhibition efficiency increases with increasing inhibitor concentration, but decreases with raising temperature. Langmuir and Frumkin adsorption isotherms fit well with the experimental data. Thermodynamic functions for both dissolution and adsorption processes were determined. The obtained results from weight loss and potentiodynamic polarization techniques are in good agreement with contact angle measurements.

1. Introduction

Aluminum and its alloys have a remarkable economic and attractive material for engineering applications owing to its low cost, light weight, high thermal and electrical conductivity. The resistance of aluminum against corrosion in aqueous media can be attributed to a rapidly formed surface oxide film. Therefore, aluminum has been known to exhibit widely different electrochemical properties in different aqueous electrolytes.

---

[*] Corresponding author at: Chemistry Department, Faculty of Science, Beni Suef University, 62514 Beni Suef, Egypt. Tel.: +966 530 176 588.
E-mail address: eldeebm@yahoo.com (M.M. El-Deeb).

Peer review under responsibility of King Saud University.

Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.arabjc.2013.09.018

Hackerman and Sudbury (1950), Hackerman and Markrides (1954), Hackerman (1962) showed that, the adsorption of surfactant molecules on the metal surface can markedly change the corrosion resisting property of the metal. Various surfactants as well as octyl sulfate sodium salt are being studied as a corrosion inhibitor for aluminum in acidic media (Elewady et al., 2008; Zhao and Mu, 1999). Many of organic compounds such as electroactive conducting polymers (Perucki and Chandrasekhar, 2001; Breslin et al., 2005; Gelling et al., 2001; Epstein et al., 1999; Yang et al., 2002), carboxylic organic acids (Muller, 2004; Bereket and Yurt, 2001), fatty acids (Foad El-Sherbini et al., 2003) dicyandiamide and some of its related compounds (Maitra and Barua, 1974), hydrazine compounds (Moussa et al., 1976), triazole and thiazole derivatives (Zheludkevich et al., 2004) were also found to inhibit the corrosion of aluminum.

The inhibition of most these compounds occurs via their adsorption on the metal surfaces which can markedly change the corrosion – resisting property of the metal and so the study of the relations between the adsorption and corrosion inhibition is of great importance.

Abd El Rehim et al. (2001) studied the effect of sodium dodecyl benzene sulfonate on the corrosion of aluminum and its alloy in 1 M HCl. The data show that, the addition of this surfactant inhibits the hydrochloric acid corrosion of aluminum and the inhibition occurs through adsorption of the surfactant on the metal surface and fits Frumkin adsorption isotherm.

EL-Deeb and Mohamed (2011) studied the effect of 3-(10-sodiumsulfonate decyloxy) aniline monomeric surfactant and its analog polymer on the corrosion of aluminum in 0.5 M HCl. The results show that, the inhibition occurs through the adsorption of surfactant molecules on the aluminum surface as well as the inhibition efficiency increases with increasing inhibitor concentrations and decreases with raising temperature.

The present study aims to investigate the inhibition effect of 3-(12-sodiumsulfonate dodecyloxy) aniline monomeric surfactant (MC_{12}) and its analog polymer Poly 3-(dodecyloxy sulfonic acid) aniline (PC_{12}) on the corrosion of aluminum in 0.5 M HCl solution using weight-loss and potentiodynamic polarization techniques as well as the thermodynamic functions for the dissolution and adsorption were investigated.

2. Experimental

2.1. Materials

3-Aminophenol, potassium persulfate and 1,12-dibromododecane were obtained from Aldrich Chemical Co., England. Sodium sulfite used in the synthetic process was obtained from Merck chemical Co., (Germany). Concentrated hydrochloric acid was chemically pure grade products provided by Prolab-o-Chemical Co., (U.K.). Twice distilled water was used as a medium for the polymerization reactions.

2.2. Weight loss measurements

Aluminum metal provided by the Egyptian Aluminum Company, Naghammady of the following chemical composition: 99.57% Al, 0.31% Fe, 0.07% Si, 0.015% Ti%, 0.0016% Zn, 0.0003% Cr, 0.0019% Mg, 0.0021% Mn and 0.0007 Cu and

Table 1 Elemental analysis of the prepared MC_{12} and PC_{12}.

Name	C%		H%		Cl%		S%		N%	
	Cal.	Found	Cal.	Found	Cal.	Found	Cal.	Found	Cal.	Found
MC_{12}	73.22	72.93	10.17	10.02	–	–	10.85	10.63	4.75	7.66
PC_{12}	54.65	55.37	7.97	7.69	4.44	4.51	8.10	8.04	3.54	3.52

Table 2 Infrared absorption bands and their assignments for MC_{12} and PC_{12}.

Wave number (cm^{-1})		Assignments Silversyein et al. (1974)
MC_{12}	PC_{12}	
510^{b}	493^{s}	Bending deformation of NH in primary aromatic amines
628^{sh}	–	Out-of-plane bending deformation of CH in 1,3-disubstituted benzene ring
753^{s}	758^{b}	In-plane rocking vibration for CH in aliphatic chain
–	818^{m}	Out-of-plane bending deformation of CH in 1,3,4-trisubstituted benzene ring
920^{m}	974^{s}	Symmetric stretching vibration for S–O or C–N group
–	1056^{sh}	Symmetric stretching vibration for C–O group
1121^{b}	1126^{b}	
1329^{w}	1325^{w}	Symmetric stretching vibration for S═O group
1457^{s}	1405^{s}	Scissoring deformation for CH in methylene group
–	1566^{m}	Stretching vibration for quinoide structure in benzene ring
1617^{s}	1624^{b}	Stretching vibration for C═C in benzene ring
2839^{sh}	2840^{w}	Symmetric stretching vibration for CH group in aliphatic chain
3042^{sh}	3041^{sh}	Symmetric stretching vibration for CH group in benzene ring
3235^{m}	3148^{b}	Stretching vibration for OH group in SO_3H group strongly hydrogen bond
3414^{m}	–	Symmetric stretching vibration for NH in aromatic amine
3478^{m}	3400^{b}	Asymmetric stretching vibration for NH in aromatic amine
3550^{m}	–	Stretching vibration for free OH group in SO_3H group

Abbreviations: s, sharp; m, medium; w, weak; sh, shoulder.

the diminutions of the tested samples 2 × 2 × 0.1 (thickness) is used in this study. The samples were polished successively with fine grade emery papers, cleaned with acetone, washed with doubly distilled water and finally dried, weighed and then introduced into test solution.

2.3. Potentiodynamic polarization measurements

The working electrode made from aluminum rod has the same composition as mentioned in Section 2.2. The rod is axially embedded in araldite holder to offer an active flat disk shaped surface of an area of 0.785 cm^{-2}. Prior to each experiment, the working electrode was polished successively with fine emery paper. The polished metal surface was rinsed with acetone and distilled water before dipping it into the electrolytic cell. A platinum wire was used as the counter electrode and a saturated calomel electrode as a reference electrode to which all potentials are referred.

The electrochemical experiments are performed using the Potentiostat/Galvanostat Wenking PGS95, connected to computer. *I–E* curves are recorded using computer software (model ECT). The experiments were carried out by changing the electrode potential automatically from the starting potential toward more positive values at the required scan rate till the end of the experiments.

2.4. Synthesis of monomeric 3-(12-sodiumsulfonate dodecyloxy) aniline (MC_{12})

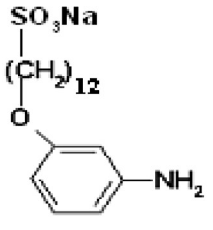
3-(12-Bromododecyloxy) aniline was prepared by the equilomolar reaction, between 3-aminophenol and 1,12-dibromododecane in the presence of sodium ethoxide. The product 3-(12-Bromododecyloxy) aniline was reacted with sodium sulfite to produce 3-(12-sodiumsulfonate dodecyloxy) aniline.

2.5. Synthesis of Poly 3-(dodecyloxy sulfonic acid) aniline (PC_{12})

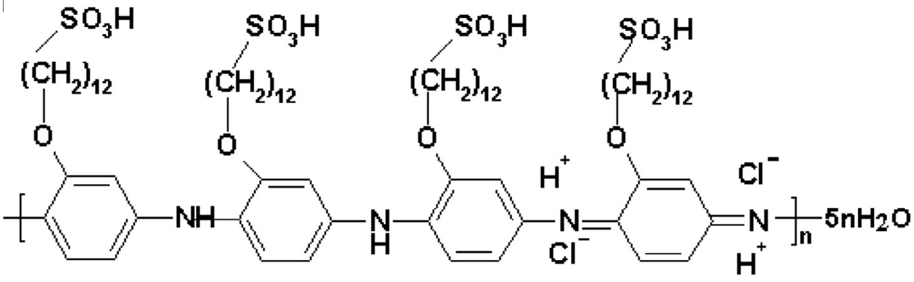
The amount of 3-(12-sodiumsulfonate dodecyloxy)aniline in 25 ml 2.0 M HCl solution was introduced into a well stoppered conical flask of 250 ml capacity followed by the addition of the required amount of potassium per sulfate dissolved in 25 ml 2.0 M HCl solution to the reaction mixture under nitrogen atmosphere. The order of addition of substances was kept constant in all the performed experiments. The stoppered conical flask was then placed in an automatically controlled thermostat at 25 °C. The flask was shaken (50 shakings/10 s/15 min) for one hour by using an automatic shaker. The flask was left for 72 h at room temperature to continue the reaction and then filtrated using a Buchner funnel. Then the solid was washed with distilled water, and finally dried under vacuum at room temperature until constant weight.

2.6. Elemental and spectroscopic analysis

Elemental analysis of the prepared monomeric and polymeric surfactant was carried out in the microanalytical laboratory at the Cairo University by using oxygen flask combustion and a dosimat E415 titrator (Switzerland). The elemental analysis of the prepared monomeric and polymeric surfactant is summarized in Table 1. Infrared spectroscopic analysis of the prepared MC_{12} and PC_{12} was carried out in the microanalytical laboratory at the Cairo University by using a shimadzu FTIR-430 Jasco Spectrophotometer and KBr disk techniques. IR absorption bands and their assignments (Silversyein et al., 1974) of MC_{12} and PC_{12} are summarized in Table 2. Data of Tables 1 and 2 show that, there is a good agreement with the suggested structures present in Scheme 1.



A: Structure of monomer (MC_{12})



B: Structure of polymer (PC_{12})

Scheme 1 Structure of monomeric and polymeric surfactants.

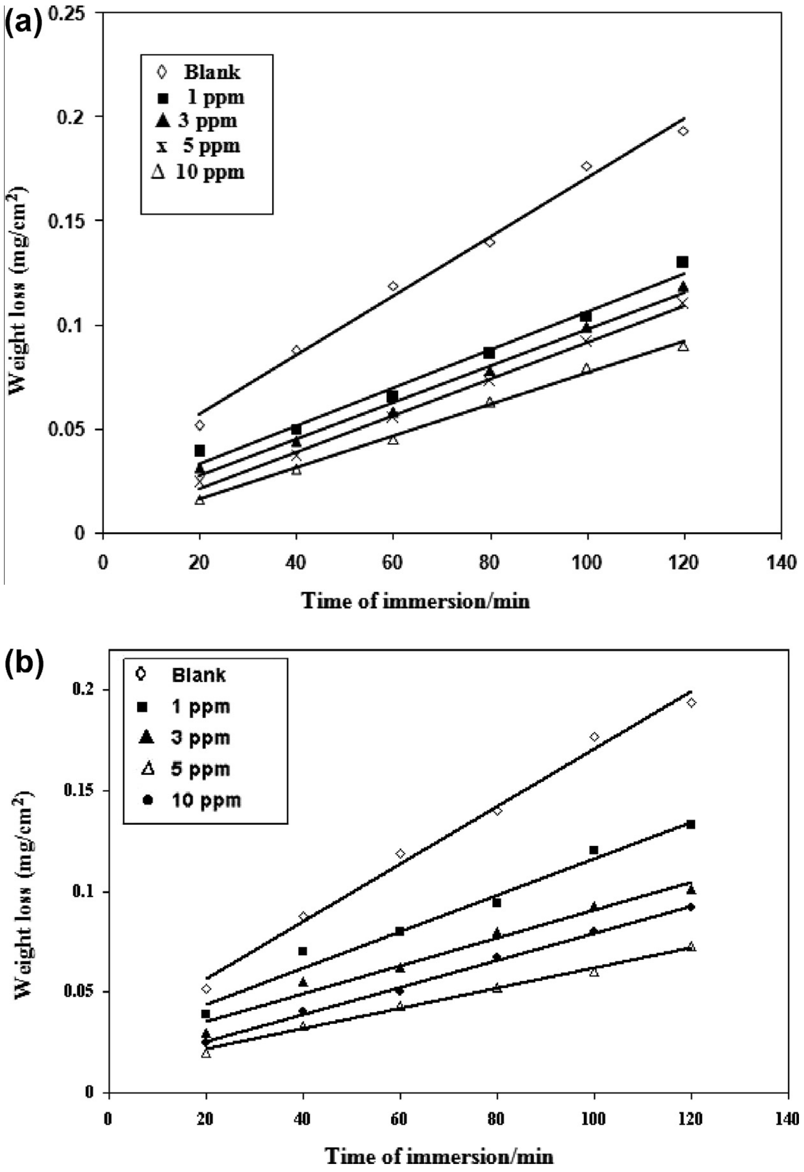


Figure 1 Weight loss vs. immersion time for aluminum in 0.5 M HCl solution in the absence and presence of different concentrations of MC_{12} (a) and PC_{12} (b) at 30 °C.

2.7. Critical micelle concentration and contact angle

Critical micelle concentration (CMC) of the prepared MC_{12} and PC_{12} was measured by using K100 Tensiometer (KRUSS Type) for the hydrochloric form of synthesized monomeric and polymeric surfactants using different concentrations.

Table 3 Variation of inhibition efficiency (P%) and contact angle of aluminum at different inhibitor concentrations using weight loss and polarization measurements at 30 °C.

Conc. (ppm)	P%				Contact angle	
	Weight loss		Polarization			
	MC_{12}	PC_{12}	MC_{12}	PC_{12}	MC_{12}	PC_{12}
1	28.1	35.5	25.8	36.2	83.16	76.91
3	43.5	48.6	42.0	50.9	50.12	47.12
5	55.0	71.3	56.5	69.0	16.82	10.78
10	49.0	56.1	50.0	55.1	22.34	21.45

3. Results and discussion

3.1. Weight loss measurements

Weight loss (in mg cm^{-2}) of aluminum in 0.5 M HCl solution in the absence and presence of different concentrations of 3-(12-sodiumsulfonate dodecyloxy) aniline (MC_{12}) monomeric surfactant and its analog polymer Poly 3-(dodecyloxy sulfonic acid) aniline (PC_{12}) at 30 °C was determined as a function of the immersion time and the data are graphically represented in Fig. 1. The slope of each line (mg cm^{-2} min^{-1}) represents the corrosion rate of aluminum at the specified conditions. From these data, the weight loss (and hence rate of corrosion) of aluminum enhances with the immersion time.

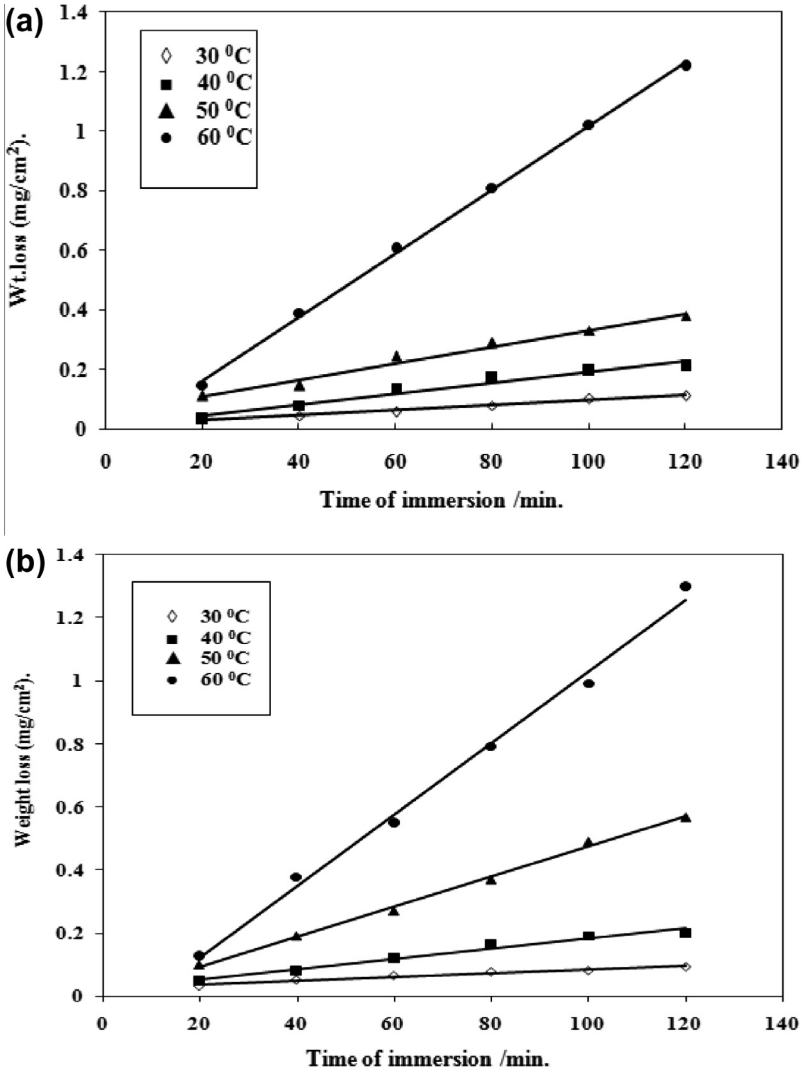


Figure 2 Weight loss vs. immersion time for aluminum in 0.5 M HCl solution in the presence of 10 ppm of MC_{12} (a) and PC_{12} (b) at different temperatures.

Table 4 Effect of MC_{12} and PC_{12} concentrations on the thermodynamic of the dissolution process of Al in 0.5 M HCl solution.

Conc. (ppm)	E_a (kJmol^{-1})				$\Delta H°$ (kJmol^{-1})			
	Weight loss		Polarization		Weight loss		Polarization	
	MC_{12}	PC_{12}	MC_{12}	PC_{12}	MC_{12}	PC_{12}	MC_{12}	PC_{12}
Blank	57.4	57.4	57.3	57.3	55.5	55.5	54.7	54.7
1	64.5	66.6	62.6	65.3	62.3	64.1	59.9	62.9
3	67.3	73.7	66.4	72.5	65.1	70.5	64.3	68.9
5	72.8	82.5	72.0	80.4	70.0	80.1	68.9	76.8
10	70.1	80.1	69.8	76.2	68.5	78.6	67.6	70.2

On one hand, the dissolution of aluminum in HCl solution is slow and increases with the immersion time as indicated by increasing the weight loss by time, this may by due to the presence of a pre-immersion hydrate Al_2O_3 film on the metal surface (Osman and Abd El Rehim, 1998). On the other hand, the addition of (MC_{12}) monomeric surfactant and its polymer (PC_{12}) retards the rate of dissolution and inhibits the acid corrosion of aluminum. The inhibition efficiency values (P%) at different inhibitor concentrations and temperatures were calculated from the following equation:

$$P\% = 100 \times [1 - (W/W_0)] \quad (1)$$

where W_0 and W are the weight loss per unit time in the absence and presence of the inhibitors, respectively and the data are summarized in Table 3. Data of Table 3 indicate that the inhibition efficiency of PC_{12} is higher than that of MC_{12}.

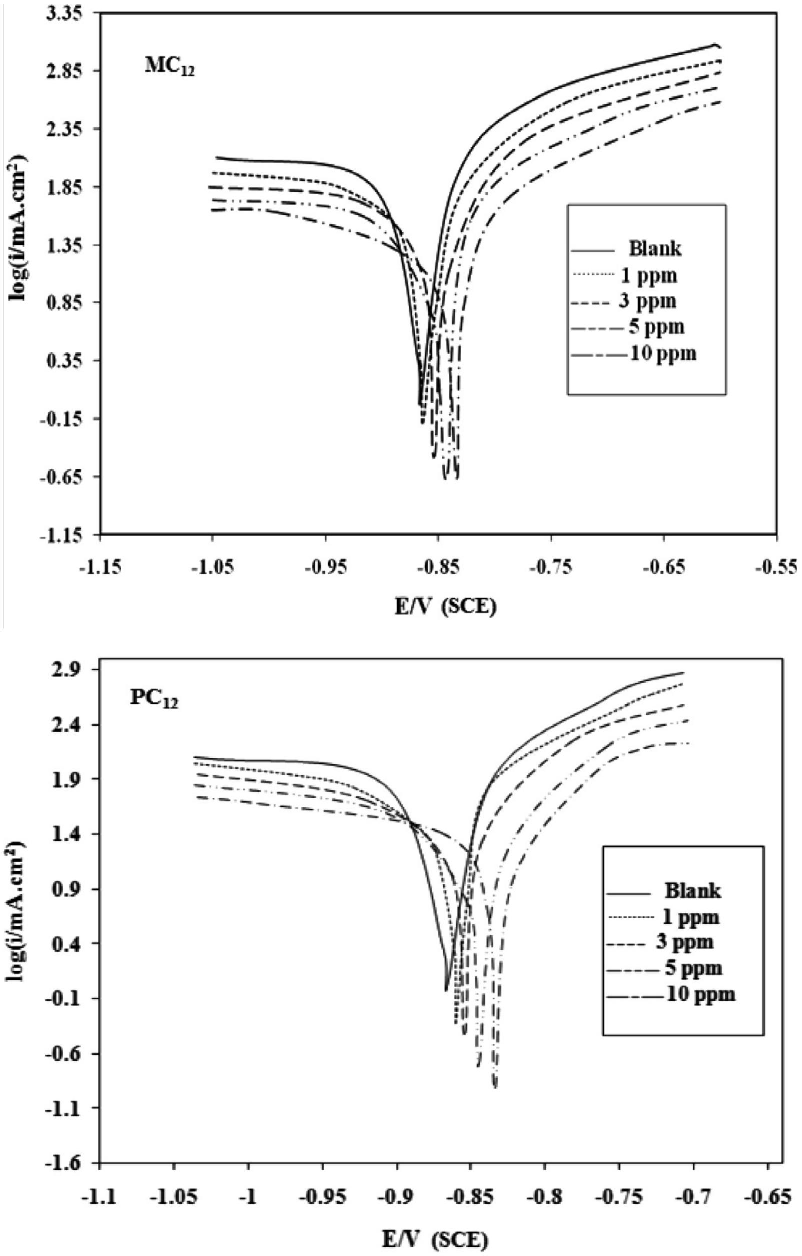


Figure 3 Effect of MC_{12} and PC_{12} concentrations on the cathodic and anodic polarization of Al in 0.5 M HCl solution with a scan rate of 25 mV/s at 30 °C.

The inhibition efficiency increases with increasing concentration of the two surfactants and reaches maximum value at critical concentration (1.32×10^{-5} mol/L in case of MC_{12} and 3.19×10^{-6} mol/L in case of PC_{12}). Beyond this critical concentration, the efficiency tends to achieve steady state values. It is seen that, the maximum efficiency is obtained at concentration less than the respective CMC (CMC is 2.51×10^{-4} mol/L in case of MC_{12} and 1×10^{-4} mol/L in case of PC_{12}). This means that, the adsorption of these surfactants on the aluminum surface reaches equilibrium before the formation of micelles (The aggregation of these surfactant long chains into fairly large charged units).

The contact angle is the angle formed when a liquid droplet is placed on the solid surface. The contact angle values vary from 0° (perfectly wetting) to 180° (completely non-wetting). The values of the contact angle for MC_{12} and PC_{12} at 30 °C are given in Table 3. The data clearly show that, the inhibition efficiency of these two inhibitors increases as their contact angles decrease. Moreover, it is observed that the contact angles for PC_{12} are lower than those for MC_{12} confirming the suggestion that PC_{12} is more effective than MC_{12} for inhibiting the acid corrosion of aluminum.

Fig. 2 shows the influence of temperature on the weight loss for aluminum in 0.5 M HCl in the absence and presence of 10 ppm of MC_{12} and PC_{12}. As can be seen from the figure, the weight loss (and hence the rate of corrosion) of aluminum sample enhances with the immersion time and the addition of both inhibitors retards the rate of dissolution at all ranges of the investigated temperatures. The data show that the weight loss increases with increasing temperature. This can be due

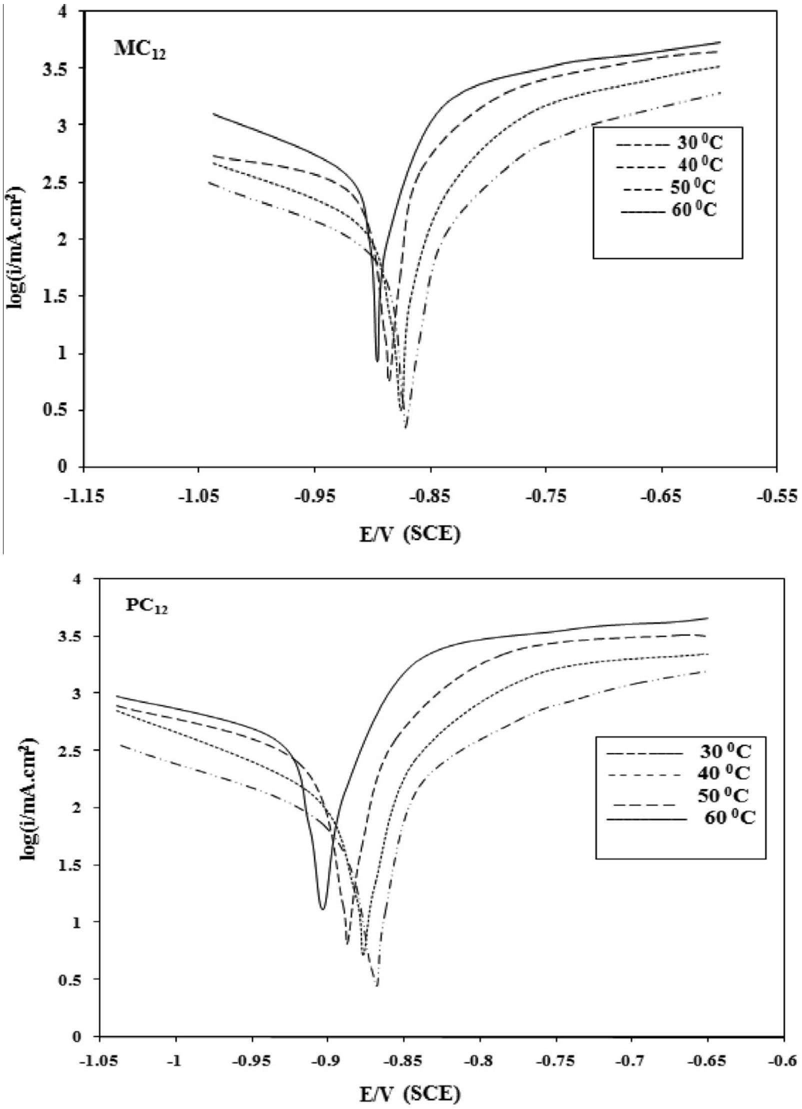


Figure 4 Effect of temperature on the cathodic and anodic polarization of Al in 0.5 M HCl in the presence of 10 ppm of MC_{12} and PC_{12} with a scan rate of 25 mV/s.

to the decrease in the strength of adsorption process with increasing temperature suggesting that physical adsorption may be the type of adsorption of the inhibitor on the sample surface. It has been reported that (EL-Deeb and Mohamed, 2011; Sayyah et al., 2001; Abd El Rehim et al., 2010), for acid corrosion of metals, the logarithm of the corrosion rate (in mg cm^{-2} min^{-1}) is a linear function with $1/T$ (following Arrhenius equation type):

$$\log\ (\text{rate}) = -E_a/2.303\ RT + A \tag{2}$$

where E_a is the apparent effective activation energy, R is the universal gas constant and A is the Arrhenius pre-exponential factor. The corrosion rate for each concentration from 1 to 10 ppm of the monomeric and its polymeric surfactant was calculated at different temperatures and the logarithm of the corrosion rate was plotted against $1/T$ for each concentration and the value of E_a was calculated and tabulated in Table 4. An alternative formula of the Arrhenius equation is the transition state equation:

$$\text{Rate} = RT/Nh\ \exp\ (\Delta S^\circ/R)\ \exp\ (-\Delta H^\circ/\text{RT}) \tag{3}$$

where h is the Planck's constant, N is the Avogadro's number, ΔS° is the entropy of the activation, and ΔH° is the enthalpy of activation. The plot of log (Rate/T) vs. $1/T$ gives a straight line with a slope of ($-\Delta H^\circ$/2.303 R), from which the value of ΔH° was calculated and listed in Table 4. These values indicate that the presence of the additives increases the activation energy and the activation enthalpy, for the corrosion process. The addition of inhibitors modified the values of the activation energy and the activation enthalpy. This may be attributed to the adsorption of inhibitors on the aluminum surface and this adsorption makes an energy barrier and this energy barrier of the corrosion reaction increases as the concentration of the inhibitor is increased.

Table 5 Electrochemical parameters associated with polarization measurements for Al in 0.5 M HCl solution in the absence and presence of different concentrations of PC_{12} at different temperatures.

C (ppm)	E_{Corr} (V)	I_{Corr} (μA cm^{-2})	β_a (mV dec^{-1})	$-\beta_c$ (mV dec^{-1})
At 30 °C				
Blank	−0.82	95.22	−0.34	0.04
1	−1.04	60.80	−0.26	0.33
3	−0.60	46.73	−0.36	0.26
5	−0.74	29.79	−0.29	0.08
10	−0.70	42.82	−0.32	0.13
At 40 °C				
Blank	−0.98	368.00	−0.39	0.12
1	−0.94	256.70	−0.32	0.11
3	−0.84	216.20	−0.39	0.11
5	−0.89	186.30	−0.34	0.15
10	−0.93	193.10	−0.43	0.09
At 50 °C				
Blank	−1.03	574.20	−0.46	0.13
1	−0.95	440.50	−0.45	0.11
3	−0.97	401.10	−0.41	0.11
5	−0.98	366.50	−0.35	0.15
10	−0.90	383.40	−0.43	0.09
At 60 °C				
Blank	−1.21	783.00	−0.48	0.13
1	−0.95	632.30	−0.55	0.12
3	−0.97	602.50	−0.43	0.14
5	−0.98	578.60	−0.46	0.14
10	−0.90	603.20	−0.56	0.10

Table 6 The electrochemical parameters associated with polarization measurements for Al in 0.5 M HCl solution in the absence and presence of different concentrations of MC_{12} at different temperatures.

C (ppm)	E_{Corr} (V)	I_{Corr} (μA cm^{-2})	β_a (mV dec^{-1})	$-\beta_c$ (mV dec^{-1})
At 30 °C				
Blank	−0.82	95.22	−0.34	0.044
1	−0.72	70.65	−0.24	0.119
3	−0.71	55.26	−0.317	0.122
5	−0.82	41.45	−0.31	0.114
10	−0.75	47.61	−0.315	0.084
At 40 °C				
Blank	−0.98	368	−0.114	0.39
1	−0.97	270.4	−0.146	0.314
3	−0.931	227.5	−0.118	0.42
5	−0.818	199.1	0.221	0.51
10	−0.812	206.3	0.181	0.099
At 50 °C				
Blank	−1.033	574.2	−0.128	0.46
1	−0.912	432.7	−0.137	0.41
3	−1.03	401.6	−0.132	0.454
5	−0.917	356.4	−0.119	0.45
10	−0.915	378.1	0.154	0.71
At 60 °C				
Blank	−1.21	783	−0.13	0.48
1	−1.11	675.6	−0.161	0.45
3	−0.963	653.7	−0.127	0.461
5	−0.96	623.1	−0.121	0.46
10	−0.923	635.4	−0.141	0.41

3.2. Potentiodynamic polarization measurements

Potentiodynamic polarization measurements of aluminum in 0.5 M HCl containing different concentrations of both MC_{12} and PC_{12} at different temperatures with a scan rate of $25\,mVs^{-1}$ are graphically represented in Figs. 3 and 4 and the electrochemical parameters (l_{corr}, E_{corr}, β_c and β_a) are listed in Tables 5 and 6. The data clearly show that the addition of MC_{12} and PC_{12} enhances both the anodic and cathodic overpotential and decreases the corresponding partial anodic (dissolution of the metal) and partial cathodic (evolution of hydrogen) current densities as well as decreases the values of I_{corr} confirming the inhibition of the corrosion process. Moreover, the corrosion potentials are displayed to more positive values in the presence of the inhibitors revealing that these surfactants predominately act as anodic inhibitors. This could be interpreted on the basis that the potential at the anodic sites is more positive than that at the cathodic sites and consequently the adsorption of the surfactant is much more negative anion surfactant likely to adsorb at the anodic sites.

The inhibition efficiency (*P*%) was calculated at different inhibitor concentrations and the data are given in Table 3. It is seen that, the inhibition efficiency increases with increasing surfactant concentrations up to critical concentrations but decreases with raising temperature. The presence of these inhibitors does not change significantly the values of cathodic and anodic Tafel line slopes .These results indicate that these inhibitors act by simply blocking the available surface area for the corrosion process. In other words, each inhibitor decreases the surface area for corrosion without affecting the mechanism of the corrosion process and only causes inactivation of a part of the aluminum surface with respect to the corrosive medium.

3.3. Adsorption isotherm

In order to get more information about the mode of adsorption of the inhibitors on the metal surface at different temperatures, the data obtained from the two different techniques have been tested with several adsorption isotherms. Langmuir adsorption isotherm was found to fit well with our experimental data. Fig. 5 represent curves fitting of MC_{12} and PC_{12} using

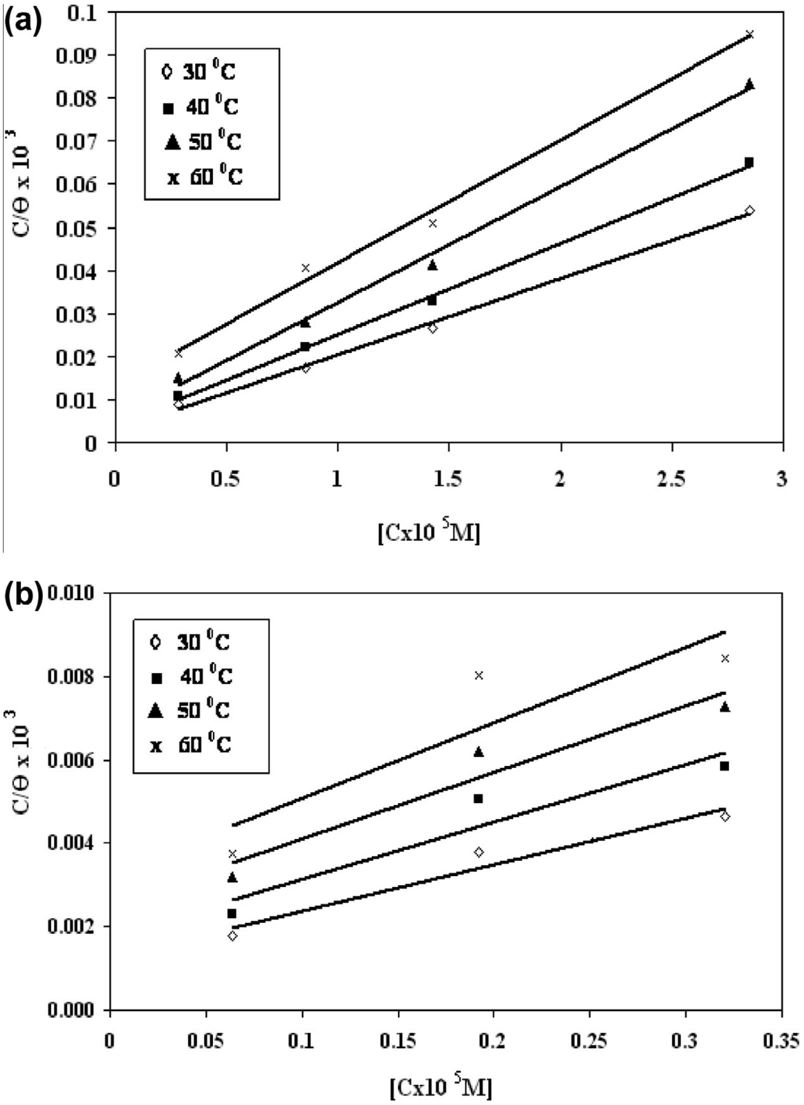


Figure 5 Langmuir adsorption isotherm of MC_{12} (a) and PC_{12} (b) based on polarization data at different temperatures.

data obtained from potentiodynamic polarization measurements respectively. Similar results were obtained from weight loss technique. The adsorption isotherm relationship of Langmuir is represented by the following equation (EL-Deeb and Mohamed, 2011; Migahed et al., 2004):

$$C_i/\theta = 1/K_{ads} + C_i \tag{4}$$

where C_i is the concentration of the inhibitor in bulk solution, θ is the surface coverage $(\theta = P/100)$ and K_{ads} is the adsorption equilibrium constant.

Frumkin isotherm (Frumkin, 1915) was also found to fit well with the obtained experimental data. The adsorption isotherm relationship of Frumkin is represented by the following equation:

$$\ln\ \theta/C_i(1-\theta) = \ln K_{ads} + 2a\theta \tag{5}$$

where (a) is the lateral interaction term describing the molecular interactions in the adsorption layer and the heterogeneity of the surface and is a measure for the steepness of the adsorption isotherm. It may be positive or negative values. The more positive the value of (a), the steeper is the adsorption isotherm. Curves fitting of the weight loss data for MC_{12} and PC_{12} are graphically represented in Fig. 6. Similar results are obtained from the data of the polarization technique.

The adsorption thermodynamic parameters (ΔH_{ads} and ΔS_{ads}) for the surfactant adsorption on the aluminum surface in 0.5 M HCl at different temperatures were determined from the slopes and intercepts of the lines of log K_{ads} vs. $1/T$ plots using the following equation:

$$\log\ K_{ads} = -\Delta H_{ads}/2.303RT + \Delta S_{ads}/2.303R \tag{6}$$

where ΔH_{ads} and ΔS_{ads} are the enthalpy and entropy of the adsorption process respectively. The calculated values for ΔH_{ads}, ΔS_{ads} and ΔG_{ads} are listed in Table 7 ($\Delta G_{ads} = \Delta\varpi H_{ads} - T\Delta S_{ads}$). The thermodynamic functions of the adsorption process which obtained from two different techniques confirm each other. The calculated values of ΔG_{ads} are low suggesting that the nature of the inhibitor adsorption is mainly physical adsorption and their negative sign indicating spontaneous interaction of the inhibitor with the aluminum surface (Ateya et al., 1984). The negative value of ΔH_{ads} indicates that the adsorption of the inhibitors on the aluminum surface is an exothermic process. The values of ΔH_{ads} and ΔS_{ads} are characteristic of the occurrence of a replacement process during the

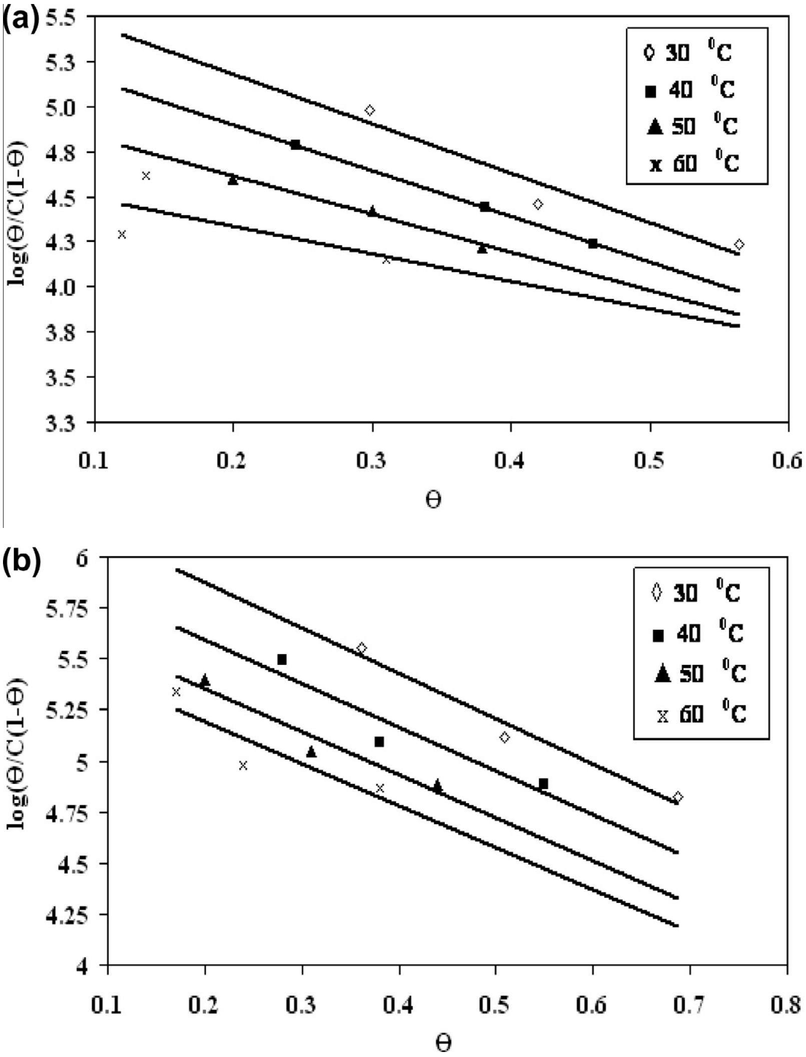


Figure 6 Frumkin adsorption isotherm of MC_{12} (a) and PC_{12} (b) based on weight loss data at different temperatures.

Table 7 Thermodynamic parameters of the adsorption process based on Frumkin isotherm.

Surfactant	Weight loss			Polarization		
	$-\Delta H_{ads}$ (kJmol^{-1})	$-\Delta S_{ads}$ (kJmol^{-1} K^{-1})	$-\Delta G_{ads}$ (kJmol^{-1})	$-\Delta H_{ads}$ (kJmol^{-1})	$-\Delta S_{ads}$ (kJmol^{-1} K^{-1})	$-\Delta G_{ads}$ (kJmol^{-1})
MC_{12}	65.95	0.1105	32.47	67.21	0.1128	33.01
PC_{12}	46.32	0.0298	37.28	45.57	0.0301	36.45

adsorption of inhibitor compound on the metal surface (Iampinen and Fomino, 1993).

4. Conclusion

- Addition of MC12 and PC12 surfactants inhibits the corrosion of aluminum in 0.5 M HCl solution.
- The inhibition efficiency of polymeric surfactant is higher than that of monomeric surfactant.
- The inhibition efficiency of the two surfactants increases with an increase in inhibitor concentration but decreases with an increase in temperature.
- The data obtained from weight loss and polarization technique fit well the Langmuir and Frumkin isotherms.
- The data obtained from contact angle, weight loss and potentiodynamic polarization techniques are in good agreements.

References

Hackerman, N., Sudbury, J.D., 1950. J. Electrochem. Soc. 94, 4.
Hackerman, N., Markrides, A.C., 1954. Ind. Eng. Chem. 46, 523.
Hackerman, N., 1962. Corrosion 18, 332.
Elewady, G.Y., El-Said, I.A., Fouda, A.S., 2008. Int. J. Electrochem. Sci. 3, 177–190.
Zhao, T., Mu, G., 1999. Corros. Sci. 41, 1937.
Perucki, M., Chandrasekhar, P., 2001. Synth. Met. 119, 385.
Breslin, C., Fenelon, A., Conroy, K., 2005. Mater. Des. 26, 233.
Gelling, V.J., Wiest, M.M., Tallman, D.E., Gordon, P., 2001. Prog. Org. Coat. 43, 149.
Epstein, A.J., Smallfield, J.A., Guan, H., Fahlman, M., 1999. Synth. Met. 102, 1374.
Yang, S.C., Racicot, R., Lin, Y., Mcclarnon, F., 2002. Am. Chem. Soc. 41, 1776.
Muller, B., 2004. Corros. Sci. 46, 159.
Bereket, G., Yurt, A., 2001. Corros. Sci. 43, 1179.
Foad El-Sherbini, E.E., Abd-El-Wahab, S.M., Deyab, M.A., 2003. Mater. Chem. Phys. 82, 631.
Maitra, A., Barua, S., 1974. Corros. Sci 14, 587.
Moussa, M.N., Taha, F.I., Gouda, M.A., Singab, G., 1976. Corros. Sci. 16, 379.
Zheludkevich, M.L., Yasakau, K.A., Poznyak, S., Ferrira, M., 2004. Corros. Sci. 47, 3368.
Abd El Rehim, S.S., Hassaan, H.H., Amin, M.A., 2001. J. Mater. Chem. Phys. 70, 64.
EL-Deeb, M.M., Mohamed, S.M., 2011. J. Appl. Polym. Sci. 122, 3030.
Silversyein, R.M., Bassler, C.G., Morill, T.C., 1974. Spectroscopic Identification of Organic Compounds. Willey, New York.
Osman, M.M., Abd El Rehim, S.S., 1998. Mater. Chem. Phys. 53, 34.
Sayyah, S.M., Abd EL-Rehim, S.S., EL-Deeb, M.M., 2001. Int. J. Polym. Mater. 49, 59.
Abd El Rehim, S.S., Sayyah, S.M., El-Deeb, M.M., Kamal, S.M., Azooz, R.E., 2010. Mater. Chem. Phys. 123, 20.
Migahed, M.A., Azzam, E.M., Al-Sabagh, A.M., 2004. Mater. Chem. Phys. 85, 273.
Frumkin, A.N., 1915. Z. Phys. Chem. 116, 166.
Ateya, B., El-anadouli, B., El–Nizamy, F., 1984. Corros. Sci. 24, 509.
Iampinen, M.J., Fomino, M., 1993. J. Electrochem. Soc. 140, 3537.