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ORIGINAL ARTICLE

Novel Synthesized Gemini Surfactant as Corrosion Inhibitor for Carbon Steel in HCl Solution

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Abstract A quaternary ammonium gemini surfactant containing an ester spacer, namely (diethylhexanedioate)diyl-α,ω-bis(dimethyl myristyl ammonium bromide) (**14-DEHA-14**) was synthesized using a two-step procedure with dimethyl hexanedioate, dimethylaminoethanol, and 1-bromotetradecane. The chemical structure of the compound was confirmed by infrared (IR) spectrum, ^{1}H nuclear magnetic resonance (NMR), and elemental analysis. The critical micelle concentration was determined by conductivity and tensiometry measurements, and its inhibition effect on corrosion of carbon steel in dilute (1.0 M) hydrochloric acid solution was investigated by weight loss measurements. The results show that the synthesized gemini surfactant acts as an excellent corrosion inhibitor in 1.0 M HCl solution. The adsorption of the inhibitor via chemical adsorption onto the carbon steel surface obeyed the Langmuir adsorption isotherm. A possible corrosion mechanism of the compound is discussed in relation to the calculated thermodynamic parameters and adsorption isotherm.

Keywords Corrosion inhibition · Gemini surfactant with ester spacer · CMC · Adsorption mechanism

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Introduction

Use of corrosion inhibitors is one of the most convenient means for protecting metals against corrosion, especially in acidic media [1, 2]. Most organic corrosion inhibitors interact with the metal surface through heteroatoms, such as nitrogen, oxygen, phosphorus, sulfur, aromatic rings, and multiple bonds, which can markedly change the corrosion resistance of the metal [3–6]. The inhibition efficiency is mainly due to the compatibility and affinity of the organic inhibitors with the metal surface, and their chemical structure [7]. Among organic inhibitors, oxygenated compounds and quaternary ammonium compounds are considered to be excellent corrosion inhibitors for many metals and alloys in various aggressive solutions [8–14]. As a result, exploitation of novel gemini surfactants containing oxygen atoms may be a good choice.

As a new generation of surfactants, gemini surfactants have attracted increasing research attention. Gemini surfactants consist of two hydrophobic chains and two polar headgroups covalently linked by a spacer. It has been demonstrated that gemini surfactants exhibit superior properties compared with conventional surfactants, such as lower critical micelle concentration (CMC) values, higher surface activity, better solubility, etc. [15–18]. In recent years, increasing research attention has been devoted to the corrosion inhibition behavior of gemini surfactants for highly viscous or aggressive media.

We report herein the synthesis of a quaternary ammonium gemini surfactant containing an ester spacer. The CMC was investigated by conductivity and tensiometry measurements. The inhibition effect of this gemini surfactant for carbon steel was evaluated by weight loss measurements in 1.0 M hydrochloric acid solution. The results show that this novel corrosion inhibition system is

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very efficient for carbon steel in 1.0 M hydrochloric acid solution. The possible adsorption mechanism of the gemini surfactant onto the surface of carbon steel in acidic medium was also explored.

Experimental

Synthesis of Gemini Surfactant

*Synthesis of Compound **A***

A mixture of dimethyl hexanedioate (9.80 g, 56.32 mmol) with dimethylaminoethanol (30.07 g, 337.92 mmol) in the presence of dibutyltin dilaurate (1.69 g, 2.67 mmol) as catalyst was stirred for 6 h at reflux. Then, the methanol byproduct and residual dimethylaminoethanol were removed under reduced pressure. The residue was purified by column chromatography to give **A** as white solid (9.00 g, yield 62.50 %).

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm: 1.66–1.73 (m, 4H, CCH_2CH_2C), 2.33–2.56 (t, 4H, 2× $COCH_2$), 3.48 (s, 12H, 4× CH_3), 4.14–4.17 (t, $J = 7.2$ Hz, 4H, 2× NCH_2), 4.46–4.72 (m, 4H, OCH_2). IR (KBr, cm^{-1}): 2947, 2822, 1736, 1460, 1383, 1172, 1041.

*Synthesis of **14-DEHA-14***

A mixture of compound **A** (3.00 g, 10.44 mmol) and 1-bromotetradecane (8.72 g, 31.49 mmol) in acetone (30 mL) was refluxed for 24 h. After the reaction mixture had cooled to room temperature, the crude product was isolated by filtering and then recrystallized twice from a mixture of acetone and acetonitrile to give **14-DEHA-14** as white crystal (8.04 g, yield 91.60 %).

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm: 0.86–0.89 (t, $J = 6.8$ Hz, 6H, $2(CH_2)_{11}\underline{CH_3}$), 1.25–1.36 (m, 44H, $2(\underline{CH_2})_{11}CH_3$), 1.70–1.77 (m, 8H, $CH_2\underline{CH_2}\underline{CH_2}CH_2$ and $2CH_2\underline{CH_2}(CH_2)_{11}$), 2.44 (m, 4H, $2\underline{CH_2}COO$), 3.48 (s, 12H, $4N\underline{CH_3}$), 3.62–3.66 (t, $J = 7.6$ Hz, 4H, 2 $N\underline{CH_2}CH_2$(-$CH_2)_{11}$), 4.15 (t, $J = 7.2$ Hz, 4H, $2OCH_2\underline{CH_2}N$), 4.63 (m, 4H, $2O\underline{CH_2}CH_2N$); IR (KBr, cm^{-1}): 2919, 2850, 1723, 1473, 1381, 1274, 1153; Anal. Calcd. Found %: C, 59.81; H, 10.63; N, 3.56; Theory %: C, 59.82; H, 10.21; N, 3.32.

Electrical Conductivity Measurements

The conductivity of solutions of the synthesized gemini surfactant was measured as a function of concentration at 308 ± 0.1 K using a DDS-11D conductivity meter (Shanghai Precision Scientific Instrument Co.). Each measurement was repeated twice [19]. Triple-distilled water was added to the surfactant solution to adjust the surfactant concentration.

Measurements of Surface Tension

The surface tension of gemini surfactant solutions was measured using the drop-volume technique at 308 ± 0.1 K [20]. All solutions were prepared with triple-distilled water. The surface tension of pure water was measured as being 71.99 ± 0.05 mN/m at 298.0 K. The critical micelle concentration (CMC) and surface tension at the CMC (γ_{CMC}) were determined from the break point of the surface tension versus logarithm of concentration curve. From the curve of surface tension versus concentration, the amount of surfactant adsorbed (Γ_{max}) and the area occupied by a surfactant molecule (A_{min}) at the air–water interface were calculated according to the following Gibbs adsorption Eqs. 1 and 2 [21]:

$$\Gamma_{\max} = -\left(\frac{1}{2.303nRT}\right)\left(\frac{d\gamma}{d\log C}\right), \tag{1}$$

$$A_{\min} = \frac{10^{16}}{N_A \Gamma_{\max}}, \tag{2}$$

where R is the gas constant (8.314 J mol^{-1} K^{-1}), T is the absolute temperature (K), C is the surfactant concentration (mol L^{-1}), and $d\gamma/d\log C$ is the slope below the CMC of the surface tension versus concentration curve. The value of n (the number of species at the interface whose concentration changes with the surfactant concentration) is taken as 3 [15, 22, 23]. N_A is Avogadro's number (6.02×10^{23} mol^{-1}).

Test Solutions

All tests were carried out in 1.0 M hydrochloric acid solution without or with addition of the synthesized quaternary ammonium gemini surfactant. Gas chromatography spectrometry was used to check the presence of hydrolysis for the gemini surfactant with ester spacer hydrolyzed in 1.0 M HCl solution at 308 K for half an hour in advance, and no peaks for hydrolysis products were observed. The test solutions were directly prepared by using reagent-grade hydrochloric acid and distilled water. During the measurement, the temperature of the test solutions was controlled by using a water bath with thermostatic control, and all experiments were performed under static conditions.

Weight Loss Measurements

Gravimetric analysis was performed on an analytical balance (model HR 200, readability 0.1 mg, standard

Table 1 Composition of carbon steel panels

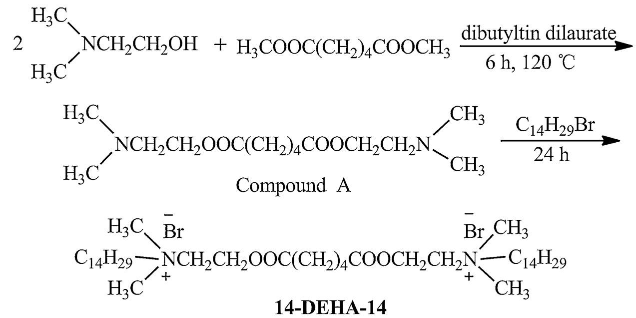
Element	C	P	S	Si	Mn	Cr	Co	Cu	Fe
Wt.%	0.252	0.082	0.051	0.296	1.26	0.031	0.395	0.378	Balance

deviation ±0.2 mg). Carbon steel panels with area of 9 cm^2 were abraded with a series of emery papers (grades 320-400-600-800-1000-1200), followed by successive washing with distilled water, ethanol, and acetone, and finally dried in a low-humidity atmosphere. The composition of the carbon steel panels is presented in Table 1. After precise weighing, the carbon steel panels were immersed in 200 mL of 1 M hydrochloric acid solution without or with addition of the synthesized quaternary ammonium gemini surfactant for different concentrations at 308 K. After keeping for 6 h, the steel samples were taken out from solution, rinsed two times with distilled water, degreased with ethanol and acetone, and finally dried in dry air and precisely weighed [24]. To achieve good reproducibility and high reliability, the experiments were carried out in triplicate under aerated conditions. The average weight loss of three parallel steel samples was calculated.

Results and Discussion

Synthesis of Gemini Surfactant Containing Ester Spacer

The synthesis route for the gemini surfactant **14-DEHA-14** containing ester spacer is shown in Scheme 1. It was easily prepared through a two-step procedure. First, dimethyl hexanedioate was reacted with stoichiometric excess of dimethylaminoethanol in the presence of dibutyltin dilaurate to generate the important intermediate compound **A**. Subsequently, the target compound **14-DEHA-14** was prepared with high yield of 91.60 % by reaction of the intermediate with 1-bromotetradecane. The chemical structure of **14-DEHA-14** was confirmed by IR, ^{1}H NMR, and elemental analysis.



Scheme 1 Synthetic route for **14-DEHA-14**

Conductivity of Surfactant Solutions

The CMC was determined as the concentration at the intersection of the linear portions of the plots [19]; the curves of conductivity versus concentration of the synthesized gemini surfactant at 308 K are shown in Fig. 1. The CMC value for the gemini surfactant was calculated as 0.281 mmol L^{-1}, which is about one or two orders of magnitude lower than those of traditional surfactants. This illustrates that the synthesized gemini surfactant easily forms micelles in aqueous solution.

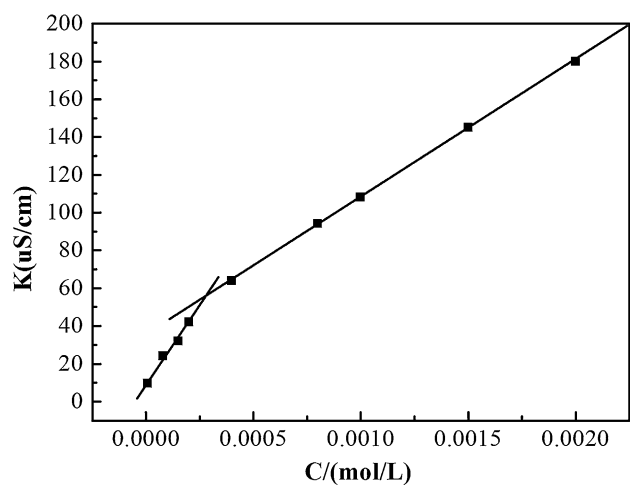


Fig. 1 Conductivity (*K*) versus surfactant concentration (*C*)

Surface Chemical Properties

In general, the CMC and the surface tension at the CMC (γ_{CMC}), usually taken to be the minimum surface tension achievable by a surfactant, are the most important parameters to characterize the surface activity of a surfactant [25]. The surface tension isotherm for **14-DEHA-14** versus molar concentration (*C*) at 308 K is shown in Fig. 2. The values of CMC and γ_{CMC} of **14-DEHA-14** were determined from the intersection points in Fig. 2, and the pertinent data are summarized in Table 2.

As shown in Table 2, the CMC of **14-DEHA-14** was determined as 0.267 mmol L^{-1} at 308 K and the γ_{CMC} value in aqueous solution was 39.6 mN m^{-1}. The CMC value of the gemini surfactant is about one or two orders of magnitude lower than those of traditional surfactants, suggesting that it forms micelles easily in bulk solution.

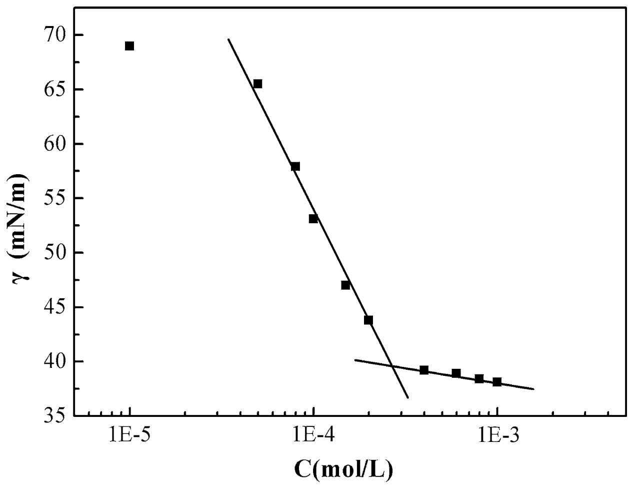


Fig. 2 Surface tension versus aqueous molar concentration of **14-DEHA-14**

Table 3 Weight loss results of carbon steel corrosion in 1.0 M HCl at different concentrations of synthesized gemini surfactant

C (mol L^{-1})	Weight loss (mg)	k (g m^{-2} h^{-1})	E (%)	θ
0	66.46	18.46	0	0
1.0×10^{-7}	58.28	16.19	12.31	0.127
5.0×10^{-7}	37.67	10.46	43.32	0.449
7.5×10^{-7}	32.15	8.93	51.62	0.535
1.0×10^{-6}	19.16	5.32	71.17	0.720
2.5×10^{-6}	8.61	2.39	87.05	0.914
5.0×10^{-6}	5.56	1.49	91.63	0.950
7.5×10^{-6}	4.79	1.33	92.79	0.962
1.0×10^{-5}	4.28	1.19	93.56	0.971
5.0×10^{-5}	2.80	0.78	95.78	0.993
1.0×10^{-4}	2.68	0.74	95.96	0.996
5.0×10^{-4}	2.40	0.67	96.39	0.996
1.0×10^{-3}	1.99	0.55	96.14	0.997

The γ_{CMC} of the gemini surfactant was lower than those for common surfactants. This shows that the gemini surfactant possessed high surface activity.

The values of Γ_{max} and A_{min} for **14-DEHA-14** are also shown in Table 2. The efficiency can be expressed by the logarithm of the surfactant concentration at which the surface tension of water is reduced by 20 mN m^{-1}. The larger the pC_{20} value, the greater the surfactant adsorption at the air–water interface [26]. As shown in Table 2, the pC_{20} value of the synthesized gemini surfactant was 3.84 at 308 K. It is obvious that the Gemini surfactant shows strong adsorption at the air–water interface.

Weight Loss Measurements

The corrosion inhibition efficiency of the synthesized quaternary ammonium gemini surfactant was measured in dilute (1.0 M) hydrochloric acid solution on carbon steel surface at 308 K. The percentage values of corrosion rate (k) and inhibition efficiency (E) obtained by the weight loss method for different concentrations of the inhibitor are summarized in Table 3. The corrosion rate (k) and inhibition efficiency (E) were calculated from Eqs. 3 and 4 [12, 27, 28]:

$$k = \frac{m_1 - m_2}{S \times t}, \tag{3}$$

$$E(\%) = \frac{W_0 - W_i}{W_0} \times 100, \tag{4}$$

where m_1 and m_2 are the sample weight before and after immersion, respectively, S is the total area of the specimen, t is the corrosion time, and W_0 and W_i are the weight loss in absence and presence of inhibitor, respectively.

Figure 3 shows the corrosion behavior of carbon steel in the presence of the synthesized gemini surfactant at 308 K. The results obtained from weight loss measurements of the quaternary ammonium gemini surfactant are listed in Table 3. The inhibition efficiency of the gemini surfactant increased with increasing inhibitor concentration in 1.0 M HCl solution. These results suggest that the inhibitor molecule acts through adsorption onto the metal surface. Thus, the inhibition efficiency may depend on the amount adsorbed and the surface coverage of the inhibitor [29, 30].

Adsorption Isotherm

From the adsorption isotherm, basic information about the interaction between the organic inhibitor and the carbon steel surface can be acquired. To obtain the isotherm, values of the fractional coverage as a function of inhibitor concentration must be determined. According to Eq. 5 [31, 32], the degree of surface coverage (θ) for the different

Table 2 Surface properties and micellization parameters of gemini surfactant

Compound	CMC[a] (mM)	CMC[b] (mM)	γ_{CMC} (mN/m)	Γ_{max} ($\times 10^6$ mol/m^2)	A_{min} (nm^2)	pC_{20}
14-DEHA-14	0.267	0.281	39.60	1.11	1.50	3.84

[a] Measured by tensiometry

[b] Measured by conductometry

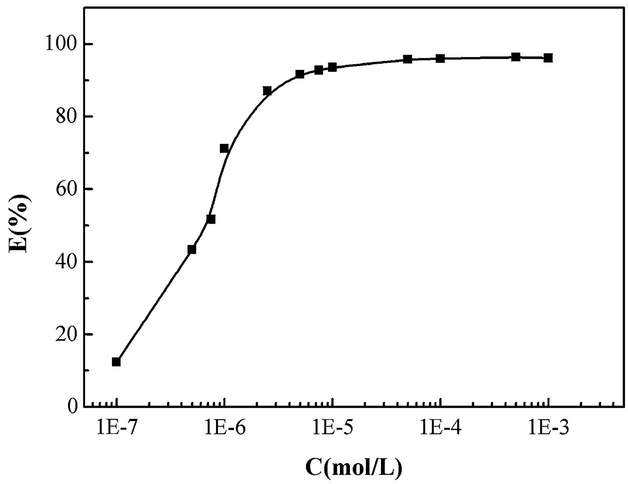


Fig. 3 Curve of $E\%$ versus concentration for **14-DEHA-14**

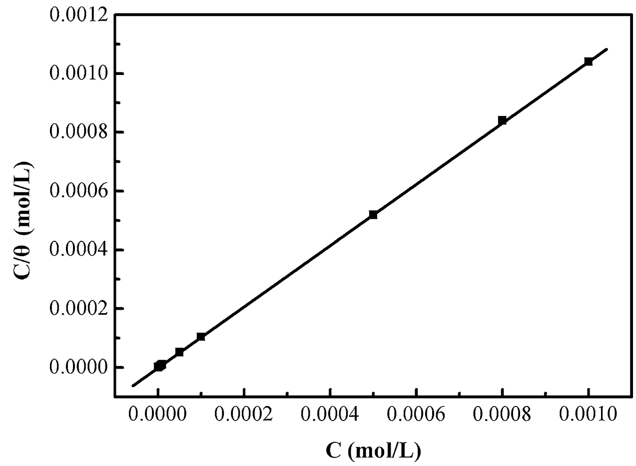


Fig. 4 Langmuir adsorption plots for carbon steel in 1.0 M HCl solution with various concentrations of **14-DEHA-14**

concentrations of organic inhibitor was estimated from weight loss measurements:

$$\theta = \frac{W_0 - W_i}{W_0 - W_m}, \quad (5)$$

where W_m is the smallest weight loss. The best correlation between the experimental results and isotherm functions at high concentrations of the organic inhibitor was acquired for the Langmuir adsorption isotherm, as shown by the following equation [33]:

$$\frac{C_{inh}}{\theta} = \frac{1}{K_{ads}} + C_{inh}, \quad (6)$$

where K_{ads} is the adsorption equilibrium constant of the adsorption/desorption process, and free energies of adsorption (ΔG_{ads}) were calculated using the following relationship [34, 35]:

$$\Delta G_{ads} = -2.303RT \log(55.5K_{ads}), \quad (7)$$

where R is the universal gas constant (the molar concentration of water in solution being 55.5). The plots of C_{inh}/θ versus C_{inh} at 308 K (Fig. 4) show that the linear correlation coefficient (r^2) and the slope are close to 1, confirming that adsorption of **14-DEHA-14** onto the carbon steel surface obeys the Langmuir adsorption isotherm. The inhibitor molecules adsorb onto the steel surface, forming a film that prevents corrosion induced by the medium. The adsorption parameters derived from Eqs. 6 and 7 are given in Table 4. The negative ΔG_{ads} indicates that the inhibitor adsorption is a spontaneous process. The value of ΔG_{ads} is below -40 kJ mol^{-1}, which means that there is strong chemical adsorption between the charged inhibitor molecules and the carbon steel surface [36, 37].

Relationship Between CMC and Corrosion Inhibition

As shown in Fig. 4, the inhibition efficiency of the gemini surfactant increased with increasing inhibitor concentration (below the CMC) in 1.0 M HCl solution. However, when the inhibitor concentration was close to the CMC, increasing the inhibitor concentration led to relatively small changes in inhibition efficiency. Below the CMC, increasing the inhibitor concentration results in relatively high surface coverage. As the inhibitor concentration reaches the CMC, the amount of gemini surfactant molecule adsorbed onto the carbon steel surface reaches a maximum, and the inhibition efficiency is higher than 96.6 %. Additionally, with increasing inhibitor concentration (near the CMC), a multilayer may form on the carbon steel surface, which leads to little change in the inhibition efficiency. Therefore, when the CMC of the synthesized gemini surfactant is low, good corrosion inhibition can be achieved at low concentration.

Mechanism of Corrosion Inhibition

The adsorption parameters above indicate that the adsorption behavior of the synthesized quaternary ammonium gemini surfactant is more complicated than that of traditional surfactants. To investigate the mechanism of corrosion inhibition, the different modes of adsorption available to the gemini surfactant are shown in Fig. 5. At extremely low concentrations of organic inhibitor, adsorption will take place through electrostatic interaction between the two ammonium groups (N^+) and the negatively charged metal surface in acidic media (Fig. 5a). As the concentration of organic inhibitor increases, the inter-hydrophobic chain interactions will become stronger, which may lead to desorption of one or two ammonium groups from

Table 4 Adsorption parameters of gemini surfactant on carbon steel surface at 308 K

Linear correlation coefficient	Slope	K_{ads} (M^{-1})	ΔG_{ads} (kJ mol^{-1})
0.9999	1.043	7.38×10^7	−56.69

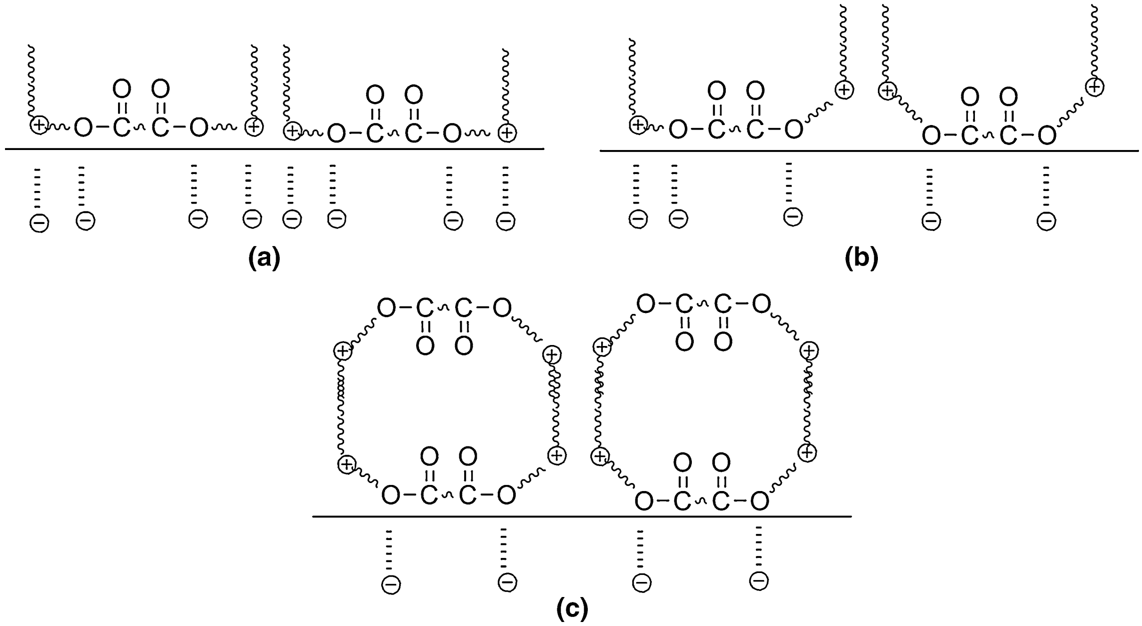


Fig. 5 Model of gemini surfactant adsorption onto carbon steel surface

the metal surface (Fig. 5b) [12, 14]. When the concentration exceeds the CMC, increasing the gemini surfactant concentration will result in gradual formation of multilayers (Fig. 5c). However, it is obvious that variation of the concentration above the CMC has little effect on the corrosion inhibition. This is mainly because a change in the concentration above the CMC only results in additional coverage beyond the monolayer level, which is already sufficient for significant inhibition.

In addition, as shown in Table 4, using the ΔG_{ads} value of -56.69 kJ mol^{-1}, the potential can be calculated as 0.29 V according to the equation $\Delta_r G = -nEF$, where F is the Faraday constant and n is taken as 2 for the two ammonium groups (N^+). This result indicates that carbon steel does not corrode easily under these experimental conditions.

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References

1. Mahdavian M, Tehrani-Bagha AR, Holmberg K (2011) Comparison of a cationic gemini surfactant and the corresponding monomeric surfactant for corrosion protection of mild steel in hydrochloric acid. J Surfact Deterg 14:605–613
2. Khamis A, Saleh MM, Awad MI (2013) Synergistic inhibitor effect of cetylpyridinium chloride and other halides on the corrosion of mild steel in 0.5 M H_2SO_4. Corros Sci 66:343–349
3. Axci G (2008) Corrosion inhibition of indole-3-acetic acid on mild steel in 0.5 M HCl. Colloids Surf A Physicochem Eng Aspects 317:730–736
4. Saliyan AR, Adhikari AV (2008) Quinolin-5-ylmethylene-3-{[8-(trifluoromethyl)quinolin-4-yl]thio}propanohydrazide as an effective inhibitor of mild steel corrosion in HCl solution. Corros Sci 50:55–61
5. Chebabe D, Chikh ZA, Hajjaji N et al (2003) Corrosion inhibition of Armco iron in 1 M HCl solution by alkyltriazoles. Corros Sci 45:309–320
6. Motamedi M, Tehrani-Bagha AR, Mahdavian M (2013) Effect of aging time on corrosion inhibition of cationic surfactant on mild steel in sulfamic acid cleaning solution. Corros Sci 70:46–54
7. Shukla SK, Quraishi MA, Prakash R et al (2008) A self-doped conducting polymer "polyanthranilic acid": an efficient corrosion inhibitor for mild steel in acidic solution. Corros Sci 50:2867–2872
8. Wang X, Yang H, Wang F (2010) A cationic gemini-surfactant as effective inhibitor for mild steel in HCl solutions. Corros Sci 52:1268–1276
9. El-Maksoud SAA (2008) The effect of organic compounds on the electrochemical behavior of steel in acidic media, a review. Int J Electrochem Sci 3:528–555
10. Migahed MA, Hegazy MA, Al-Sabagh AM (2012) Synergistic inhibition effect between Cu^{2+} and cationic gemini surfactant on the corrosion of downhole tubing steel during secondary oil recovery of old wells. Corros Sci 61:10–18
11. Seal S, Sapre K, Kale A et al (2000) Effect of multiphase flow on corrosion of C-steel in presence of inhibitor: a surface morphological and chemical study. Corros Sci 42:1623–1634

12. Ansari FA, Quraishi MA (2011) Inhibitive effect of some gemini surfactants as corrosion inhibitors for mild steel in acetic acid media. Arab J Sci Eng 36:11–20
13. Popova A, Christov M, Raicheva S et al (2004) Adsorption and inhibitive properties of benzimidazole derivatives in acid mild steel corrosion. Corros Sci 46:1333–1350
14. Qiu LG, Xie AJ, Shen YH (2005) A novel triazole-based cationic gemini surfactant: synthesis and effect on corrosion inhibition of carbon steel in hydrochloric acid. Mater Chem Phys 91:269–273
15. Zhang Q, Gao Z, Xu F et al (2012) Surface tension and aggregation properties of novel cationic gemini surfactants with diethylammonium headgroups and a diamido spacer. Langmuir 28:11979–11987
16. Patial P, Shaheen A, Ahmad I (2013) Synthesis of ester based cationic pyridinium gemini surfactants and appraisal of their surface active properties. J Surfact Deterg 16:49–56
17. Zhang Y, Ding M, Zhou L et al (2012) Synthesis and antibacterial characterization of gemini surfactant monomers and copolymers. Polym Chem 3:907–913
18. Mivehi L, Bordes R, Holmberg K (2011) Adsorption of cationic gemini surfactants at solid surfaces studied by QCM–D and SPR: effect of the rigidity of the spacer. Langmuir 27:7549–7557
19. Pankaj P, Arifa S, Ishtiaque A (2013) Synthesis of ester based cationic pyridinium gemini surfactants and appraisal of their surface active properties. J Surfact Deterg 16:49–56
20. Zhao GX (1991) Physical chemistry of surfactants. Beijing University Press, Beijing, pp 13–18
21. Alami E, Beinert G, Marie P, Zana R (1993) Alkanediyl-a,w-bis(dimethylalkylammonium bromide) surfactants. 3. Behavior at the air–water interface. Langmuir 9:1465–1467
22. Devinsky F, Lacko I, Bittererova F, Tomeckova L (1986) Relationship between structure, surface activity, and micelle formation of some new bisquaternary isosteres of 1,5-pentanediammonium dibromides. J Colloid Interface Sci 114:314–322
23. Li ZX, Dong CC, Thomas RK (1999) Neutron reflectivity studies of the surface excess of gemini surfactants at the air–water interface. Langmuir 15:4392–4396
24. Hegazy MA, Badawi AM, Abd El Rehim SS et al (2013) Corrosion inhibition of carbon steel using novel *N*-(2-(2-mercaptoacetoxy)ethyl)-*N*, *N*-dimethyl dodecan-1-aminium bromide during acid pickling. Corros Sci 69:110–122
25. Zhao GX, Zhu BY (2003) Principles of surfactant action. China Light Industry Press, Beijing, p 66
26. Perez L, Pinazo A, Rosen MJ, Infante MR (1998) Surface activity properties at equilibrium of novel gemini cationic amphiphilic compounds from arginine, bis(args). Langmuir 14:2307–2315
27. Li XH, Deng SD, Fu H et al (2010) Synergistic inhibition effect of rare earth cerium (IV) ion and sodium oleate on the corrosion of cold rolled steel in phosphoric acid solution. Corros Sci 52:1167–1178
28. El-Tabei AS, Hegazy MA (2013) A corrosion inhibition study of a novel synthesized gemini nonionic surfactant for carbon steel in 1 M HCl solution. J Surfact Deterg 16:757–766
29. Maaya AK, Al-Rawashdeh NAF (2004) Inhibition of acidic corrosion of pure aluminum by some organic compounds. Corros Sci 46:1129–1140
30. Qiu LG, Xie AJ, Shen YH (2005) The adsorption and corrosion inhibition of some cationic gemini surfactants on carbon steel surface in hydrochloric acid. Corros Sci 47:273–278
31. Qiu LG, Wu Y (2007) In: Bettini EL (ed) Progress in corrosion research. Nova Science, Inc., New York, pp 159–185
32. Qiu LG, Wu Y, Wang YM, Jiang X (2008) Synergistic effect between cationic gemini surfactant and chloride ion for the corrosion inhibition of steel in sulphuric acid. Corros Sci 50:576–582
33. Lebrini M, Traisnel M, Lagrenee M et al (2008) Inhibitive properties, adsorption and a theoretical study of 3,5-bis(*n*-pyridyl)-4-amino-1,2,4-triazoles as corrosion inhibitors for mild steel in perchloric acid. Corros Sci 50:473–479
34. Oguzie EE, Njoku VO, Enenbebeaku CK, Akalezi CO, Obi C (2008) Effect of hexamethyl pararosaniline chloride (crystal violet) on mild steel corrosion in acidic media. Corros Sci 50:3480–3486
35. Ferreira ES, Giancomelli C, Giacomelli FC, Spinelli A (2004) Evaluation of the inhibitor effect of L-ascorbic acid on the corrosion of mild steel. Mater Chem Phys 83:129–134
36. Solmaz R, Kardsa G, Yazici B, Erbil M (2008) Adsorption and corrosion inhibitive properties of 2-amino-5-mercapto-1,3,4-thiadiazole on mild steel in hydrochloric acid media. Colloids Surf A Physicochem Eng Aspects 312:7–17
37. Moretti G, Guidi F, Grion G (2004) Tryptamine as a green iron corrosion inhibitor in 0.5 M deaerated sulphuric acid. Corros Sci 46:387–403

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