Inhibition of metal corrosion in neutral aqueous solutions by succinic acid salts

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Abstract

The adsorption, protective and passivating effect of sodium succinate and a blend of sodium alkenylsuccinates SKAP-25 on the oxidized surface of copper, copper-nickel alloy MNZh5-1 and low-carbon steel St3 in a neutral chloride solution were studied. The free adsorption energy $\left(-\Delta G_{a,max}^0\right)$ values for all studied metals suggest chemisorption interaction of these organic anion with oxidized metals surfaces: $\left(-\Delta G_{a,max}^0\right)$ for St3 60.2 kJ/mol, for copper 77.4 kJ/mol and for copper alloy 89.3 kJ/mol. Sodium succinate is able to stabilize the passive state of the MNZh5-1 alloy in a neutral chloride buffer solution. On copper, copper alloy and St3, protection against local depassivation is observed up to a certain concentration, above which the protective properties of sodium succinate decrease. Polarization measurements on the air-oxidized surface of low-carbon steel St3 showed that sodium succinate and SKAP-25, as well as their compositions with 2-mercaptobenzothiazole (2-MBT), are able to reduce anodic dissolution currents and increase the local depassivation potential. Corrosion tests of St3 in a 0.01 M NaCl solution proved the advantage of using the composition of SKAP-25 with 2-MBT (7.1:1) in comparison with the individual compound: the degree of protection of St3 at $C_{inh}=7$ mmol/L is 99%, and sodium succinate+SKAP-25 (1:1) at $C_{inh}=7$ mmol/L is $Z=93\%$.

Introduction

Taking into account modern requirements for environmental protection and environmental problems arising when using a wide range of chemical compounds in it, the traditional approach to inhibiting the corrosion of ferrous and non-ferrous metals has changed significantly [1, 2]. Among corrosion inhibitors (CIs), organic compounds of different classes can be distinguished. In most cases, they are used in aqueous neutral [3–7] and acidic [8–13] solutions or in environments of oil and gas production and oil refineries [14, pp. 141–196; 15, 16]. CIs are well known and widely used in practice for the protection of metals in vapor-phase systems. Volatile CIs (VCIs) are primarily used to protect metals from atmospheric corrosion [17–25], although they can also be successfully used in power

equipment [26, 27] or to protect steel in concrete [28]. Over the past decade, a new direction of temporary protection of metals from atmospheric corrosion has developed, based on the use of CI with low equilibrium vapor pressure p^0, called chamber corrosion inhibitors (CCIs). Even in [29], it was proposed to use vapor treatment of such CI when preserving metal products in a chamber with an elevated temperature in order to increase the volatility of CI and accelerate its chemisorption on the metal. In addition, the closed space of the chamber with CCI vapors and the product protected by them eliminates environmental pollution and forms a thin adsorption coating that is preserved for a long time (more than 1 year) at normal temperatures outside the chamber. This became possible because the CCI, if desorbed, is very slow. Such a simple technology has opened up the possibility of using VCI with a low p^0 value, *i.e.* low-volatile chemical compounds for temporary protection of various metals [30–34].

Among the numerous classes of organic compounds, salts of carboxylic acids attract attention as CI of many metals. However, while salts of monocarboxylic acids in neutral media have been well studied, the same cannot be said about salts of dicarboxylic acids. The most studied salts of α,ω-dicarboxylic acids, although greater effectiveness of protective anti-corrosion action can be expected from derivatives of malonic and succinic acids containing an alkyl, alkylene or hydrocarbon ring. These substituents increase the hydrophobicity of the molecules, which gives them surface activity. Salts of dicarboxylic acids can be used as CI in various environments and wide areas of industry [35–39].

Succinic acid HOOC–(CH$_2$)$_2$–COOH belongs to the class of dicarboxylic acids and is widely used in various industries. It finds its greatest application in the food industry (in the production of beverages as an acidity regulator). It is a safe chemical compound and is approved by the US Food and Drug Administration [40]. Since it does not harm the environment, it can be used as an organic CI even in hydrochloric acid solutions [41].

Succinic acid and its salts – succinates – are actively used in the petrochemical industry to inhibit the corrosion of carbon steel in crude oil formation water. In [42], using the methods of potentiodynamic polarization, electrochemical impedance spectroscopy (EIS), and FTIR techniques, it was shown that succinic acid is an effective CI of carbon steel in the associated water of crude oil at pH 3. The inhibition efficiency is maximum at $C_{inh}=50$ mg/L and pH 3. The results showed that the inhibition efficiency increased with increase in succinic acid concentration but decreased with rise in temperature.

A similar picture is observed on low-alloy steel (with a Cr content <2.38%) in a sulfuric acid solution at pH 2–3. Succinic acid slows down the cathodic and anodic reactions in a wide range of potentials. The maximum protection efficiency is 75% for a solution of sulfuric acid with pH 3 and 0.1 mmol/L succinic acid. However, at pH>4, the inhibitory effect disappears. The authors believe that at pH<4, adsorption of undissociated inhibitor molecules occurs, and with increasing pH, dissociated particles (monohydrogen succinate and succinate anions) participate in complex formation reactions.

The inhibition of corrosion of low-carbon steel by succinic acid was studied in an aerated environment without stirring in solutions of 1.0 M HCl at 25°C and pH 2–8 [41].

The maximum inhibition efficiency ($Z \approx 97.5\%$) is achieved at $C_{inh} > 0.01$ M and pH 8, which allows the use of this "green" inhibitor when protecting low-carbon steel in HCl solutions with sodium hydroxide additives to regulate the pH of the solution. The effectiveness of inhibition increases with increasing concentration of succinic acid, pH of the solution and immersion time.

Earlier we studied the adsorption, passivation and protective properties of sodium succinate on copper and copper alloy MNZh5-1 in neutral chloride solutions [43, 44]. The adsorption isotherm of sodium succinate and its lower homologue, sodium malonate, on oxidized copper surface in borate buffer with pH 7.4 was obtained from the results of adsorption measurements [43]. At $E=0.0$ V, adsorption is adequately described by the complete Temkin equation with the free energy of adsorption $\left(-\Delta G^0_{a,\,max}\right)=77.4$ and 47.7 kJ/mol, respectively. These values $\left(-\Delta G^0_{a,\,max}\right)$ suggest chemisorption interaction of organic anions on the surface of the oxidized copper electrode. Malonate and succinate anions, despite their high hydrophilicity, are able to inhibit the anodic dissolution of copper in a borate buffer pH 7.4 containing 0.01 M NaCl. Sodium succinate was effective in inhibiting copper corrosion in an aqueous solution containing 0.01 M NaCl for 7 days at room temperature. At 3 mmol/L, the degree of copper protection was 80%.

On a copper alloy, the adsorption and passivation characteristics of sodium succinate are enhanced [44]. The free energy of adsorption on the oxidized surface of MNZh5-1 alloy is 89.3 kJ/mol, which is higher than for adsorption on copper. Unlike copper, spontaneous passivation in the presence of sodium succinate on the MNZh5-1 alloy occurs at $C_{inh}=0.25$ mmol/L, and with an increase in C_{inh} to 1.5 mmol/L, the value of the local depassivation potential E_{ld} increases, reaching 0.91 V, but at $C_{inh}=2$ mmol/L it decreases to 0.69 V. Apparently, this is due to an increase in the concentration of the ligand, *i.e.* succinate anions, which begins to form water-soluble complexes with metal cations, which weakens the corrosion inhibition effect of the MNZh5-1 alloy.

In our work we studied the adsorption of succinate anions on low-carbon steel St3 from a neutral borate buffer, as well as its protective effect in solutions containing aggressive chlorides. Using low-carbon steel St3, the effect of sodium succinate, its alkylene derivative SKAP-25 and a composition based on them with 2-mercaptobenzothiazole (2-MBT) on the passive state in a borate buffer and in a 0.01 M chloride aqueous solution was studied.

Experimental

The working electrodes were made of M1 copper; MNZh5-1 alloy [45] containing in %: 90.6–93.7 Cu; 5.0–6.5 Ni+Co; 1.0–1.4 Fe; 0.3–0.8 Mn; ≤0.5 Zn; ≤0.15 Si; ≤0.1 Sn; ≤0.04 P; ≤0.01 S; and low-carbon steel grade steel St3.

Commercial succinic acid (CAS Number 110-15-6, Sigma Aldrich) was used in the studies. Sodium salts of succinic acid were prepared by the neutralization reaction with sodium hydroxide solution.

SKAP-25 (TU 2499-080-05015207-2003 Antirust additive KAP-25 from May 20, 2003, OAO PO TOS).

The exact composition of the additive SKAP-25 is unknown, so the amount of alkali needed to convert acids from its composition into salts was taken from the acid number listed in the product data sheet, namely 382 mg/g KOH. Because the exact composition of SKAP-25 is unknown, the product obtained after its neutralization is referred to in the article as SKAP-25, and its concentration is given in g/L. The concentration of the substance in the working solution was 33.7 g/L. The pH values of SKAP-25 working solutions were maintained between 6.7 and 7.4.

For ellipsometric measurements, solutions with $C_{inh}=10^{-6}-10^{-8}$ M were used, for electrochemical and polarization studies 0.02–0.05 M. Before all experiments, the working electrode was first cleaned using sandpaper of different grain sizes 180–1000 and degreased with acetone.

Studies of adsorption on the oxidized surface of metals were carried out using a hand-held ellipsometer RR2000 in an electrochemical cell, which simultaneously allows maintaining the electrode potential E set by the potentiostat and measuring the ellipsometric phase shift angle Δ. Accuracy in determining the angle $\pm0.05°$. The potentials E of the electrode in solution were measured relative to the silver chloride reference electrode; in the article their values are given in terms of a standard hydrogen electrode. Potential of the oxidized electrode surface for copper and alloy $E=0.0$ V (SHE), St3 $E=0.2$ V (SHE).

At the thickness of a homogeneous film $d \leq 10$ nm, the Drude equation is valid, which allows us to pass from changes Δ angle to the degree of surface coverage θ [46]:

$$\theta = -\alpha\delta\Delta = -\alpha(\Delta-\Delta_0) \tag{1}$$

where α is a proportionality coefficient, Δ_0 is the value of the angle for the initial surface, and Δ is the value of the angle during the experiment.

If adsorption occurs, then $\delta\Delta = (\Delta-\Delta_0) < 0$. To obtain the CI adsorption isotherm on the pre-oxidized electrode at $E=0.0$ V, its concentrate was added in portions to the cell with borate buffer solution pH 7.4. For each C_{inh}, the angle Δ decreased in time and stopped changing after 60–90 min. Thus, we determine the angle difference $(-\delta\Delta)$ to plot its dependence on C_{inh}. The value of C_{inh}, at which the angle change stops, corresponds to a certain degree of coverage θ.

The C_{inh}, at which the value $(-\delta\Delta)$ stops changing, corresponds to the concentration of the first monolayer formation, *i.e.*, $\theta \to 1$ [47, 48]. The experimental dependence of the $\delta\Delta$ *vs.* $\log C_{inh}$ is rearranged into the adsorption isotherm $\theta=f(\ln C)$ and the adsorption free energy $\left(-\Delta G_a^0\right)$ is calculated. The adsorption of these compounds is adequately described by the full Temkin equation:

$$\theta = \frac{1}{f}\ln\frac{1+B_{max}C}{1+B_{min}C} \tag{2}$$

where f is the surface heterogeneity factor characterizing the change in the enthalpy of adsorption with surface coverage; B_{max} and B_{min} are the adsorption equilibrium constants corresponding to the highest and lowest values of adsorption energy. The value of B is related to the free energy of adsorption $\left(-\Delta G_a^0\right)$ by the relation:

$$B_{max,min} = \exp\left[\frac{\left(-\Delta G_{a,max(min)}^0\right)}{RT}\right] \qquad (3)$$

When determining $\left(-\Delta G_{a,max}^0\right)$, $\left(-\Delta G_{a,min}^0\right)$, f, B_{max}, and B_{min}, we used the technique described earlier in [49].

Electrochemical studies consisted in recording anodic polarization curves in borate buffer solution with the addition of 0.01 M NaCl and different concentrations of sodium succinate. They were obtained on St3 electrodes in an electrochemical cell with separated electrode spaces using IPC-PRO MF potentiostat.

The working electrode was preliminarily roughened on sandpaper of different grit 400–1000 and degreased with acetone. After removal of air formed film of metal oxides on the alloy (by keeping the electrode for 15 min in borate buffer with pH 7.4 and 0.01 M NaCl at $E=-0.85$ V) the potentiostat was turned off till the free corrosion potential E_{cor} was established. After establishing a new value of E_{cor} formed by adsorption of organic CI molecules introduced into the buffer solution on the electrode, the potentiostat was reconnected and polarization curves were recorded at the potential sweep rate of 0.2 mV/sec.

Another series of experiments consisted of measuring anodic polarization curves on St3 without preliminary reduction of the electrode. A steel sample was immersed in a chloride-buffer solution of 0.01 M NaCl and kept at free corrosion potential for 15 min, then a certain amount of C_{inh} was introduced and left for another 15 min. After this, the potential was fixed and its sweep rate was set with simultaneous recording of the anodic polarization curve.

The potential of local depassivation of metal by chlorides, E_{ld}, was determined by a sharp increase in current on the polarization curve followed by visual identification of pitting on the surface of the electrode. The error in the measurement of E_{ld} is 0.01 V.

Corrosion studies of low-carbon steel St3 were carried out in distilled water containing 0.01 M NaCl and various C_{inh}. Before the experiment, the plates were cleaned on abrasive paper of different grit (from 180 to 1000), degreased with acetone and weighed with ±0.0005 g accuracy. Then the samples were placed in chloride solution with additives of CI, or various concentrations of their mixtures with 2-MBT at room temperature $t=(22\pm2)°C$ and natural aeration of the solution. After 7 days, the plates were removed, cleaned of corrosion products and weighed again. According to the difference in mass of the plate before and after the test, the corrosion rates in the background (K_0) and inhibited solution (K_{inh}) were calculated and the degree of protection of copper Z was determined by the formula:

$$Z = \left[\frac{(K_0 - K_{inh})}{K_0} \right] \cdot 100\% \tag{4}$$

Results and Discussion

The adsorption of sodium succinate from a borate buffer solution was studied by measuring the ellipsometric angle Δ. The obtained dependence of the angle Δ change on the degree of surface coverage θ is described in Equation (1). Figure 1a shows the dependence of $(-\delta\Delta)$ *vs.* $\log C_{inh}$, obtained in this article for the adsorption of succinate on St3 steel. For comparison, similar dependences are shown for its adsorption on copper and the MNZh5-1 alloy, which we obtained earlier in [44].
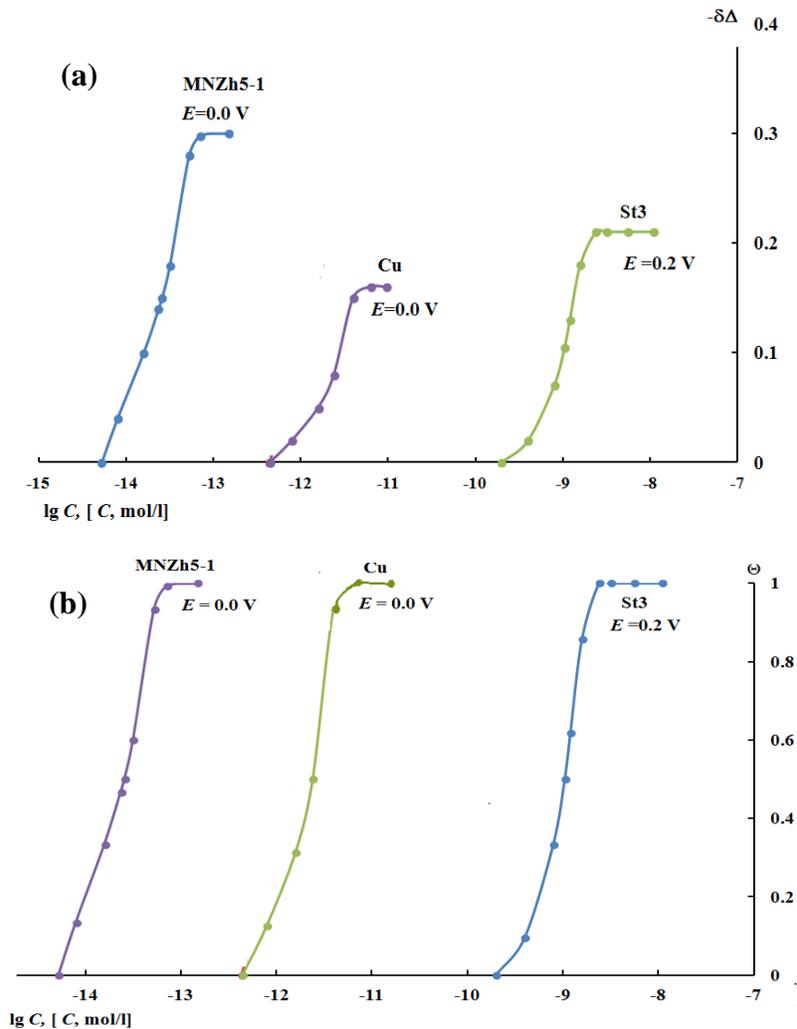

Figure 1. Plots of $(-\delta\Delta)$ *vs.* lg*C* of sodium sussinic anions (a) and plots of θ *vs.* lg*C* (b) on the oxidized surface of metals at the indicated potentials in a borate buffer solution pH 7.4.

The study of the adsorption of sodium succinate on the surface of St3 was carried out at $E=0.2$ V and begins at the highest C_{inh} for all the metals studied ($\log C=-9.7$). At $\log C=-8.62…-7.96$, a conditional monolayer is formed. On the MNZh5-1 alloy, the adsorption of sodium succinate begins in the concentration range $\log C=-14.2$, which is 2 orders of magnitude lower than on copper ($\log C=-12.35$). The calculated values $\left(-\Delta G^0_{a,max}\right)$ for all metals, despite their large difference for St3 and MNZh5-1, are significantly higher than 40 kJ/mol, which suggests a chemical interaction of succinate anions with the oxidized surface of the electrode, *i.e.* their chemisorption (Table 1).

The effect of sodium succinate on the appearance of the anodic polarization curve of copper and the MNZh5-1 alloy in a borate buffer solution with a chloride content of 10 mmol/L was shown by us earlier [44, 50]. Anodic polarization curves of copper and MNZh5-1 alloy with the addition of small concentrations of sodium succinate reduce the anodic dissolution currents. However, as C_{inh} increases, it apparently forms soluble complexes with Cu(I), which prevent passivation of the electrode.

Table 1. Adsorption characteristics of sodium succinate adsorption isotherms on the surface of oxidized metals: minimum and maximum values of B, $\left(-\Delta G^0_{a,min}\right)$, $\left(-\Delta G^0_{a,max}\right)$ and factor f.

Metal, E, V	$B_{i,max}$, mol^{-1}	$B_{i,min}$, mol^{-1}	$\left(-\Delta G^0_{a,min}\right)$, kJ/mol	$\left(-\Delta G^0_{a,max}\right)$, kJ/mol	f
Cu $E=0.0$ V	$6.7\cdot10^{11}$	$1.5\cdot10^{11}$	73.7	77.4	1.49
MNZh5-1 $E=0.0$ V	$8.3\cdot10^{13}$	$2.3\cdot10^{13}$	86.1	89.3	1.26
St3 $E=0.2$ V	$6.6\cdot10^8$	$3.3\cdot10^8$	58.9	60.2	0.70

For copper, the addition of sodium succinate at $C_{inh}=0.5$ mmol/L reduces the anodic passivation current density i_p and increases E_{ld} by almost 0.30 V. However, at $C_{inh}>1.0$ mmol/L i_p increases, and at $C_{inh}=5.0$ mmol/L i_p reaches 120 μA/cm^2.

On low-carbon St3, with increasing succinate concentration, i_p also increases (Figure 2). The value of i_p on St3 in the background solution is 69 μA/cm^2, and with the introduction of 1.0; 2.0; 5.0 and 7.0 mmol/L succinate it increases to 82, 89, 135 and 164 μA/cm^2, respectively. A slight inhibition of anodic dissolution occurs only in the region of local depassivation potential.

The increase in i_p with increasing sodium succinate concentration is associated with the formation of water-soluble complexes, similar to what happened on copper and the MNZh5-1 alloy [44]. However, if there is an oxide on the electrode, succinate can prevent local depassivation of the metal. A similar phenomenon was observed with the effect of sodium benzoate on the anodic dissolution of steel [3].
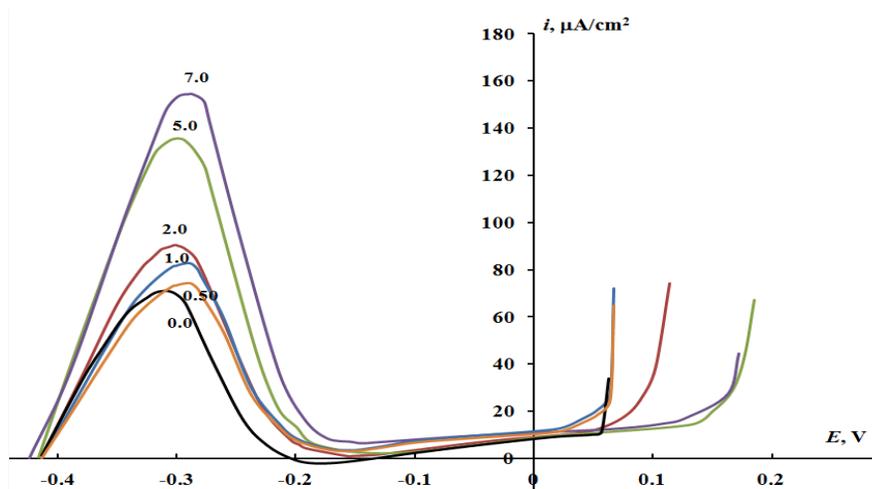
Figure 2. Anodic polarization curves of St3 in a chloride-buffer solution pH 7.4 with addition of sodium succinate. The numbers next to the curves show the C_{inh} values (in mmol/L).

Sodium succinate does not suppress the peak of anodic dissolution of St3 and its adsorption isotherm begins in the region of higher concentrations than on copper or the MNZh5-1 alloy. In order to enhance the protective properties of sodium succinate, we changed the surface preparation for polarization measurements and investigated the possibility of creating mixed CI. Thus, the polarization curves of St3 in a chloride-containing buffer solution were recorded without preliminary reduction at $E=-0.65$ V (Figure 2). The electrode was immersed in the test solution, kept in it for 15 min at the free corrosion potential, then an inhibitor was added and after 15 min the recording of the anodic polarization curve.
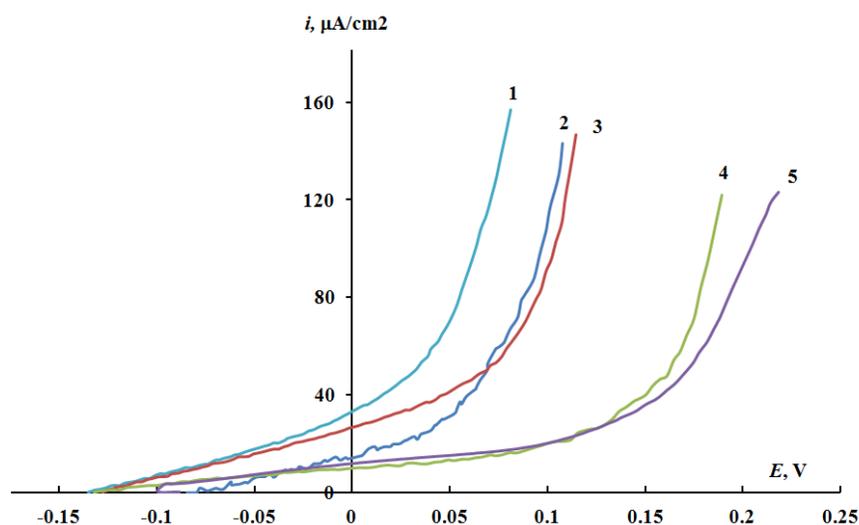

Figure 3. Anodic polarization curves of St3 without preliminary reduction in a borate buffer solution pH 7.4 containing 0.01 M NaCl (1) and sodium succinate with C_{inh} in mmol/L: 2 – 1.0; 3 – 2.0; 4 – 5.0; 5 – 7.0.

As can be seen from Figure 3, the values of E_{cor} and E_{ld} increase with increasing concentration of sodium succinate, up to $C_{inh}=5$ mmol/L. At 7.0 mmol/L, E_{ld} remains virtually unchanged, but unlike an electrode with a pre-reduced surface, *i.e.*, free of oxide, there is no increase in the anodic current density. The maximum protective effect in this case is observed for additives of 5.0 and 7.0 mmol/L sodium succinate and is 0.14 V.

More promising is the use of an alkyl derivative of sodium succinate – SKAP-25, which contains hydrocarbon chains $C_{12}-C_{15}$.

We recently developed an inhibitory composition to protect copper and copper alloy MNZH5-1 from corrosion [44]. It consists of alkylene-substituted sodium succinate – SKAP-25 and 2-MBT in a mass ratio of 7.1:1. This composition suppressed the corrosion of copper ($C_{inh}=1.537$ g/L) and the MNZh5-1 alloy ($C_{inh}=1.685$ g/L) in a 3.5% aqueous solution of NaCl. Spontaneous passivation of the alloy occurs in a chloride buffer solution when 0.0843 g/L SKAP-25 or 0.025 g/L mixture of SKAP-25+2-MBT (7.1:1) is added to the solution.

Figure 4 shows the anodic polarization curves of St3 in a chloride buffer solution with various SKAP-25 additives. Over the entire studied concentration range of 1.0–5.0 mmol/L, there is a decrease in anodic dissolution currents and a shift of E_{ld} to the region of positive values (Figure 4). For the composition of SKAP-25 with 2-MBT (7.1:1), an increase in protective properties of St3 is observed (Figure 5). When $C_{inh}=1.0-2.0$ mmol/L, the anodic current density decreases and E_{ld} increases to 0.08 V. When C_{inh} increases to 3.0 mmol/L, E_{ld} shifts by 0.34 V, which is significantly better than even for a solution with 5.0 mmol/L of the SKAP-25.

Based on the presented results, we can conclude that when inhibiting St3 corrosion in a chloride solution, the best results will be obtained when using SKAP-25 or a composition based on it. Indeed, in corrosion tests, sodium succinate manifests itself as a weak CI: only at $C_{inh}=5.0-7.0$ mmol/L in a 0.01 M chloride solution protects St3 very weakly (degree of steel protection $Z \le 18\%$).

The effectiveness of SKAP-25 and its composition with 2-MBT (7.1:1) is confirmed by corrosion tests of low-carbon steel St3 in 0.01 M NaCl aqueous solution (Table 2). The degree of protection of low-carbon steel by SKAP-25 itself increases from 3 to 68% when C_{inh} increases from 1.0 to 5.0 mmol/L. In the same C_{inh} range, in the case of a mixture of SKAP-25+2-MBT (7.1:1), Z increases from 9 to 99% for 7.0 mmol/L.

The composition of sodium succinate with SKAP-25 (at a 1:1 ratio) increases the degree of protection Z from 63% to 93%, respectively, at 2.0 mmol/L and 7.0 mmol/L. It is interesting that in the latter case the composition contains 3.5 mmol/L of each component, with such a C_{inh}. Z reaches 93%, when succinate itself gives $Z \sim 18\%$, and SKAP-25 about 67%, *i.e.* the mixed CI is more effective than its components.
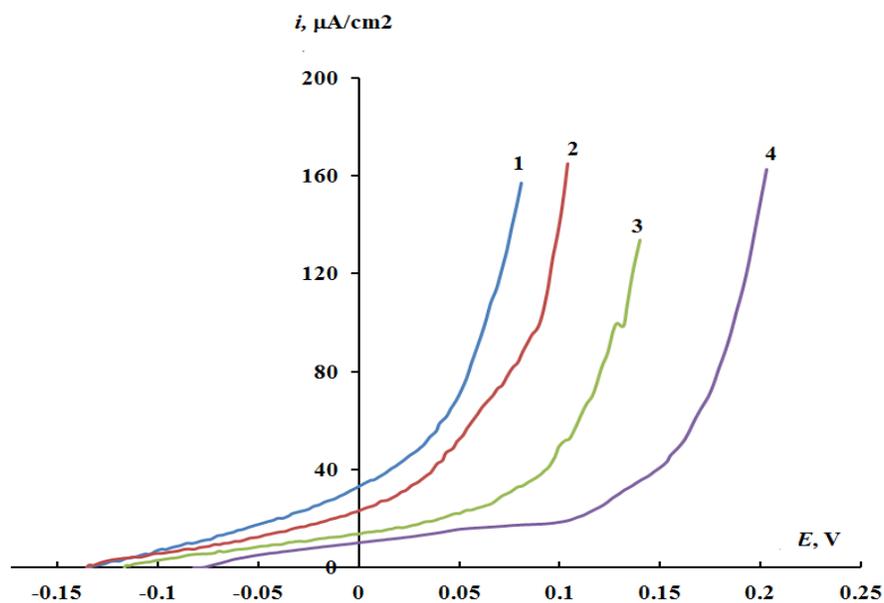
Figure 4. Anodic polarization curves of St3 without preliminary reduction in borate buffer pH 7.4 containing 0.01 M NaCl (1) and SKAP-25 with C_{inh} in mmol/L: 2 − 1.0; 3 − 2.0; 4 − 5.0.
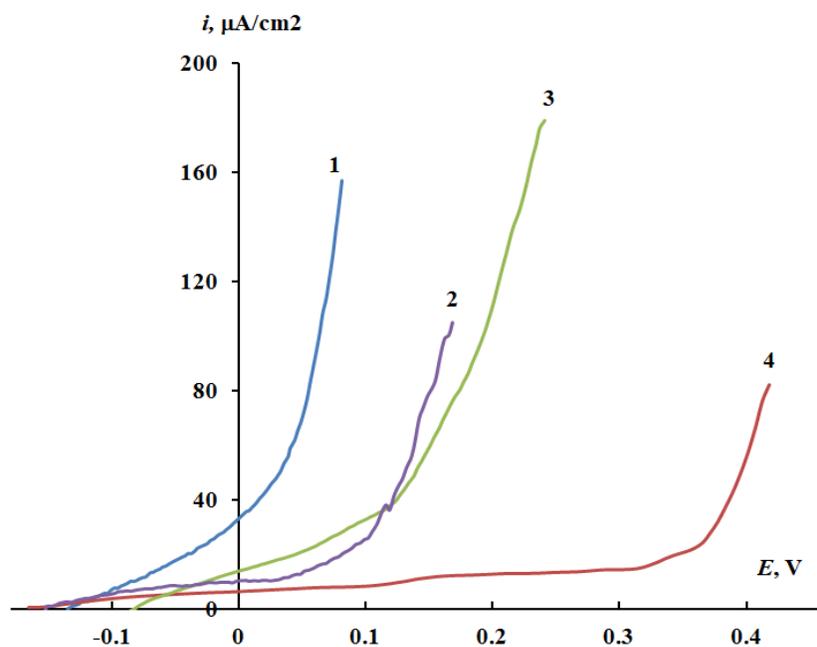

Figure 5. Anodic polarization curves of St3 without preliminary reduction in borate buffer pH 7.4 containing 0.01 M NaCl (1) and SKAP-25+2-MBT (7.1:1) with C_{inh} in mmol/L: 2 − 1.0; 3 − 2.0; 4 − 3.0.

Table 2. Corrosion rate (g/m^2·day), weight loss Δm (g) and degree of protection Z (%) for low-carbon steel St3 with additions of SKAP-25 and their composition with 2-MBT and sodium succinate in 0.01 M NaCl aqueous solution.

Test compound	C_{inh}, mmol/L	Weight loss Δm, g	Corrosion rate K, g/m^2·day	Z (%)	pH
0.01 M NaCl	0.0	0.0279	1.32	–	6.85
SKAP-25	1.0	0.0268	1.27	4	7.15
	2.0	0.0130	0.62	53	7.09
	3.0	0.0091	0.43	67	7.05
	5.0	0.0088	0.42	68	6.92
	6.0	0.0023	0.11	92	6.75
	8.0	0.0004	0.02	98	6.72
	10.0	0.0000	0.0	100	6.68
SKAP-25+2-MBT (7.1:1)	1.0	0.0254	1.21	9	7.19
	2.0	0.0115	0.55	58	7.24
	3.0	0.0072	0.34	75	7.29
	6.0	0.0026	0.12	90	7.42
	7.0	0.0003	0.014	99	7.59
Sodium succinate+SKAP (1:1)	2.0	0.0104	0.49	63	6.96
	5.0	0.0055	0.26	80	7.32
	7.0	0.0022	0.10	93	7.46

Conclusions

1. Adsorption of the sodium succinate on a pre-oxidized metal surface in a borate buffer solution is adequately described by the complete equation of the Temkin isotherm. The values of the standard free adsorption energy $\left(-\Delta G^0_{a,max}\right)$ calculated from this equation are for St3 – 60.2 kJ/mol, copper – 77.4 kJ/mol and its alloy MNZh5-1 – 89.3 kJ/mol. This indicates the chemisorption nature of the interaction of succinate anions with the oxidized surface of metals.

2. When preliminary removing the oxide formed in air from the surface of the electrode, sodium succinate does not facilitate, but rather complicates, the passivation of steel in a solution of borate buffer containing, apparently, due to the formation of a soluble complex with iron cations. At the same time, its adsorption on steel, as well as on copper or its alloy, can prevent local depassivation of the metal to a certain C_{inh}, the excess of which reduces the protective properties of sodium succinate.

3. Polarization measurements on the air-oxidized surface of low-carbon steel St3 showed that sodium succinate, its derivative SKAP-25, as well as their compositions with 2-MBT are able to reduce anodic dissolution currents and prevent local depassivation of steel, the most effective in this is the mixed CIs SKAP-25+2-MBT (7.1:1).

4. Corrosion tests of low-carbon steel St3 in a solution of 0.01 M NaCl showed the advantage of using the SKAP-25 composition with 2-MBT (7.1:1) in comparison with the individual substance. The degree of protection of steel at 7 mmol/L SKAP-25+2-MBT (7.1:1) is 99%. This is higher than for the composition of sodium succinate+SKAP-25 at the same C_{inh}.

References

1. S. Yadav, A.P.S. Raman, M.B. Singh, I. Massey, P. Singh, C. Verma and A. AlFantazi, Green nanoparticles for advanced corrosion protection: Current perspectives and future prospects, *Appl. Surf. Sci. Adv.*, 2024, **21**, 100605. doi: 10.1016/j.apsadv.2024.100605

2. N. Ferraa, M. Ouakki, H. El Harmouchi, M. Cherkaoui and M.B. Ziatni, Investigation of the inhibition behavior of an octacalcium phosphate as a green corrosion inhibitor against carbon steel in 3% NaCl medium, *Inorg. Chem. Commun.*, 2023, **157**, 111343. doi: 10.1016/j.inoche.2023.111343

3. Yu.I. Kuznetsov, A.D. Mercer and J.G.N. Thomas, *Organic Inhibitors of Corrosion of Metals*, 1996, New York, Plenum Press, pp. 283. doi: 10.1007/978-1-4899-1956-4

4. A.M. Semiletov, Protection of aluminium alloys from atmospheric corrosion by thin films of inhibitors, *Int. J. Corros. Scale Inhib.*, 2017, **6**, no. 4, 449–462. doi: 10.17675/2305-6894-2017-6-4-5

5. K. Aramaki, Effects of organic inhibitors on corrosion of zinc in an aerated 0.5 M NaCl solution, *Corros. Sci.*, 2001, **43**, no. 10, 1985–2000. doi: 10.1016/S0010-938X(00)00174-8

6. F.F. Mozheiko, T.N. Potkina and I.I. Goncharik, Effect of inhibitors on corrosion resistance of carbon steel in suspensed liquid combined fertilizer, *Russ. J. Appl. Chem.*, 2008, **81**, 1705–1709. doi: 10.1134/S1070427208090437

7. M. Starostin, G.E. Shter and G.S. Grader, Corrosion inhibition of carbon steel in aqueous solution of ammonium nitrate and urea, *Mater. Corros.*, 2014, **65**, no. 6, 626–636. doi: 10.1002/maco.201206786

8. S.M. Reshetnikov, *Inhibitors of acid corrosion of metals*, 1986, Leningrad, Chemistry, pp. 144 (in Russian).

9. E.S. Ivanov, *Corrosion inhibitors in acidic environments*, Directory, 1986, Moscow, Metallurgy, pp. 175 (in Russian).

10. G. Shmitt, Inhibition in Acid Media, *Working Party Report on Corrosion Inhibitors*, 1994, London: The Institute of Materials, 1–12.

11. N.I. Podobaev and Ya.G. Avdeev, A Review of Acetylene Compounds as Inhibitors of Acid Corrosion of Iron, *Prot. Met.*, 2004, **40**, no. 1, 7–13. doi: 10.1023/B:PROM.0000013105.48781.86

12. Ya.G. Avdeev, Protection of metals in phosphoric acid solutions by corrosion inhibitors. A review, *Int. J. Corros. Scale Inhib.*, 2019, **8**, no. 4, 760−798. doi: [10.17675/2305-6894-2019-8-4-1](10.17675/2305-6894-2019-8-4-1)

13. Ya.G. Avdeev, A.V. Panova and T.E. Andreeva, Features of corrosion and inhibitory protection of steels in acid solutions containing iron (III) salts, Review, *Korroz.: Mater., Zashch.*, 2022, **2**, 1−27 (in Russian). doi: [10.31044/1813-7016-2022-0-2-1-27](10.31044/1813-7016-2022-0-2-1-27)

14. V.V. Burlov, A.I. Altsybeyeva and T.M. Kuzinova, *Corrosion protection system for oil refining equipment*, 2015, Sankt-Peterburg, "Professiya" publishing house, 336 pp. (in Russian).

15. I.A. Gafarov, V.M. Kushnarenko and V.Ye. Bugay, *Corrosion Inhibitors. Vol. 2. Diagnostics and Protection against Corrosion under Stress of Oil and Gas Equipment*, Moscow, Khimiya, 2002, 367 pp. (in Russian).

16. S. Elhady, E.G. Zaki, O.E. El-Azabawy and I. Samy Fahim, Electrochemical evaluation of green corrosion inhibitor based on ground coffee waste in Petroleum fields, *Results Eng.*, 2024, **21**, 101880. doi: 10.1016/j.rineng.2024.101880

17. B. Valdez, M. Schorr, N. Cheng, E. Beltran and R. Beltran, Technological Applications of Volatile Corrosion Inhibitors, *Corros. Rev.*, 2018, **36**, no. 3, 227−238. doi: 10.1515/corrrev-2017-0102

18. I.L. Rozenfel'd and V.P. Persiantseva, *Ingibitory atmosfernoi korrozii (Inhibitors of atmospheric corrosion)*, Moscow, Nauka, 1985 (in Russian), 277 pp. (in Russian).

19. P.D. Donovan, *Protection of Metals from Corrosion in Storage and Transit*, Chichester, Ellis Horwood Limited, 1986, 228 pp.

20. E.M. Agres and A.I. Altsybeeva, On predicting the effectiveness of volatile atmospheric corrosion inhibitors, *Prot. Met.*, 1989, **25**, no. 6, 1009−1012 (in Russian).

21. B.A. Miksic, Use of Vapor Phase Inhibitor for Corrosion Protection of Metal Products, *Reviews on Corrosion Inhibitor Science and Technology*, 1993, Houston, TX, NACE, II-16-1−II-16-13.

22. C. Fiaud, Theory and Practice of Vapour Phase Inhibitors, *Working Party Report on Corrosion Inhibitors*, 1994, London: The Institute of Materials, pp. 1−12.

23. A.Y. Furman, M. Kharshan and C.J. Chandler, Performance and Testing of Vapor Phase Corrosion Inhibitors, *Reviews on Corrosion Inhibitor Science and Technology*, 2004, **3**, NACE International. Houston, TX, 13-1−13-12.

24. A.I. Altsybeeva, V.V. Burlov, N.S. Fedorova, T.M. Kuzinova and G.F. Palatik, Volatile inhibitors of atmospheric corrosion of ferrous and nonferrous metals. II. Prediction of the efficiency of volatile inhibitors of atmospheric corrosion of steel (with Schiff and Mannich bases as examples), *Int. J. Corros. Scale Inhib.*, 2012, **1**, no. 2, 99−106. doi: [10.17675/2305-6894-2012-1-2-099-106](10.17675/2305-6894-2012-1-2-099-106)

25. A.A. Mikhaylov, Yu.M. Panchenko and Yu.I. Kuznetsov, *Atmospheric corrosion and protection of metals (Atmosfernaya korroziya i zashchita metallov)*, 2016, Tambov, Pershin Publishing House, pp. 554 (in Russian).

26. P.A. Akol'zin, *Korroziya i zashchita metalla teploenergeticheskogo oborudovaniya*, 1982, M.: Energoizdat, 304 pp. (in Russian).

27. M. Finšgar and J. Jackson, Application of corrosion inhibitors for steels in acidic media for the oil and gas industry: A review, *Corros. Sci.*, 2004, **86**, 17–41. doi: 10.1016/j.corsci.2014.04.044

28. M.K. Kamat, G.V. Prabhu Gaonkar and A. Raman, VCIs for Protection of Steel in Concrete, *Reviews on Corrosion Inhibitor Science and Technology*, 2004, **3**, NACE International, Houston, TX, 12-1–1-14.

29. Yu.I. Kuznetsov, N.N. Andreev, O.A. Goncharova and A.V. Agafonkin, On the protection of metals from corrosion when moisture condenses on them with volatile inhibitors, *Korroz.: Mater., Zashch. (Corrosion: Materials, Protection)*, 2009, no. 10, 25–29 (in Russian).

30. A.Yu. Luchkin, O.A. Goncharova, N.N. Andreev and Yu.I. Kuznetsov, Steel protection by treatment with octadecylamine, 1,2,3-benzotriazole and mixtures thereof at elevated temperature, *Korroz.: Mater., Zashch. (Corrosion: Materials, Protection)*, 2017, **12**, 20–26 (in Russian).

31. A.Yu. Luchkin, O.A. Goncharova, D.S. Kuznetsov, I.V. Tsvetkova, O.S. Makarova, D.M. Sudorgin, S.S. Vesely and N.N. Andreev, Screening of individual organic compounds as chamber corrosion inhibitors, *Int. J. Corros. Scale Inhib.*, 2022, **11**, no. 1, 257–265. doi: 10.17675/2305-6894-2021-11-1-14

32. O.S. Makarova, A.Yu. Luchkin, O.A. Goncharova and S.S. Vesely, Chamber protection of galvanized steel. IFKhAN-121, IFKhAN-154 and some mixed inhibitors, *Int. J. Corros. Scale Inhib.*, 2022, **11**, no. 2, 762–773. doi: 10.17675/2305-6894-2022-11-2-21

33. O.A. Goncharova, A.Yu. Luchkin, N.N. Andreev, O.Yu. Grafov, O.S. Makarova, I.A. Kuznetsov and S.S. Vesely, Chamber Protection of Zinc with Ethylhexanoic Acid, *Materials*, 2023, **16**, no. 10, 3679. doi: 10.3390/ma16103679

34. A.Yu. Luchkin, O.S. Makarova, O.Yu. Grafov, I.A. Kuznetsov, O.A. Goncharova, N.N. Andreev, Chamber protection of zinc with individual connections. Ethylhexanoic acid, *Korroz.: Mater., Zashch. (Corrosion: Materials, Protection)*, 2023, **1**, no. 2, 49–71 (in Russian).

35. Yu.I. Kuznetsov, Organic corrosion inhibitors: where are we now? A review. Part II. Passivation and the role of chemical structure of carboxylates, *Int. J. Corros. Scale Inhib.*, 2016, **5**, no. 4, 282–318. doi: 10.17675/2305-6894-2016-5-4-1

36. U. Rammelt, S. Koehler and G. Reinhard, Electrochemical characterisation of the ability of dicarboxylic acid salts to the corrosion inhibition of mild steel in aqueous solutions, *Corros. Sci.*, 2011, **53**, no. 11, 3515–3520. doi: 10.1016/j.corsci.2011.06.023

37. U. Rammelt, S. Koehler and G. Reinhard, EIS characterization of the inhibition of mild steel corrosion with carboxylates in neutral aqueous solution, *Electrochim. Acta*, 2008, **53**, 6968–6972. doi: 10.1016/j.electacta.2008.01.004

Int. J. Corros. Scale Inhib., 2024, **13**, no. 2, 1322–1336

1336

38. I.A. Kuznetsov, A.A. Chirkunov, Yu.I. Kuznetsov, Kh.S. Shikhaliev, M.O. Agafonkina, N.P. Andreeva and Yu.A. Kovygin, Protection of copper against corrosion in neutral solutions by salts of 2-alkylmalonic acids, *Int. J. Corros. Scale Inhib.*, 2022, **11**, no. 3, 1407–1417. doi: 10.17675/2305-6894-2022-11-3-29

39. F. Giacomelli, C. Giacomelli, M. Amadori, V. Schmidt and A. Spinelli, Inhibitor effect of succinic acid on the corrosion resistance of mild steel: electrochemical, gravimetric and optical microscopic studies, *Mater. Chem. Phys.*, 2004, **83**, no. 1, 124–128. doi: 10.1016/j.matchemphys.2003.09.013

40. *Inactive Ingredient Search for Approved Drug Products*, Link

41. M.A. Amin, S.S. Abd El-Rehim, E.E.F. El-Sherbini and R.S. Bayoumi, The inhibition of low carbon steel corrosion in hydrochloric acid solutions by succinic acid: Part I. Weight loss, polarization, EIS, PZC, EDX and SEM studies, *Electrochim. Acta*, 2007, **52**, no. 11, 3588–3600. doi: 10.1016/j.electacta.2006.10.019

42. M.A. Deyab and S.S.A. El-Rehim, Effect of succinic acid on carbon steel corrosion in produced water of crude oil, *J. Taiwan Inst. Chem. Eng.*, 2014, **45**, no. 3, 1065–1072. doi: 10.1016/j.jtice.2013.09.004

43. M.O. Agafonkina, I.A. Kuznetsov, N.P. Andreeva and Yu.I. Kuznetsov, Copper protection with sodium salts of lower dicarboxylic acids in neutral aqueous solution, *Int. J. Corros. Scale Inhib.*, 2020, **9**, no. 3, 1000–1013. doi: 10.17675/2305-6894-2020-9-3-13

44. M.O. Agafonkina, I.A. Kuznetsov, Yu.I. Kuznetsov and N.P. Andreeva, Corrosion inhibition of copper and its alloy MNZh5-1 by salts of succinic and alkenylsuccinic acids in chloride solution, *Int. J. Corros. Scale Inhib.*, 2021, **10**, no. 4, 1606–1620. doi: 10.17675/2305-6894-2021-10-4-14

45. GOST 492–2006 Nickel, nickel and copper-nickel alloys processed by pressure. Stamps.

46. R.M. Azzam and N.M. Bashara, *Ellipsometry and Polarized Light*, North-Holland, Amsterdam, 1977, 529 pp.

47. P. Silva-Bermudez, S.E. Rodil and S. Muhl, Albumin adsorption on oxide thin films studied by spectroscopic ellipsometry, *Appl. Surf. Sci.*, 2011, **258**, no. 5, 1711–1718. doi: 10.1016/j.apsusc.2011.10.020

48. L. Wang, C. Zhao, M.H.G. Duits, F. Mugele and I. Siretanu, Detection of ion adsorption at solid–liquid interfaces using internalreflection ellipsometry, *Sens. Actuators, B*, 2015, **210**, 649–655. doi: 10.1016/j.snb.2014.12.127

49. M.O. Agafonkina, N.P. Andreeva, Yu.I. Kuznetsov and S.F. Timashev, Substituted Benzotriazoles as Inhibitors of Copper Corrosion in Borate Buffer Solutions, *Russ. J. Phys. Chem. A*, 2017, **91**, no. 8, 1414–1421. doi: 10.1134/S0036024417080027

50. Yu.I. Kuznetsov, I.A. Kuznetsov and D.B. Vershok, Copper corrosion protection in neutral media by dicarboxylic acid salts, *Int. J. Corros. Scale Inhib.*, 2019, **8**, no. 4, 1022–1034. doi: 10.17675/2305-6894-2019-8-4-13

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