Research Article

Corrosion Inhibition of Carbon Steel in Saline Solution Using Amino Acids

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ABSTRACT

The inhibiting effect of L-serine and L-lysine, that characterized as eco-friendly compounds for corrosion of carbon steel in 3.5% NaCl solution at pH 2 have been investigated at various concentrations and at five temperatures in the range 293-313 K. Potentiodynamic polarization and scanning electron microscopy (SEM) techniques have been used for studying the behavior of the steel alloy in the saline solution. Corrosion of carbon steel in the saline solution became less feasible on increasing L-serine and L-lysine concentrations. Corrosion feasibility on the other hand increased with the rise of temperature. Inhibition efficiency (%Z) values were increased with increasing of the inhibitors concentration and decreased with increasing of temperature. Inhibition processes were summarized by adsorption of inhibitors on the metal surface. Potentiostatic studies show that both inhibitors decrease mainly the anodic process so they considered to be anodic type inhibitors. Adsorption of L-serine and L-lysine on metal surface obeys Langmuir adsorption isotherm. Addition of L-serine and L-lysine to the saline solution enhanced both the activation energy and the pre-exponential factor of the alloy corrosion and the extent became larger with increasing inhibitors concentrations. Quantum mechanical completion using DFT method with B3LYP/6-31G basis set was applied to achieve correlation between the inhibitive effect and molecular structure of L-serine and L-lysine.

Keywords: Corrosion, Carbon Steel, Saline solution, Inhibitor, Adsorption, DFT Calculations.

INTRODUCTION

Corrosion is a surface phenomenon known as the attack of metal with its environment as air, water or soil in electrochemical reaction to form more stable compound[1]. Carbon steel is an important engineering and construction material in the world. Corrosion problems have received a huge amount of interest because of their attack on materials[2]. Inhibitors are chemical substances when added in small amount into a system can protect metals from corroding. Inhibitors can be adsorbing to the substrate, in order to provide protection via the formation of a passive layer and protect metals[1].

Amino acids are important organic compounds consisting of amine ($-NH_2$) and carboxylic acid (-COOH) functional groups, with a side-chain specific to each amino acid.

The essential atoms of an amino acid are carbon, hydrogen, oxygen, and nitrogen, in addition to other atoms are found in the side-chains of certain amino acids[3]. Amino acids form a type of eco-friendly organic compounds which are highly soluble in aqueous media with high purity at low cost. It has the ability to control the corrosion of a awful vary of metals such as pure iron, carbon steel, zinc and tin. It can be used as corrosion inhibitor in acid medium, neutral medium and in deaerated carbonate solution[4].

The aim of the present work is to investigate the inhibiting effect of the L-serine and L-lysine on the corrosion of carbon steel in saline solution at pH 2. The results have been analyzed in view of determining the protection efficiencies of L-serine and L-lysine and on both thermodynamic and kinetic grounds.

MATERIALS AND METHODS

Sample Preparation

The working electrode used in this research was carbon steel set out in its chemical composition in weight percentage (P 0.018, Mo 0.03, Ni 0.017, C 0.19, Si 0.35, Cr 0.04, Cu 0.02, Al 0.06, and the rest iron). Data were provided by the European Corrosion Supplies Ltd (UK).

The electrodes were polished to mirror finish with emery paper in different grades (320, 500, 1000, 2400, 4000) μm with diamond product spray that contain ethanol with different size of diamond particles (1, 3, 6, 9) μm, then washed with ethanol, aceton and finally rinsed with distilled water.

Preparation of Solutions

1. Saline solution, 3.5% NaCl (E. Merck), was prepared by dissolving 35 g of analytical-grade NaCl in 1000 mL distilled water.

2. L-Lysine and L-serine used in the present study are of analytical grade purchased from Sigma Aldrich and used as received without further purification. Inhibition solutions were prepared with four different concentrations (5×10^{-4}, 1×10^{-3}, 5×10^{-3}, and 1×10^{-2})M by dissolving appropriate amount of each amino acid in 1000 mL of 3.5% NaCl solution at pH 2.

3. 1M H_2SO_4 solution was prepared to adjust the pH for saline solution.

Potentiodynamic Polarization Measurements

Potentiodynamic polarization measurements were carried out in a typical three-electrode electrochemical cell with a reference electrode (RE) was Saturated Calomel Electrode (SCE), a platinum electrode as auxiliary electrode and the working electrode (WE) was carbon steel. M Lab (WENKING MLab multichannel and SCI-MLab corrosion measuring system from Bank Electronics-Intelligent controls GmbH, Germany 2007) is a significant advance instrument for electrochemical measurements. M Lab is adjusted by computer desktop Window XP. It is pack up with electrochemical calculation such as Tafel line evaluation.

Quantum Chemical Calculations

Quantum calculations were carried out using Gaussian 09W program package using the density functional theory (DFT) with Beck's three parameter exchange functional along with Lee-Yang-Parr non-local correlation functional (B3LYP) with 6–31G basis set.

The energy of the highest occupied molecular orbital (E_{HOMO}), the lowest unoccupied molecular orbital (E_{LUMO}), energy gap (ΔE), dipole moment (μ), total energy (E_{Total}) of the inhibitor, absolute electronegativity (χ), global hardness(γ) and the fraction of electrons transferred (ΔN) were calculated by using the above given computer code package.

Scanning Electron Microscopy (SEM)

The polished carbon steel specimens were immersed in 3.5% NaCl solutions in the absence and presence of the L-serine and L-lysine at concentration 1×10^{-2} M. After 24 hours, the specimens were taken out, washed with distilled water and dried. The SEM photographs of the surfaces of the specimens were obtained using FEI Inspect-S50 scanning electron microscope.
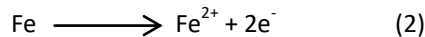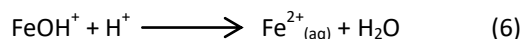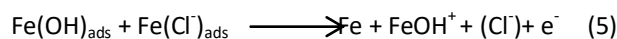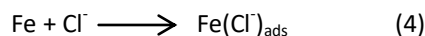
RESULTS AND DISCUSSION

Polarization Curves

The cathodic reaction for metals in aerated solutions is the reduction of oxygen according to[5]:

$$O_2 + 2H_2O + 4e^- \longrightarrow 4OH^- \tag{1}$$
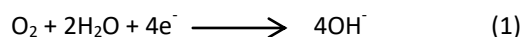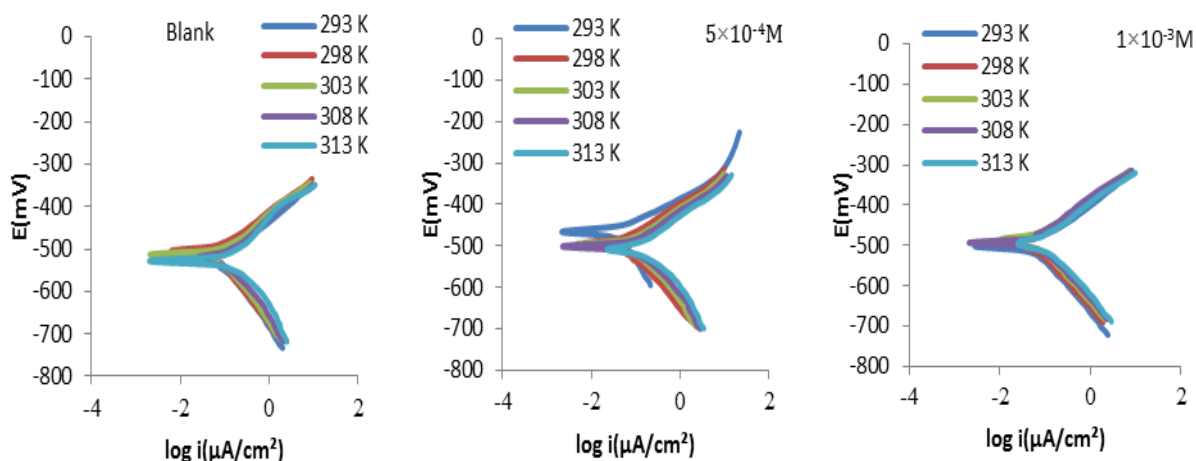
The oxidation reaction for metals consumes the released of electrons from iron, where the corrosion was occur[5]:

$$Fe \longrightarrow Fe^{2+} + 2e^- \tag{2}$$

We can explain the process of dissolution of iron in saline solution into ferrous cation according to the following equations[6]:

$$Fe + H_2O \longrightarrow Fe(OH)_{ads} + H^+ \tag{3}$$

$$Fe + Cl^- \longrightarrow Fe(Cl^-)_{ads} \tag{4}$$

$$Fe(OH)_{ads} + Fe(Cl^-)_{ads} \longrightarrow Fe + FeOH^+ + (Cl^-) + e^- \tag{5}$$

$$FeOH^+ + H^+ \longrightarrow Fe^{2+}_{(aq)} + H_2O \tag{6}$$
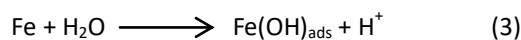
The electrochemical studies for corrosion of carbon steel alloy in uninhibited and inhibited saline solutions at pH 2 are presented in Figures 1 and 2 and the data obtained are listed in Tables 1 and 2.

It is evident from the data presented in tables that the values of E_{corr} for carbon steel are moved towards more positive potentials when L-serine and L-lysine were introduced into the saline solution, and the extent of shift increase with increasing amino acids concentration, that means the L-serine and L-lysin act as anodic inhibitors[7,8].

On the other hand the corrosion current densities (i_{corr}), increased with increasing temperature and decrease with increasing inhibitors concentrations. Values of the both anodic (b_a) and cathodic (b_c) Tafel slopes changed with increasing the concentrations of inhibitors and temperature.

This variation of the Tafel slopes could be interrupted in terms of the variation of the rate- determining step from charge transfer process to either chemical-deposition or to electrochemical desorption in the cathodic reactions and to the variation of the rate-determining step in the metal dissolution reaction[9].

Figure 1: Polarization curves for the corrosion of carbon steel in 3.5% NaCl at pH 2 in absence and presence of L-serine at different concentrations with various temperatures in the range (293-313) K.
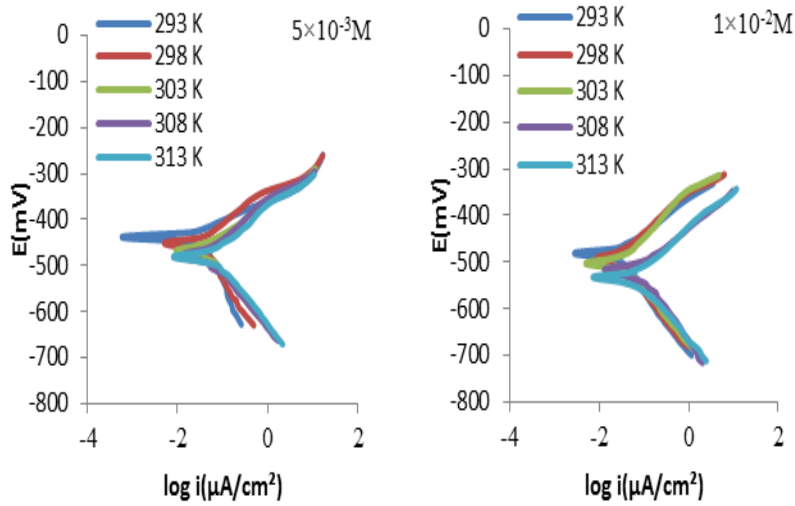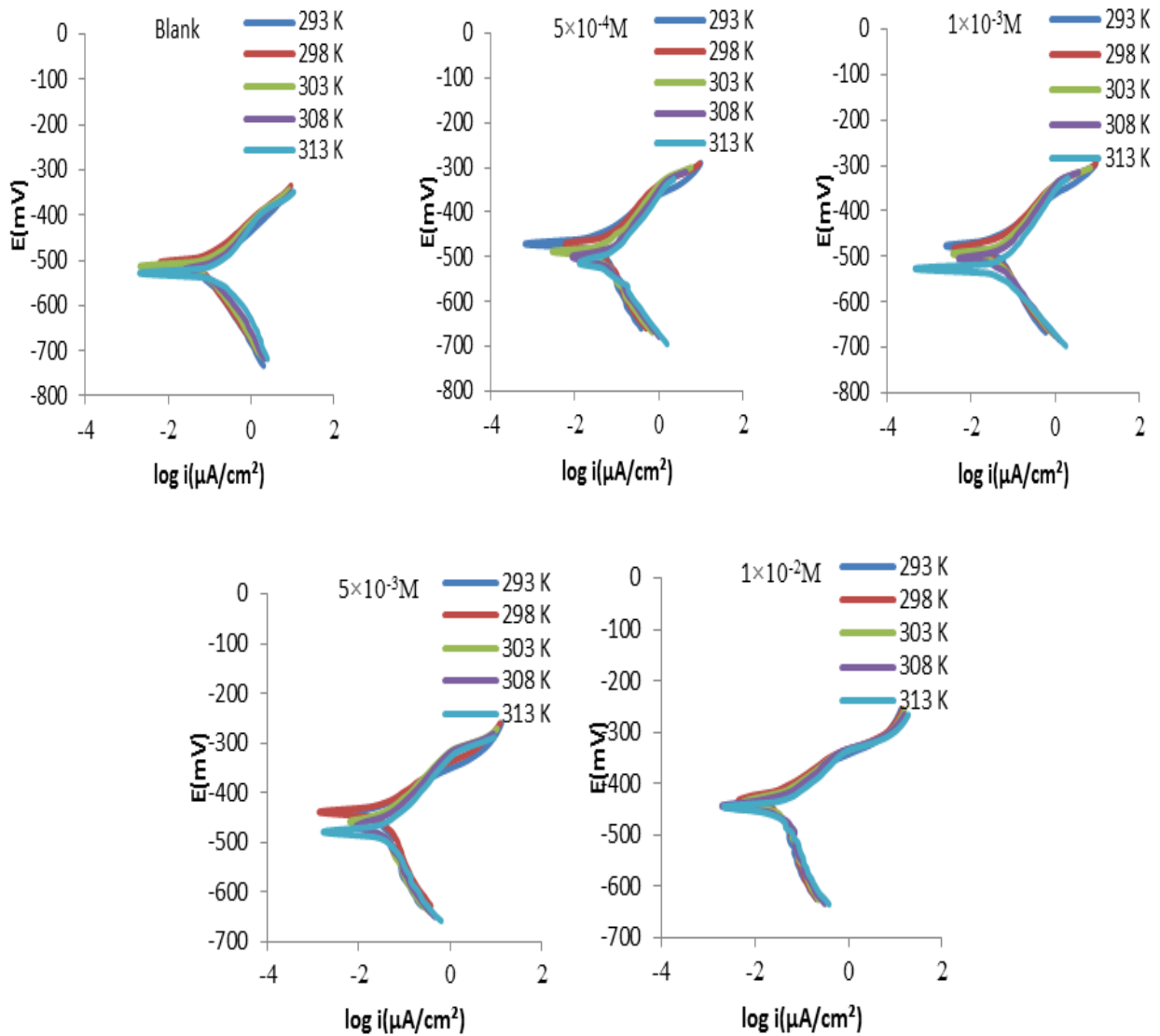

Figure 2: Polarization curves for the corrosion of carbon steel in 3.5% NaCl at pH 2 in absence and presence of L-lysine at different concentrations with various temperature in the range (293-313) K.

Table 1: Corrosion parameters of carbon steel in 3.5% NaCl at pH 2 in absence and presence of L-serine at different concentrations (5×10^{-4}, 1×10^{-3}, 5×10^{-3} and 1×10^{-2})M with various temperatures in the range (293-313) K.

Inh. Con.	T (K)	-E$_{cor}$ (mV)	i$_{corr}$ (μA/cm²)	Tafel Slope (mV/dec)		θ	%Z
				-b$_c$	+b$_a$		
Blank	293	507.1	51.09	92.5	62.6	-	-
	298	513.9	55.67	136.7	73.2	-	-
	303	516.8	66.99	120.9	81.3	-	-
	308	525.8	87.14	107.0	95.1	-	-
	313	530.3	92.28	103.5	91.9	-	-
5×10^{-4} M	293	485.2	33.76	151.9	50.7	0.339	33.92
	298	490.9	37.71	93.10	70.0	0.323	32.26
	303	499.1	46.67	77.90	63.4	0.303	30.33
	308	503.6	60.42	86.60	73.0	0.307	30.66
	313	509.7	67.31	75.30	66.7	0.271	27.06
1×10^{-3} M	293	490.3	25.50	53.90	51.8	0.501	50.09
	298	492.7	30.48	78.70	58.6	0.453	45.25
	303	494.9	37.43	75.50	68.7	0.441	44.13
	308	496.4	49.64	96.60	85.1	0.430	43.03
	313	497.1	53.15	89.00	73.9	0.424	42.40
5×10^{-3} M	293	437.7	23.10	118.0	50.4	0.548	54.79
	298	453.7	27.17	120.1	78.4	0.512	51.19
	303	463.9	32.85	111.3	64.8	0.510	50.96
	308	475.8	43.08	114.3	87.4	0.506	50.56
	313	479.4	50.18	116.6	71.7	0.456	45.62
1×10^{-2} M	293	480.2	19.30	99.70	58.2	0.622	62.22
	298	491.3	25.41	127.7	86.0	0.544	54.36
	303	502.5	30.70	118.4	95.9	0.542	54.17
	308	520.8	40.73	64.70	61.7	0.533	53.26
	313	533.8	47.41	89.40	73.4	0.486	48.62

Table 2: Corrosion parameters of carbon steel in 3.5% NaCl at pH 2 in absence and presence of L-lysine at different concentrations (5×10^{-4}, 1×10^{-3}, 5×10^{-3} and 1×10^{-2}) M with various temperature in the range (293-313) K.

Inh. Con.	T (K)	-E$_{corr}$ (mV)	i$_{corr}$ (μA/cm²)	Tafel Slope (mV/dec)		θ	%Z
				-b$_c$	+b$_a$		
Blank	293	507.1	51.09	92.5	62.6	-	-
	298	513.9	55.67	136.7	73.2	-	-
	303	516.8	66.99	120.9	81.3	-	-
	308	525.8	87.14	107.0	95.1	-	-
	313	530.3	92.28	103.5	91.9	-	-
5×10^{-4} M	293	469.7	27.16	127.6	74.40	0.468	46.84
	298	475.0	32.03	136.9	80.70	0.425	42.46
	303	487.6	38.63	164.8	91.40	0.423	42.33
	308	500.6	51.00	147.8	111.6	0.415	41.47
	313	515.4	57.01	126.9	115.6	0.382	38.22
1×10^{-3} M	293	471.9	22.93	141.0	57.00	0.551	55.12
	298	482.4	27.76	122.5	85.90	0.501	50.13

Con.	T						
	303	493.2	33.75	131.4	92.70	0.496	49.62
	308	507.5	44.38	129.2	121.6	0.491	49.07
	313	528.6	49.40	160.4	131.8	0.465	46.47
5×10^{-3} M	293	433.2	19.76	106.5	57.10	0.613	61.32
	298	437.7	25.61	148.4	64.70	0.540	54.00
	303	458.7	30.90	208.2	99.90	0.539	53.87
	308	469.2	41.24	240.6	112.4	0.527	52.67
	313	477.1	45.25	203.7	112.6	0.510	50.96
1×10^{-2} M	293	431.4	16.47	101.9	54.20	0.678	67.76
	298	434.1	21.89	153.7	65.00	0.607	60.68
	303	437.8	28.18	196.6	66.10	0.579	57.93
	308	440.8	37.47	252.5	77.70	0.570	57.00
	313	448.2	43.80	214.5	89.20	0.525	52.54

Table 3: Activation energy (E_a), activation ethalpy (ΔH_a) and activation entropy (ΔS_a) for the corrosion of carbon steel in 3.5% NaCl aqueous solution in the absence and presence of different concentration of L-serine and L-lysine at different temperatures (293, 298, 303, 308 and 313) K and thermodynamic parameters for adsorption of the inhibitors L-serine and L-lysine on the surface of carbon steel in 3.5% NaCl solution.

Inh.	Con. [M]	E_a [kJ.mol^{-1}]	A [mole.cm^{-2}.s^{-1}]	ΔH_a [kJ.mol^{-1}]	$-\Delta S_a$ [J.K^{-1}.mol^{-1}]	Inh.	T [K]	K_{ads} [M^{-1}]	$-\Delta G_{ads}$ [kJ.mol^{-1}]	ΔS_{ads} [J.K^{-1}.mol^{-1}]	$-\Delta H_{ads}$ [kJ.mol^{-1}]
Blank	-	24.86	0.80	22.34	250.97	L-serine	293	1369.86	27.38		
L-serine	5×10^{-4}	28.22	2.11	25.70	242.93		298	1666.67	28.33		
	1×10^{-3}	30.39	3.97	27.86	237.67		303	1470.59	28.49	105.8	3.475
	5×10^{-3}	30.67	3.98	28.15	237.65		308	1515.15	29.04		
	1×10^{-2}	34.64	17.7	32.12	225.26		313	1612.90	29.67		
L-lysine	5×10^{-4}	29.71	3.17	27.19	239.53	L-lysine	293	2083.33	28.40		
	1×10^{-3}	30.59	3.88	28.06	237.85		298	1851.85	28.59		
	5×10^{-3}	32.59	7.83	30.07	232.03		303	2325.58	29.65	142.5	13.57
	1×10^{-2}	38.09	62.1	35.56	214.81		308	2380.95	30.19		
							313	2857.14	31.16		

Surface Coverage and Inhibition Efficiency

Values of inhibition efficiency (%Z) and surface coverage (θ) of the carbon steel in 3.5% NaCl in the presence of L-serine and L-lysine and with different temperatures were calculated by using equations 7 and 8 respectively and the results are given in Tables 1 and 2.

$$Z\% = \frac{i_{uninh} - i_{inh}}{i_{uninh}} \times 100 \qquad (7)$$

$$\theta = \frac{i_{uninh} - i_{inh}}{i_{uninh}} \qquad (8)$$

where i_{uninh} and i_{inh} are the corrosion current densities in the absence and presence of inhibitors respectively[10].

The results of Tables 1 and 2 indicate that the values of protection efficiency increased with increasing L-serine and L-lysine concentrations in the saline solution.

This indicates that the inhibition of corrosion of steel by inhibitors is due to their adsorption on the metal surface, that may be physisorption or chemisorption depending on the molecular structure and solubility of L-serine and L-lysine[4].

Corrosion Kinetic Parameters

In order to explain the effect of temperature on the corrosion process and examine the mechanism of inhibition, Arrhenius equation has been used:

$$log\,i_{corr} = \frac{-E_a}{2.303\,R\,T} + logA \qquad (9)$$

Where E_a is the activation energy, R is the gas constant, T is the absolute temperature, A is the pre-exponential factor and i_{corr} is the corrosion current density. Arrhenius plots for the corrosion current density of carbon steel in the absence and presence of L-serine and L-lysine in 3.5% NaCl solution are shown in Figure 3. Values of activation energy are calculated from the slope of log i_{corr} versus 1/T plots and tabulated in Table 3. It is noted that the activation energy (E_a) is higher in the presence of the inhibitors than in blank solution, and it increases with increasing the inhibitors concentrations. Such an increase

in the values of E_a indicates the inhibiting effect of L-serine and L-lysine on the corrosion of carbon steel in saline solution. A replacement formulation of Arrhenius equation is

$$i_{corr} = \left(\frac{RT}{Nh}\right) exp\left(\frac{\Delta s_a}{R}\right) exp\left(\frac{-\Delta H_a}{RT}\right) \qquad (10)$$

Where h is planks constant, N is Avogadro's number, ΔS_a is the entropy of activation energy and ΔH_a is the enthalpy of activation energy. Arrhenius equation will transition into:

$$ln\,i_{corr} = \left(\frac{-\Delta H_a}{R}\right)\left(\frac{1}{T}\right) + \left[ln\left(\frac{R}{Nh}\right) + \left(\frac{\Delta S_a}{R}\right)\right] \qquad (11)$$

Values of the activation enthalpy (ΔH_a) are calculated from the slopes ($-\Delta H_a/R$) of linear relationship between Ln (i_{corr}/T) versus $1/T$, while the activation entropy (ΔS_a) is obtained from the intercepts [Ln (R/Nh) + ($\Delta S_a/R$)], the higher values of (ΔH_a) and (ΔS_a) in presence of inhibitors than blank due to the covered surface by inhibitor molecules (occurs adsorption)[11]. The data obtain are listed in Table 3 and the plots of Ln (i_{corr}/T) versus $1/T$ are shown in Figure 3.

Thermodynamic Adsorption Parameters

The adsorption process of the inhibitors affected by many factors, such as nature of the corrosive medium, pH, temperature, concentration of the inhibitor and its functional groups present in the molecule[12]. To determine the effect of inhibitor concentration on the corrosion rate, it is common usage to acceptable rate data to equilibrium adsorption expressions such as Langmuir equation[13]:

$$\left(\frac{C_{inh}}{\theta}\right) = \frac{1}{K_{ads}} + C_{inh} \qquad (12)$$

Where θ is the surface coverage, C_{inh} is the inhibitor concentration and K_{ads} is the equilibrium constant for the adsorption process. The values of K_{ads} were calculated from the intercept of linear relationship between C_{inh}/θ vs. C_{inh}[13], these data listed in Table 3. The standard free energy of adsorption, ΔG_{ads}, on the surface of carbon steel is regarding to the K_{ads} with the following equation:

$$\Delta G°_{ads} = -RT ln(55.5 K_{ads}) \qquad (13)$$

where 55.5 is the value of water concentration in solution expressed in molar. However, the adsorption of molecules on metal surfaces cannot be assumed as a purely physical or chemical phenomenon.

In addition to the chemical adsorption the inhibitor molecules can be adsorbed on the metal surface by physical interactions[14]. Generally, ΔG_{ads} values of -20 kJ.mol^{-1} or above are related with an electrostatic interaction between charged molecules of inhibitor and charged metal surface (physisorption); while those of -40 kJ.mol^{-1} or below involve charge transferring from the inhibitor molecules to the metal surface to form a coordinate covalent bond, (chemisorption)[15]. The values of ΔG_{ads} are listed in Table 3 ranged from (-31.16 to -27.38) kJ.mol^{-1}. This refered that the adsorption of L-serine and L-lysine is mixed physisorption and chemisorption. The adsorption of the inhibitors on the metal surface facilitated by the presence of hetero atoms nitrogen and oxygen. The inhibition prossece involves the formation of chelate on the metal surface, which occures by the transfer of electrons from the amino acids to the surface of the metal and then formation of a coordinate covalent bond. The metal plays as an electrophile while the inhibitor is nucleophilic[16]. For the certification of physisorption, chemisorptions or mixed, the standard enthalpy change (ΔH^0_{ads}) and standard enthalpy change (ΔS^0_{ads}) for the adsorption of inhibitors were determined from the equation:

$$\Delta G_{ads} = \Delta H_{ads} - T\Delta S_{ads} \qquad (14)$$

The plot of ΔG^0_{ads} versus T was linear have intercept equal to ΔH^0_{ads} value and slope equal to ΔS^0_{ads} value as listed in Table 3[17]. The values of free energy of adsorption (ΔG_{ads}) were calculated and given in Table 3. The negative values of ΔG_{ads} indicate that the adsorbed layer is stable on the carbon steel surface and spontaneity of the adsorption process. ΔG_{ads} may increase with the increase in temperature that indicates the state of exothermic process. ΔG_{ads} may decrease with increasing temperature indicating the state of endothermic process[18]. The entropy change (ΔS_{ads}) is positive that indicates an increase in randomness at the adsorption process[19].

Mechanism of Inhibition of Amino Acids

The inhibition process may be summarized by adsorption of the L-serine and L-lysine molecules on the alloy surface. The atoms of O and N from L-serine and L-lysine molecules act as active sites for the process of adsorption on the surface.

Availability of lone pairs in these atoms (O and N) expedites electrons transfer from the amino acids to the metal. In this case, coordinate covalent bonds may be formed (chemisorption). The strength of these bonds depends on the electron density and polarizability of the donor atom of the functional group[2].

Quantum Chemical Calculation

In last few decades' quantum chemical calculation depended on the DFT theory have been suggested as a way for calculating a number of molecular parameters which are directly concerning to inhibition efficiency of any chemical inhibitor. We can calculate from fully optimized structures of L-serine and L-lysine the energy of highest occupied molecular orbital (E_{HOMO}), the energy of lowest unoccupied molecular orbital (E_{LUMO}) that, the energy band gap (ΔE), and the dipole moment (μ)[20]. The following equations were used for the calculations of quantum chemical parameters[21]:

$$\chi = \frac{(E_{LUMO} + E_{HOMO})}{2} \qquad (15)$$

$$\gamma = \frac{(E_{LUMO} - E_{HOMO})}{2} \qquad (16)$$

The fraction of electrons transferred (ΔN) can be calculated by using the equation[21]:

$$\Delta N = \frac{(\chi_{Fe} - \chi_{inh})}{2(\gamma_{Fe} + \gamma_{inh})} \qquad (17)$$

Where $\chi Fe \approx 7.0$ eV is a theoretical value of iron and $\eta Fe = 0$.

Studies have shown that the adsorption of the inhibitor on the metal surface basis of donor–acceptor interactions between the π-electrons of the molecules and the empty d-orbital of the metal surface atoms[22].

High value of E_{HOMO} of the molecules indications its tendency to donate electrons to acceptor molecules at low energy empty molecular orbitals.

The lower value of E_{LUMO} means its ability to accept electrons. Increasing values of E_{HOMO} show enhance the inhibition efficiency[23]. ΔE_{gap} is the test of reactivity of the inhibitor molecule towards the adsorption on metallic surface.

When ΔE_{gap} decreases the reactivity of the molecule increases and then increase the inhibition efficiency of the molecule.

Dipole moment (μ) is the non-uniform distribution of charges on the atoms in the molecule. The high value of μ increases the adsorption between the chemical compound and the metal surface[24]. The fraction of electrons transferred (ΔN) can be used as indication of the ability of the molecule to donate electrons, until to bind on the metal surface. The molecule that has the highest value of transfer electrons is considered to have the highest tendency to interact with the metal surface[25]. From these calculated parameters can be concluded that L-lysine have more protection efficiency than L-serine and its protection efficiency in eqeouse phase best than in gas phase. Parameters calculated above for L-serine and L-lysine are given in Table 4.
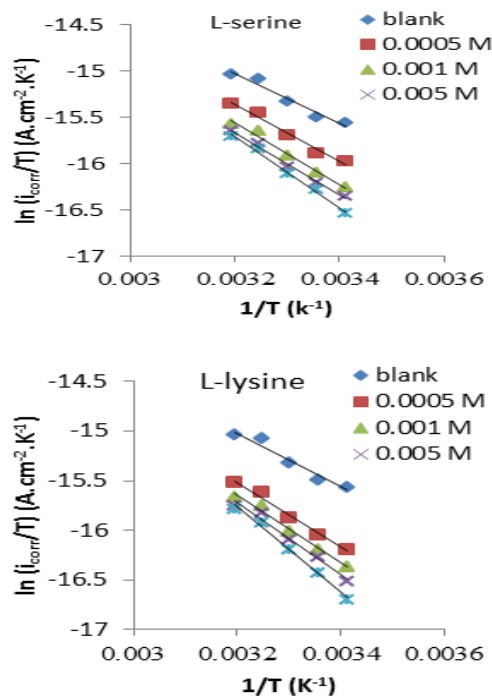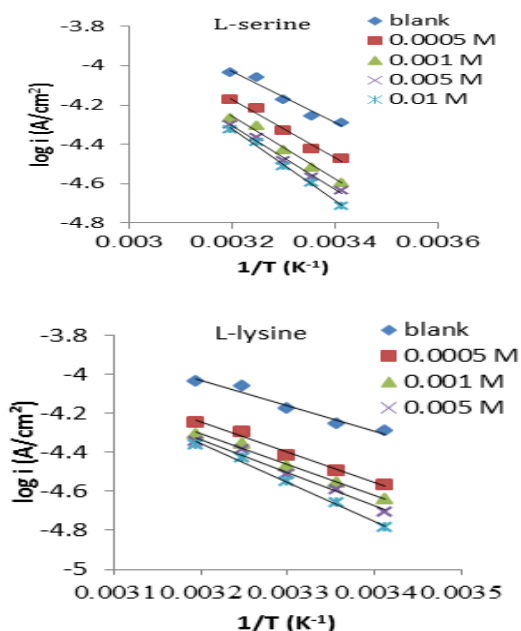

Figure 3: Arrhenius plots of log i_{corr} versus 1/T and ln (i_{corr}/T) versus 1/T for carbon steel in 3.5% NaCl aqueous solution in the absence and the presence of different concentrations of L-serin and L-lysine.

Table 4: Quantum Parameters of L-serine and L-Lysine in gas and aqueous phase.

Terms	L-serine		L-lysine	
	Gas Phase	Aqueous Phase	Gas Phase	Aqueous Phase
-E_{LUMO} (ev)	0.3494	0.2033	0.6803	0.4963
-E_{HOMO} (ev)	6.5263	6.1336	6.2307	6.0358
ΔE (ev)	6.1769	5.9303	5.5504	5.5395
μ (Debye)	2.2437	2.9643	3.2929	2.0624
-$E_{total} \times 10^4$ (kcal.mol)	25.033	24.896	31.188	31.187
χ (ev)	3.4378	3.1684	3.4555	3.2660
γ (ev)	3.0884	2.9652	2.7752	2.7698
ΔN (ev)	0.5767	0.6461	0.6386	0.6740

Scanning Electron Microscopy (SEM)

The SEM images of carbon steel specimens immersed in different solution for 24 hours in the absence and presence of inhibitors are shown in Figure 4.

The SEM micrographs of polished carbon steel surface in Figure (a) show the smooth surface of the metal without any corrosion products than the uninhibited surfaces in 3.5% NaCl solution in Figure (b) and in 3.5% NaCl solution at PH 2 in Figure (c).

Figures (d and e) shows that there was much less damage on the carbon steel surface in the presence of 1×10^{-2} M of L-serine and L-lysine respectively. This explains the

adsorption of L-serine and L-lysine on the carbon steel surface by the formation of protective film.

Energy Dispersive X-ray Spectroscopy (EDX)

EDX realizations were carried out in order to distinguish the composition of the species formed on the metal surface in 3.5% NaCl solution at PH 2 in the absence and presence of L-serine and L-lysine.

The atomic percentage of the elements presence in the EDX profile for the corroded surface of carbon steel in 3.5% NaCl solution at PH 2 is 22.35% O, 0.73% Si, 1.05% S, 3.24% Na and 71.29% Fe as shown in Figure (4) (c), this indicates that the corrosion occurs due to the formation of iron oxide on the metal surface.

In 3.5% NaCl solution at PH 2 in presence of L-serine the atomic percentage of the elements is 20.93% O, 0.39% Si and 78.43% Fe as shown in figure (4) (d).

In 3.5% NaCl solution at PH 2 in presence of L-lysine the atomic percentage of the elements is 18.30% O, 0.21% Si, 22.06% C and 82.62% Fe as shown in Figure (4) (e), this indicated the formation of inhibitor film in this area.
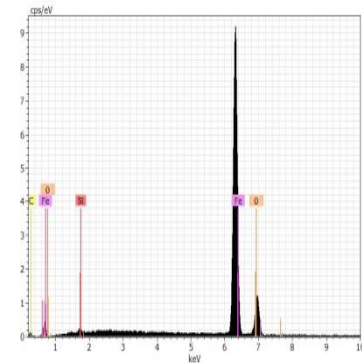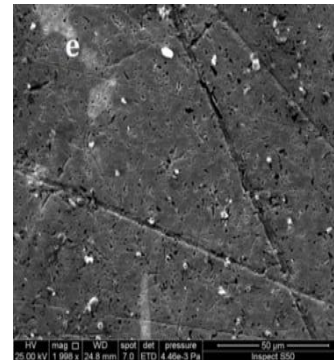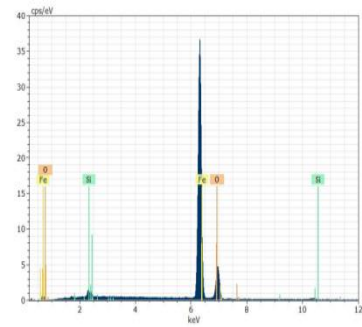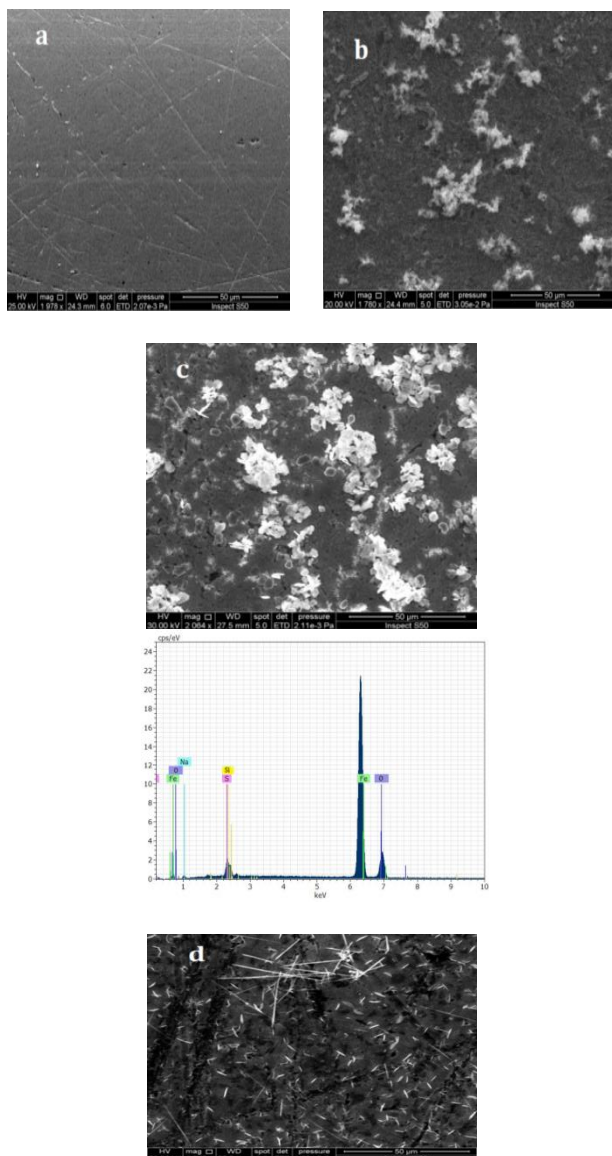

Figure 4: Scanning electron micrographs of (a) Polished carbon steel alloy, (b) 3.5% NaCl solution, (c) 3.5% NaCl solution at pH 2 (d) in presence of 1×10^{-2} M L-serine and (e) in presence of 1×10^{-2} M L-lysine respectively. And EDX spectra of (c) in 3.5% NaCl solution at pH 2 (d) in presence of 1×10^{-2} M L-serine and (e) in presence of 1×10^{-2} M L-lysine respectively.

CONCLUSION

1. Results gained from potentiodynamic polarization technique show that L-serine and L-lysine acts as effective inhibitors for carbon steel dissolution in 3.5% NaCl solution at pH 2.

2. Inhibition efficiency increases with increasing the concentration of inhibitors as well as with decreasing the temperature. The efficiency of inhibition of corrosion by both amino acids under study depends on their molecular structure. It increases in the order: L-Serine **<** L-Lysine.

3. L-Lysine is the best inhibitor of corrosion of carbon steel in saline solution.

4. Corrosion inhibition can be attributed to adsorption of the molecules by interaction of the iron with

nitrogen and oxygen atoms; this forms a barrier blocking corrosion of the carbon steel.

5. Adsorption of the inhibitors on carbon steel surface obeys langmuir isotherm.

6. Values of ΔG_{ads} indicate that the adsorption process of inhibitors on the carbon steel surface was spontaneous.

7. SEM micrographs of polished carbon steel surface show the smooth surface of the metal without any corrosion products than the uninhibited surface, while the carbon steel surface with inhibitors shows that there was much less damage on the surface.

8. Results obtained from electrochemical and quantum chemical studies were in good agreement.

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