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Inhibition effect of 4-hydroxyquinoline-2-carboxylic acid on corrosion of mild steel in 1M sulphuric acid solution

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ABSTRACT

The inhibition effect of 4-hydroxyquinoline-2-carboxylic acid was tested against mild steel in 1M H_2SO_4 solution by weight loss method, Electrochemical Impedance Spectroscopy (EIS) and Tafel polarization studies. From these studies the concentration of the inhibitor increases, inhibition action also increases. The inhibitor showed 87 % of inhibition efficiency at the optimum concentration of 300 ppm in weight loss method. The increase of inhibiting effect is also proved by EIS studies, because it shows 89 % of inhibition efficiency. A Tafel polarization curve indicates the used inhibitor is a mixed-type. Inhibitor is adsorbed on the mild steel surface followed by Langmuir adsorption isotherm. Surface morphology of the mild steel was analyzed using Scanning Electron Microscope (SEM) and Atomic Force Microscope (AFM) studies.

Keywords: Acid inhibitor; Weight loss; EIS; SEM; AFM.

INTRODUCTION

Corrosion is a dangerous electrochemical reaction, which is harmful to metals and alloys. Every year million metric tones of metals and alloys are wasted due to corrosion. It is a natural phenomenon, which we cannot completely avoid corrosion but we can control by suitable preventive methods like metallic coatings, anodic protection, cathodic protection and using inhibitors. The use of inhibitor is one of the important practical methods for protection of metals and alloys against corrosion, especially in acidic media [1-3]. Inhibitors are organic or inorganic substances, which decrease the rate of corrosion. Usually very small quantities of inhibitors are added to the corrosive medium. Selection and application of inhibitor is subject to its cost, toxicity, availability and efficiency to inhibit corrosion. Previous research has shown that most of the high performance inhibitors are organic compound containing nitrogen, oxygen, sulphur and/or phosphorous and multiple bonds, which are easily adsorbed on the surface of substances (metals/alloys) [4-5]. Moreover, many N-hetero cyclic compounds have been proved to be effective inhibitors due to the presence of a $> C = N –$ group in molecules for the corrosion of metals and alloys in acid media [6-8]. The lone pair of electron present on 'N' atom is the important structure features that determine the adsorption of this molecule on the metal surface [9]. The commercial name of used inhibitor is kynurenic acid. It is a small molecule, so effectively cover more surface area (due to adsorption) of the metal. The molecular mass of the inhibitor is 189.17 g/mol and the molecular formula is $C_{10}H_7NO_3$. It contains a large number of donating atoms like Nitrogen and Oxygen.

The aim of this work is to study the inhibition effect in the absence and presence of various concentrations of kynurenic acid on corrosion of mild steel in 1M sulphuric acid solution, using different experimental techniques, such as weight loss method, electrochemical impedance spectroscopy and potentiodynamic polarization method.

The surface morphology of the mild steel is also examined by scanning electron microscope and atomic force microscope.

EXPERIMENTAL SECTION

Materials Preparation

Mild steel specimens having the composition of (wt. %) 0.104 % C, 0.58 % Mn, 0.035 % P, 0.026 % S and the balance Fe. For the weight loss studies mild steel materials were mechanically cut into the specimens size of 3.5 x 1.5 x 0.2 cm. An electrochemical study, the size of the electrode mild steel was exposed surface area of 1cm^2 and the rest being covered by using commercially available resin. The surfaces of all the specimens (both weight loss and electrochemical studies) were polished with various grades of emery polishing papers like 1/0, 2/0, 3/0, 4/0, 5/0, 6/0 and 7/0 then degreased with AR grade acetone and finally dried. The acid solutions were prepared using analytical grade 97 % H_2SO_4 and bi-distilled water.

Inhibitor Preparation

The organic compound kynurenic acid was purchased from SIGMA-ALDRICH and used as inhibitor. The chemical structure, optimized structure, IUPAC name and commercial name of the used inhibitor is shown in ***Figure 1***. Stock solutions were made in 1 gm of inhibitor was dissolved in 1000 ml of 1M H_2SO_4 solution. These solutions were used for all experimental purposes. From these, 5 ml of stock solutions are taken in 100 ml standard measuring flask and makeup to 100 ml solution with the help of 1M H_2SO_4, this solution is known as 50 ppm (5 ml stock solution + 95 ml 1M H_2SO_4 solution) inhibitor solution and without inhibitor solution (1M H_2SO_4) is taken as blank for comparison. The various concentrations of inhibitor on the weight loss method and electrochemical study were taken in PPM (Parts Per Million) by weight [10].

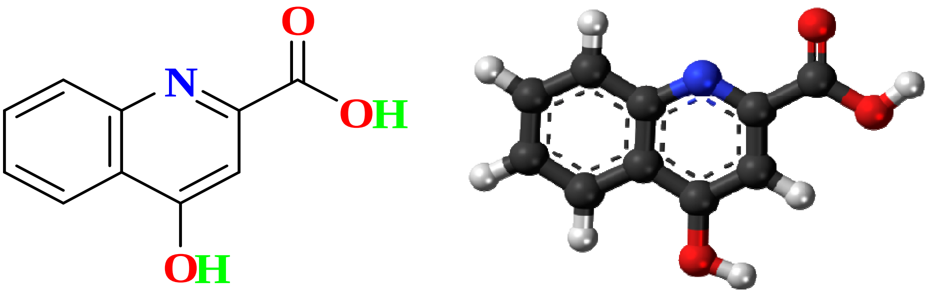

Figure 1. Chemical structure, optimized structure of the Inhibitor, IUPAC name: 4-Hydroxyquinoline-2-carboxylic acid and Commercial name of the used inhibitor: Kynurenic acid

Weight loss studies

Weight loss studies were done according to the method described previously [11-12]. In this method the mild steel specimens were immersed 3 hours in 100 ml aerated 1M H_2SO_4 solution in the absence and presence of various concentrations of inhibitor. All the above tests were conducted at room temperature. After the immersion time the specimens were taken out and washed carefully with AR grade acetone, dried and then weighed accurately. Experiments were also carried out in duplicate and the mean value of the weight loss was reported. From this study, the corrosion rate (W) was calculated by using following equation:

$$\text{C.R.} = W = \frac{m_1 - m_2}{St} \qquad (1)$$

where, m_1 is the mass of the mild steel specimen before corrosion, m_2 is the mass of the mild steel specimen after corrosion, S is the total surface area of the mild steel specimen, t is the time of corrosion and W is the rate of corrosion. The inhibition efficiency (IE %) and surface coverage (θ) was determined by using the following equation [13]:

$$\mathrm{IE}\ (\%) = \left[\frac{W_o - W_i}{W_o}\right] \times 100 \qquad (2)$$

$$\theta = \left[\frac{W_o - W_i}{W_o}\right] \qquad (3)$$

where, W_o is the rate of corrosion in the absence of inhibitor and W_i is the rate of corrosion in the presence of inhibitor.

Electrochemical studies

Two electrochemical techniques (AC-EIS and DC-Tafel Plot) were used to study the corrosion behavior of mild steel in the absence and presence of various concentrations of inhibitor in 1M H_2SO_4 solution at room temperature. All the electrochemical studies were carried out using CHI 760D Electrochemical workstation model. For these studies, a three – electrode cell system were used. In these cell system, mild steel act as a working electrode, a saturated calomel electrode as the reference electrode and platinum foil as the counter electrode. The working electrode was mild steel with the exposed surface area of 1 cm^2 and the balance being covered by epoxy resin. Before starting the Electrochemical Impedance Spectroscopy (EIS) measurements, the working electrode surface area were polished with various grades (1/0-7/0) of emery papers. The mild steel specimen was washed thoroughly with water, degreased with AR grade acetone and finally dried at room temperature. Prior to electrochemical studies, the instrument was allowed to stabilization (30 minutes) with the help of blank solution, which was proved to be sufficient to attain a stable value of Open Circuit Potential (OCP) [14].

EIS studies were carried out by using ac impedance signal of 0.1V amplitude for the frequency spectrum from 100 kHz to 0.01 Hz. The impedance curves were represented in the Nyquist plot. The Tafel plots were recorded in the potential range of + 200 mV from the OCP at a sweep rate of 0.1 mV/s. All the electrochemical tests are repeated minimum two times under the same condition to confirm the accuracy of data obtained.

Scanning Electron Microscope (SEM) studies

The surface morphology of mild steel specimens were examined in 1M H_2SO_4 solution in the absence and presence of optimum concentration (300 ppm) of inhibitor for the immersion of 3 hours at room temperature. After the immersion period, the mild steel specimens were removed from the 100 ml beaker solution, washed with running water and dried for SEM studies. The SEM studies were performed on JEOL/EO JSM-6390 model scanning electron microscope.

Atomic Force Microscope (AFM) studies

The mild steel specimens of size 1.0 x 1.0 x 0.2 cm were polished with various grades of emery papers and then the fine dust particles are removed with the help of AR grade acetone. The mirror image mild steel specimens were immersed in 1M H_2SO_4 solution in the absence (blank) and presence of optimum concentration of inhibitor at room temperature for 3 hours. After the immersion time, the mild steel specimens were taken out, dried with air blaster and then used for AFM studies. The surface Topography of mild steel specimens were investigated by using Atomic Force Microscope (AFM). A "NT-MDT Modular AFM" Ireland was used for these studies.

RESULTS AND DISCUSSION

Weight loss studies

The inhibition efficiency, corrosion rate, surface coverage and weight loss of mild steel were calculated from weight loss studies in the absence and presence of various concentrations (50-300 ppm) of inhibitor in 1M H_2SO_4 solution, after 3 hours immersion period at room temperature. The above-mentioned corrosion parameters values are summarized in ***Table 1*** and shown in ***Figure 2(a-b)***. From the *Table 1* and *Figure 2a* shows that the inhibition efficiency is increased from 47.86 % to 87.22% with the addition of inhibitor from 50 ppm to 300 ppm. The maximum inhibition efficiency was shown at optimum concentration (300 ppm) of inhibitor and further increasing the concentration of inhibitor the inhibition efficiency (IE %) remain almost same. *Figure 2b* clearly indicates that the corrosion rate was decreased with the addition of inhibitor concentration, which explains the mild steel surface is protected against corrosion by the used inhibitor. Indeed, corrosion rate values of mild steel decreases from 116.7

mmy^{-1} to 28.6 mmy^{-1} on the addition of 50 ppm to 300 ppm of used inhibitor. The increased inhibition efficiency (IE %) and decreased corrosion rate (CR) might be due to the result of increased adsorption and increased surface coverage of inhibitor on the mild steel surface with increasing concentration of inhibitor [15]. It is clear that the used inhibitor showed good inhibition for mild steel specimens in 1M H_2SO_4 solution because the inhibitor molecule is made up of a pyridine ring, benzene ring and contains lone pair electrons of N and O atoms [16].

***Table 1.* Weight loss studies, inhibition efficiency values of mild steel in the absence and presence of various concentrations of inhibitor in 1M H_2SO_4 solution**

Concentration (ppm)	*Weight loss (mg cm^{-2})*	*Corrosion rate (mm y^{-1})*	*Surface coverage (θ)*	*IE (%) η*
Blank	94	223.8	-	-
50	49	116.7	0.4786	47.86
100	33	78.6	0.6488	64.88
150	25	59.5	0.7341	73.41
200	19	45.2	0.7980	79.80
250	15	35.7	0.8404	84.04
300	12	28.6	0.8722	87.22

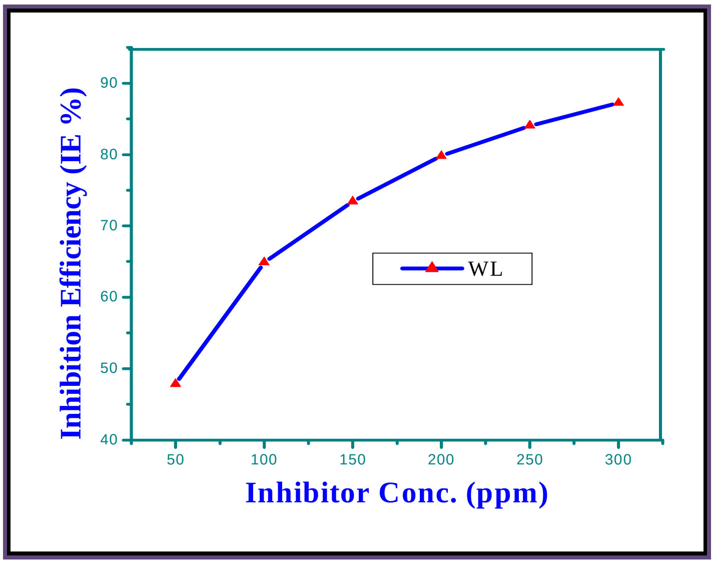

Figure 2a

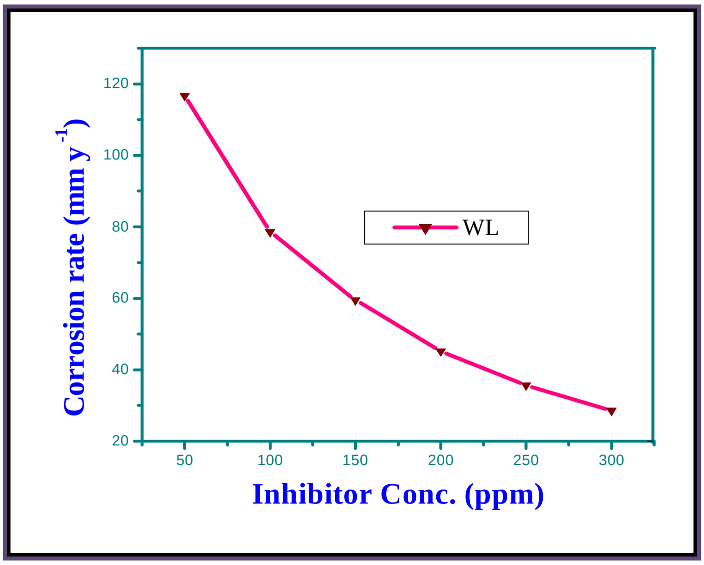

Figure 2b

Figure 2. Weight loss values of various concentrations of inhibitor in 1M H_2SO_4 solution at room temperature: a. Variation of inhibition efficiency with different concentrations of inhibitor and b. Variation of corrosion rate with different concentrations of inhibitor

Electrochemical impedance spectroscopy studies

Table 2 shows the experimental results obtained from EIS measurements for the corrosion of mild steel in the absence and the presence of various concentrations of inhibitor at room temperature. The impedance spectra obtained for mild steel in 1M H_2SO_4 solution in the absence and presence of various concentrations of tested inhibitor at room temperature are presented as Nyquist plots in ***Figure 3a***. *Figure 3a* clearly shows, the diameter of the capacitive loops in the presence of inhibitor is bigger than the absence of inhibitor (blank solution) and increases with the inhibitor concentration. This indicates that the impedance of inhibited substrate increases with the inhibitor concentration. Noticeably, these capacitive loops are not perfect semicircles, which can be attributed to the frequency dispersion effect. This anomalous behavior is generally attributed to the roughness and in-homogeneity of the mild steel surface [17]. The simplest fitting is represented by Rundles electrical equivalent circuit in ***Figure 3b***, which is a parallel combination of the charge transfer resistance, R_{ct} and the constant phase element, CPE_{dl} both in series with the solution resistance (R_s) [18]. It is seen that the addition of inhibitor, increases the values of charge transfer resistance (R_{ct}) and reduces the double-layer capacitance (C_{dl}). The interfacial double layer capacitance (C_{dl}) values have been calculated from the impedance value using Nyquist plot by the following formula:

$$C_{dl} = \left(2\pi f_{\max} R_{ct}\right)^{-1} \qquad (4)$$

The values of C_{dl} decreased with an increase in the inhibitor concentration. This is due to an increase in the surface coverage by the used inhibitor, resulting in to an increase in the inhibition efficiency (IE %). The thickness of the protective layer δ_{inh} was related to C_{dl} by the equation [19]:

$$\delta_{inh} = \frac{\varepsilon_0 \varepsilon_r}{C_{dl}} \qquad (5)$$

where, ε_0 is the dielectric constant and ε_r is the relative dielectric constant. This decrease in C_{dl} values from 11,109 to 114.695 µFcm^{-2} is due to the reduction in local dielectric constant and/or an increment in the thickness of the electrical double layer. The increase in R_{ct} values from 2.675 Ωcm^2 to 26.203 Ωcm^2 is due to the formation of protective film on the metal/solution interface [20]. These observations suggest that the tested inhibitor molecules adsorbed on the mild steel surface, thereby causing the decrease in C_{dl} values and increasing in R_{ct} values. R_{ct} values were used to determine the IE %, according to the following equation:

$$\text{IE }(\%) = \left[\frac{R_{ct}^{i} - R_{ct}^{o}}{R_{ct}^{i}}\right] \times 100 \qquad (6)$$

where, R_{ct}^{i} and R_{ct}^{o} are the charge transfer resistance values in the presence and absence of inhibitor solution, respectively.

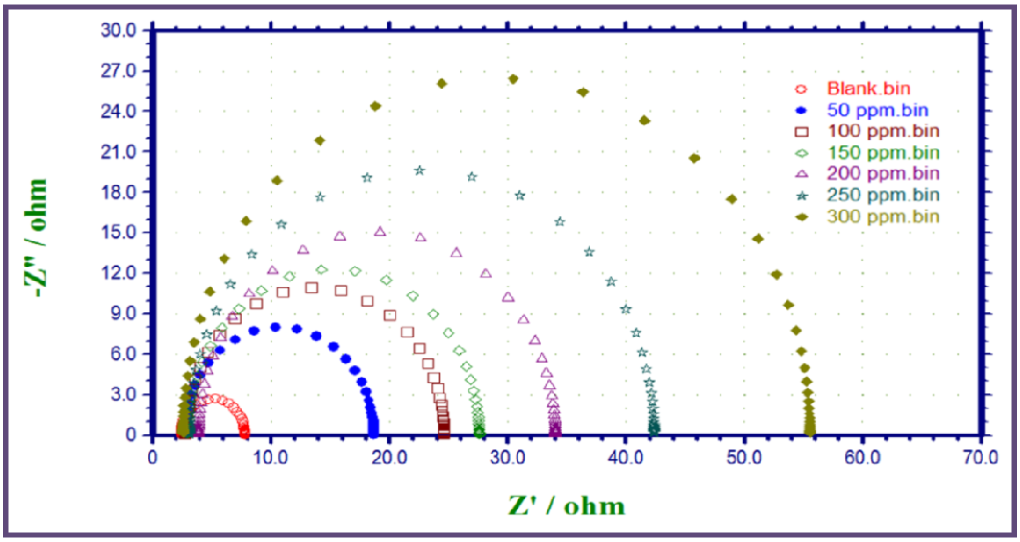

***Figure 3a*. Electrochemical impedance spectrum of mild steel in 1M H_2SO_4 solution with and without various concentrations of inhibitor**

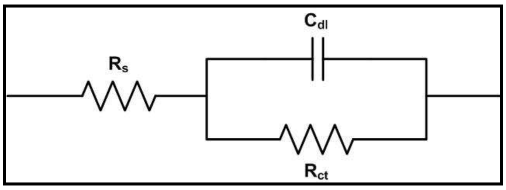

***Figure 3b*. Electrical equivalent circuit (R_s-solution resistance; R_{ct}-charge transfer resistance; C_{dl}-double layer capacitance)**

***Table 2*. Electrochemical impedance spectroscopy values of mild steel in 1M H_2SO_4 solution containing blank and various concentrations of inhibitor**

Concentration (ppm)	***Y_{max} (Ωcm^2)***	***R_{ct} (Ωcm^2)***	***C_{dl} ($\mu F\ cm^{-2}$)***	***IE (%) η***
Blank	5.358	2.675	11,109	-
50	16.016	7.941	1252.01	66.31
100	21.846	10.777	676.348	75.18
150	24.664	12.268	526.263	78.19
200	30.069	14.992	353.233	82.16
250	39.291	19.423	208.656	86.23
300	52.984	26.203	114.695	89.79

The *Table 2* confirms that the inhibition efficiency (IE %) increases with increase in the concentrations of the tested inhibitor and maximum efficiency (89.79%) reaches at optimum concentration (300 ppm) of inhibitor.

Potentiodynamic polarization studies

Potentiodynamic polarization measurements were carried out to study the nature of inhibitor such as anodic inhibitor or cathodic inhibitor or mixed-type inhibitor, mode of action and mechanism of the inhibitor reaction. The inhibition action of kynurenic acid on the electrochemical corrosion behavior of mild steel in 1M H_2SO_4 solution in the absence and presence of various concentrations of inhibitor at room temperature was studied and the polarization curves are shown in ***Figure 4***. The inhibition efficiency (IE %) of the used inhibitor values was calculated from corrosion current density (I_{corr}) using the following relationship:

$$\text{IE (\%)} = \left[\frac{I^{o}_{corr} - I^{i}_{corr}}{I^{o}_{corr}} \right] \times 100 \qquad (7)$$

where, I^{o}_{corr} and I^{i}_{corr} are the corrosion current density in the absence and presence of inhibitor solution, respectively [21]. The important electrochemical corrosion parameters such as corrosion potential (E_{corr}), corrosion current density (I_{corr}), anodic (β_a) and cathodic (β_c) Tafel plots and linear polarization resistance (R) derived from polarization curves and all the parameter values including the inhibition efficiency (IE %) values are given in ***Table 3***. *Table 3* shows that the corrosion current density (I_{corr}) values decreases from 5.540 mAcm^{-2} to 0.889 mAcm^{-2} with the addition of various concentrations of inhibitor. When the corrosion current density value decreases the inhibition efficiency (IE %) value increases from 54.49 % to 83.95 %. From the observation of the polarization studies, that the corrosion current density (I_{corr}) values are decreased prominently, the inhibition efficiency increased with increase in the concentration of the inhibitor. The maximum inhibition efficiency obtained at the optimum inhibitor concentration (300 ppm) indicates that more amount of organic inhibitor molecules are adsorbed on the surface of mild steel. The presence of inhibitor at the optimum concentration might be blocking the active sites and modifying the mild steel surface. This would lead to the shift of anodic and/or cathodic slope areas toward lower current densities (I_{corr}) [22]. The nature of used inhibitor is related to the corrosion potential (E_{corr}) values. Generally, if the value of E_{corr} is greater than 85 mV/SCE the inhibitor can be classified as cathodic or anodic type and however, if the value of E_{corr} is lower than 85 mV/SCE the inhibitor can be classified as mixed-type [23]. However, a shift of corrosion potential (E_{corr}) of the used inhibitor towards cathodic side, that is -440.3 to -272.1 mV/SCE were established. Since the larger displacement exhibited by the used inhibitor is higher than the borderline (-168.2mV/SCE), it is proved that the addition of inhibitor alter the value of corrosion potential (E_{corr}) significantly, indicating that the added inhibitor is more polarized in the cathodic side. *Table 3* also shows, a mixed mode of inhibition is indicated by the corrosion potential (E_{corr}) values, as they do not increase or decrease in a regular manner from the blank values [24]. From *Table 3* the cathodic (β_c) Tafel plots values were shifted to higher values with reference to blank in the presence of addition of various concentrations of inhibitor. This shows that the used inhibitor inhibits the corrosion mechanism by controlling cathodic reaction predominantly [25]. All the above fact tells that the used inhibitor is acted as mixed-type corrosion inhibitor, but predominantly cathodic inhibitor [26].

Table 3. Potentiodynamic polarization values of mild steel in 1M H_2SO_4 solution containing blank and various concentrations of inhibitor

Concentration (ppm)	***β_a (1/V)***	***β_c (1/V)***	***E_{corr} (mV/SCE)***	***I_{corr} (mA/cm^2)***	***R (Ohm)***	***IE (%) η***
Blank	9.062	5.211	-440.3	5.540	10	-
50	5.930	5.789	-272.1	2.521	15	54.49
100	6.962	6.307	-300.4	2.157	16	61.06
150	7.271	6.939	-276.7	1.467	21	73.52
200	9.107	5.842	-288.9	1.250	23	77.44
250	8.816	7.295	-278.1	1.031	26	81.38
300	4.804	9.535	-464.1	0.889	34	83.95

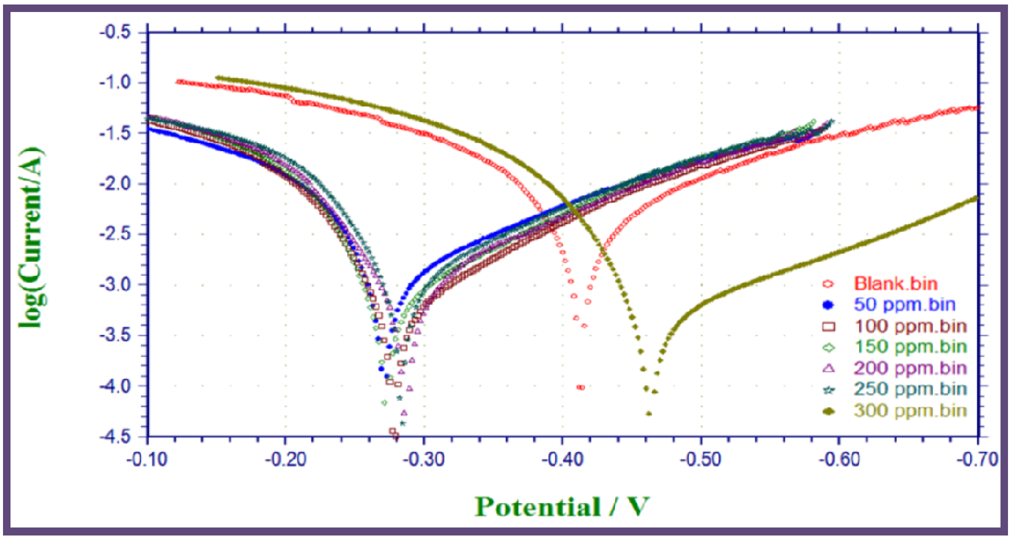

Figure 4. Potentiodynamic polarization curves of mild steel in 1M H_2SO_4 solution with and without various concentrations of inhibitor

Adsorption isotherm studies

The interaction of inhibitor on the surface of mild steel can be explained by adsorption isotherm.

The process of adsorption is usually studied through graphs known as adsorption isotherm. It is the graph between the amounts of inhibitor (adsorbate) adsorbed on the surface of mild steel (adsorbent) at room temperature.

Inhibitor (adsorbate) + Mild steel (adsorbent) → Adsorption

During corrosion inhibition of mild steel, the nature of the inhibitor at the optimum concentration on the corroding surface has been deduced in terms of adsorption characteristics of the inhibitor. In order to obtain the adsorption isotherm the linear relationship between the degrees of the surface coverage (θ) and the tested inhibitor concentration (C) must be found. Attempts were made to fit the surface coverage (θ) values to number of isotherms generally considered are [27];

Langmuir isotherm, Temkin isotherm, Frunkin isotherm, Freundlich isotherm and Flory-Huggins isotherm. Attempts to fit data obtained from weight loss measurement into the above adsorption isotherms reveal that the data best fitted in Langmuir adsorption isotherm. Assumptions of Langmuir relate the concentration of the adsorbate in the bulk of the electrolyte (C_{inh}) to the degree of surface coverage (θ) as by the following equation:

$$\frac{C_{inh}}{\theta} = \frac{1}{K_{ads}} + C_{inh} \qquad (8)$$

where, K_{ads} is the equilibrium constant of the adsorption. The linear regression parameters between C_{inh}/θ and C_{inh} were listed in ***Table 4.*** ***Figure 5*** shows the straight line of C_{inh}/θ versus C_{inh} for optimum concentration of inhibitor at room temperature. These results show that the linear regression coefficient (R^2) and slope are equal to unity, which confirms the adsorption of inhibitor on mild steel surface. The slope of the C_{inh}/θ versus C_{inh} plots shows a small deviation from unity, which means non-ideal simulating and unexpected from the Langmuir adsorption isotherm [28]. The adsorption equilibrium constant (K_{ads}) and free energy of adsorption (ΔG^{o}_{ads}) were calculated using the below equation:

$$\Delta G^{o}_{ads} = -\mathrm{RT}\ln(55.5\mathrm{K}_{ads}) \qquad (9)$$

where, 55.5 is the concentration of water in solution in mol L^{-1} and R is the universal gas constant. Generally, values of ΔG^{o}_{ads} around -20 kJ mol^{-1} or lower are consistent with the electrostatic interaction (ionic bond) or physisorption and when it is around -40 kJ mol^{-1} or higher values then this is chemical interaction (covalent bond) or chemisorption [29]. Here, the calculated ΔG^{o}_{ads} value (-17.16 kJ/mol) indicates that the adsorption of used inhibitor on the mild steel surface is followed physical adsorption (ionic) or physisorption. The negative values of ΔG^{o}_{ads} ensure the adsorption process is always spontaneous.

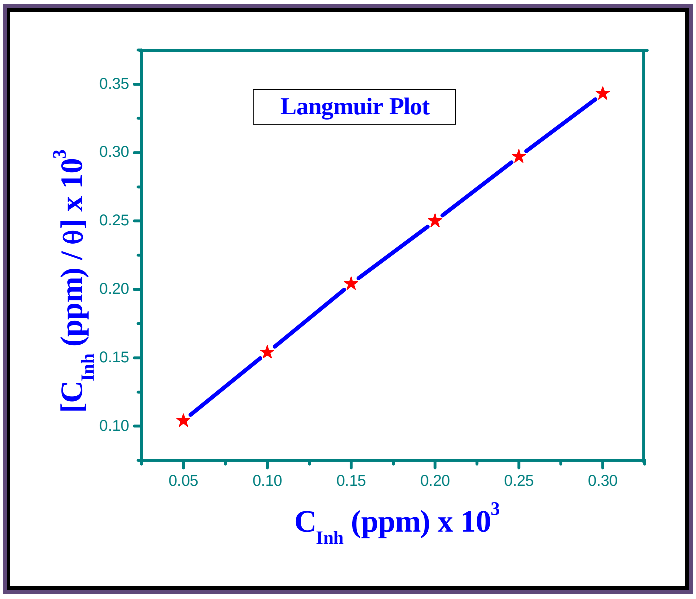

Figure 5. Langmuir adsorption plot for the adsorption of the inhibitor in 1M H_2SO_4 solution on the surface of mild steel

Table 4. Langmuir adsorption parameters for the adsorption of inhibitor in 1M H_2SO_4 solution on the surface of mild steel

Inhibitor	***R^2***	***K_{ads} ($10^4 M^{-1}$)***	***ΔG^0_{ads} (kJ mol^{-1})***
Kynurenic acid	0.9997	16.3602	-17.16

Scanning electron microscope studies

In order to evaluate the surface morphology of the mild steel in contact with 1M H_2SO_4 solution in the absence and presence of inhibitor at optimum concentration (300 ppm), a surface analysis was carried out using scanning electron microscope, after the corrosion tests. The mild steel specimens were subjected to SEM analysis and the SEM images were recorded in ***Figure 6(a-b).*** *Figure 6b* shows that, the surface corrosion of the mild steel decreased remarkably in the presence of the tested inhibitor. Inspections of the figures reveal that there is severe damage, clear pits and cavities on the surface of mild steel in the absence of inhibitor (*Figure 6a*) than in its presence **(***Figure 6b***)**. There are very few pits and cracks observed in the inhibited mild steel surface **(***Figure 6b***)**. The SEM studies confirm that the mild steel surfaces are fully covered with the used inhibitor molecule and a protective inhibitor layer was formed [30]. The SEM studies are giving better results, which supports the weight loss, electrochemical impedance and Tafel polarization results.

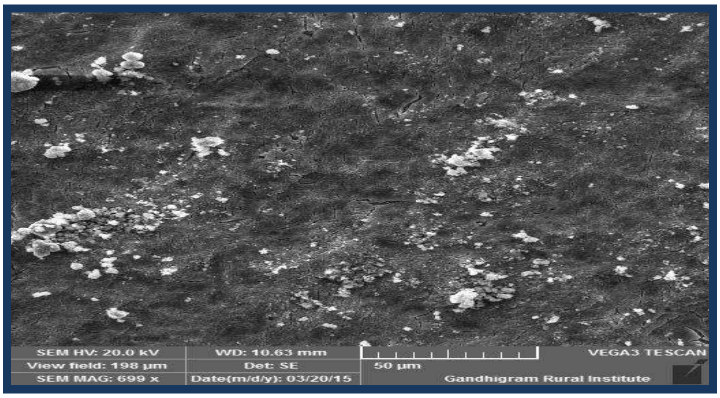

Figure 6a

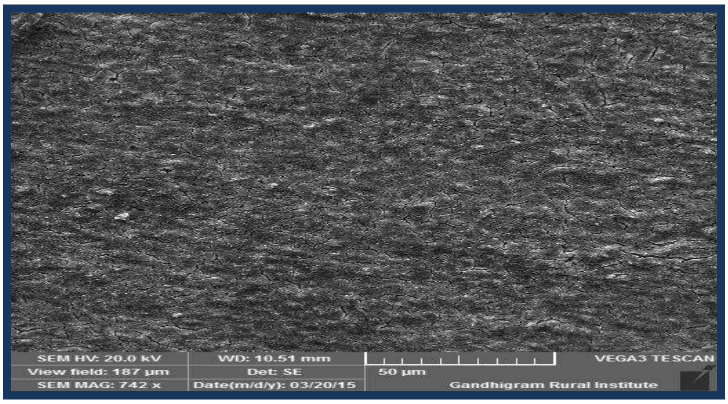

Figure 6b

Figure 6. SEM Photographs of mild steel: a. after immersion in 1M H_2SO_4 solution in absence of inhibitor and b. after immersion in 1M H_2SO_4 solution in presence of optimum concentration of inhibitor

Atomic force microscope studies

Atomic force microscope is a powerful technique to investigate the surface topography at nano-to-micro scale and has become a new choice to study the influence of inhibitor on the generation and the progress of the corrosion at the metal or glass/solution interface [31-32]. AFM is becoming an accepted method of roughness investigation of metals, alloys and glasses [33]. The three – dimensional (3D) surface topography of the polished mild steel in 1M H_2SO_4 solution in the absence and presence of inhibitor at optimum concentration was investigated through "NT-MDT Modular AFM" technique. The scanning area of all the AFM images like polished mild steel, blank and inhibited mild steel was 4 µm x 4 µm and the scan rate was 1.0 Hz per line.

The topography AFM images of polished mild steel, blank (mild steel + 1M H_2SO_4) and inhibited mild steel surface were recorded in ***Figure 7(a-c).*** The topography AFM image studies were performed to obtain the average roughness, *Ra* (the average deviation of all points roughness profile from a mean line over the evaluation length), root-mean-square roughness (rms), *Rq* (the average of the measured height deviation taken within the evaluation length and measured from the mean line), the maximum peak-to-peak height values and ten point height values [34]. The AFM parameters such as, average roughness, root-mean-square roughness, maximum peak-to-peak height and ten-point height are summarized in ***Table 5.***

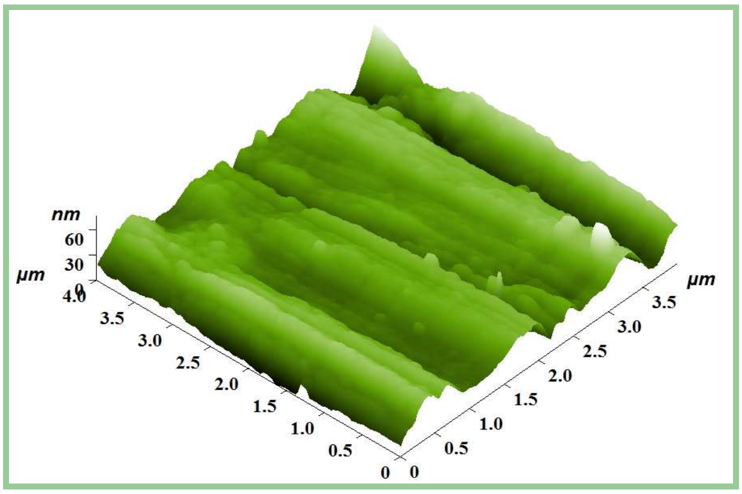

Figure 7a

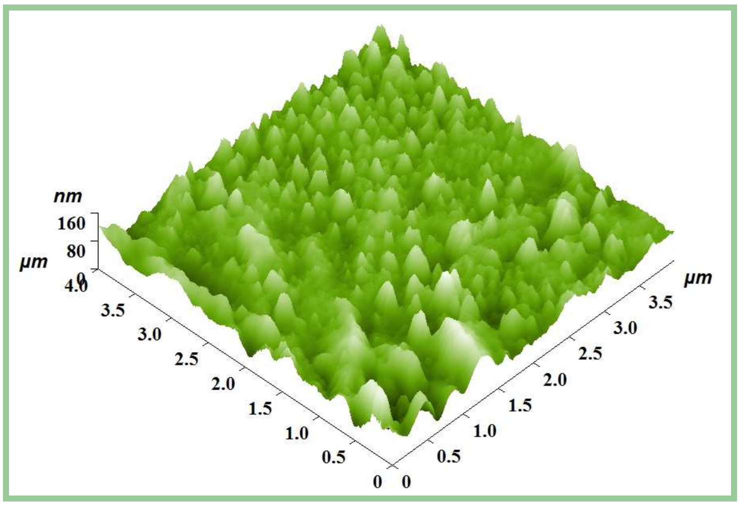

Figure 7b

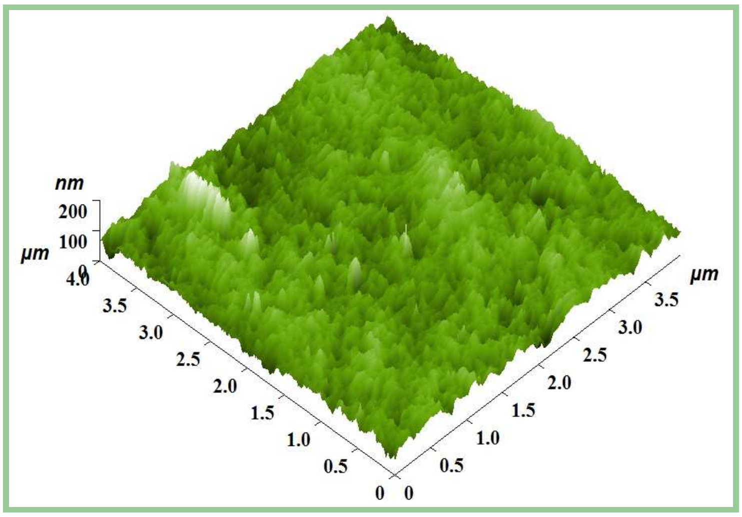

Figure 7c

Figure 7. The topography AFM images of mild steel: a. Polished mild steel, b. 1M H_2SO_4 solution without inhibitor and c. 1M H_2SO_4 solution with the optimum concentration of inhibitor

Table 5. AFM parameters data for mild steel in the absence and the presence of optimum concentration of inhibitor in 1M H_2SO_4 solution

Sample	***Root Mean Square Roughness (nm)***	***Maximum Peak-to-Peak height (nm)***	***Ten Point height (nm)***	***Average Roughness (nm)***
Polished Mild Steel Surface	9.91	73.07	36.79	7.82
1M H_2SO_4 without inhibitor	36.59	296.12	151.00	28.74
1M H_2SO_4 with inhibitor	14.30	197.29	98.13	10.61

As can be seen from the inhibited sample (*Figure 7c*), there was very less pits, cracks and damage on the surface of mild steel with the optimum concentration of inhibitor. The average roughness values of polished mild steel (*Figure 7a*) surface are 7.82 nm. The slight roughness observed on the surface of polished mild steel is due to atmospheric corrosion and some streaks made on the surface of mild steel during polishing with emery papers. The average roughness values of mild steel surface in 1M H_2SO_4 solution (*Figure 7b*) without inhibitor are 28.74 nm. The greater roughness is due to the acid attack on the surface of mild steel in the corrosion test period (3h). Therefore, the surface of mild steel in 1M H_2SO_4 solution had a considerable pores structure with deep cracks. However, in the presence of optimum concentration (300 ppm) of tested inhibitor the average roughness was reduced to 10.61 nm. The lower value of roughness reveals that the tested inhibitor protects the surface of mild steel effectively.

CONCLUSION

Based on the above experimental results the following conclusion can be drawn;

- The tested inhibitor kynurenic acid is a good corrosion inhibitor for mild steel specimens in 1M H_2SO_4 solution.
- The inhibition efficiency increases with increase in the concentration of the tested inhibitor. It showed the maximum inhibition efficiency 89.79 % in EIS studies.
- The electrochemical impedance spectroscopy study proved that the tested inhibitor inhibits on the surface of mild steel through adsorption mechanism.
- A Potentiodynamic polarization study reveals that the tested inhibitor belonged to mixed-type with more chathodic character.
- The adsorption of the studied inhibitor obeys the Langmuir adsorption isotherm. The negative values of ΔG^{o}_{ads} ensure the adsorption process is always spontaneous.
- The SEM photographic images confirm the formation of protective film on the surface of mild steel.
- The SEM results are further proved by AFM topography studies. From this, the surface roughness is decreased after the use of inhibitor.

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