Research Article

Inhibition of Corrosion of Carbon Steel in Well Water by DL-Phenylalanine- Zn^{2+} System

A. Sahaya Raja,¹ S. Rajendran,² and P. Satyabama³

¹ PG and Research Department of Chemistry, GTN Arts College, Dindigul 624005, India

² Department of Chemistry, RVS School of Engineering and Technology, Dindigul 624005, India

³ Department of Chemistry, Anna University of Technology Madurai, Dindigul Campus, Dindigul, India

Correspondence should be addressed to A. Sahaya Raja; sptheepandgl@gmail.com

Received 26 December 2011; Revised 14 May 2012; Accepted 15 May 2012

Academic Editor: Hassan Arida

Copyright © 2013 A. Sahaya Raja et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

The environmental friendly inhibitor system DL-phenylalanine- Zn^{2+} has been investigated by weight loss method. A synergistic effect exists between DL-phenylalanine and Zn^{2+} system. The formulation consisting of 150 ppm of DL-phenylalanine and 5 ppm of Zn^{2+} offers good inhibition efficiency of 90%. Polarization study reveals that this formulation functions as an anodic inhibitor. AC impedance spectra reveal that a protective film is formed on the metal surface. The surface morphology has been analysed by SEM and EDAX. A suitable mechanism of corrosion inhibition is proposed based on the results obtained from weight loss study and electrochemical studies.

1. Introduction

The use of inhibitor is one of the most practical methods to protect metals from corrosion [1, 2]. Most of the effective inhibitors are compounds containing, in their structures, nitrogen, phosphorus, and/or sulphur. Heteroatoms such as nitrogen, oxygen, and sulphur are capable of forming coordinate covalent bond with metal owing to their free electron pairs and thus, acting as inhibitor [1, 3]. Many researchers were interested in biochemical compounds based on amino acids, which exhibit excellent properties such as good water solubility and rapid biodegradability [4, 5]. These inhibitors used in protection against the corrosion of certain metals such as nickel, cobalt, copper, iron, and steel [6, 7]. The amino acids are the building block of proteins. All amino acids have a central or alpha carbon, to which are bonded four groups; hydrogen, an amino, a carboxyl group, and a unique side chain, also known as R-group [6]. These molecules differ in their unique side chain, which can be used to classify the molecules into functional types. Various amino acids have been used to inhibit the corrosion of metals and alloys [8–17]. The corrosion of mild steel has

been inhibited by leucine, alanine and glycine [8], and N,N-bis(phosphonomethyl) glycine (BPMG) [9]. The corrosion of SS 316L has been inhibited by glycine, leucine, valine, and arginine [10]. Cystein, alanine, and phenylalanine have been used to inhibit the corrosion of bronze in an aqueous solution containing sodium sulphate and sodium bicarbonate [11]. Cystein, glycine, glutamic acid, and glutathione have been used as corrosion inhibitor to prevent the corrosion of copper in HCl [12]. The corrosion of brass in O_2 -free NaOH has been prevented by methionine [13]. Wilson Sahayaraj et al. have used L-valine along with Zn^{2+} and sodium gluconate to prevent corrosion of carbon steel in rain water [14]. Amin has used glycine derivative to prevent the corrosion of aluminium in KSCN medium [15]. Amino acids have been used to prevent chloride-induced corrosion in reinforced concrete structure [16]. Amino acids such as phenylalanine have been used to prevent corrosion of Mg-Al-Zn alloy in chloride-free neutral solution [17]. The aim of this research is to investigate the inhibitive effect of amino acid such as DL-phenylalanine. For this purpose potentiodynamic polarization and impedance spectroscopy have been used in the present study.

2. Experimental Procedure

2.1. Preparation of Specimens. Carbon steel specimens (0.0267% S, 0.067% P, 0.4% Mn, 0.1% C and the rest iron) of the dimensions 1.0 cm × 4.0 cm × 0.2 cm were polished to mirror finish and degreased with trichloroethylene and used for weight loss method.

2.2. Weight Loss Method. Carbon steel specimens in triplicate were immersed in 100 mL of well water (Table 1) and various concentrations of DL-phenylalanine in the presence and absence of Zn^{2+} (as $ZnSO_4 \cdot 7H_2O$) for a period of seven days. The corrosion products were cleaned with Clarke's solution [8]. The weight of the specimens before and after immersion was determined using Shimadzu balance AY62. The corrosion inhibition efficiency was calculated with (1):

$$IE = 100 \left[1 - \left(\frac{W_2}{W_1} \right) \right] \%, \quad (1)$$

where W_1 is the corrosion rate in the absence of the inhibitor and W_2 is the corrosion rate in the presence of inhibitor. From the weight loss, the corrosion rate (mm/y) was calculated:

$$\begin{aligned} & \text{corrosion rate (mm/y)} \\ &= [\text{loss in weight (mg)}] \\ & / [\text{surface area of the specimen (dm}^2) \\ & \quad \times \text{period of immersion (day)}] \\ & \times \left(\frac{0.0365}{\rho} \right). \end{aligned} \quad (2)$$

ρ -density of the metal is g/cm³ (7.86).

2.3. Potentiodynamic Polarization Study. Potentiodynamic polarization studies were carried out using a CHI electrochemical impedance analyzer, model 660 A. A three-electrode cell assembly was used. The three-electrode cell assembly is shown in Scheme 1. The working electrode was a rectangular specimen of carbon steel with one face of the electrode (1 cm² area) exposed and the rest shielded with red lacquer. A saturated calomel electrode (SCE) was used as the reference electrode and a rectangular platinum foil was used as the counter electrode. Polarization curves were recorded using iR compensation. The results, such as Tafel slopes, and I_{corr} , E_{corr} , and LPR values were calculated. During the polarization study, the scan rate (v/s) was 0.01, hold time at E_f (s) was zero, and quit time(s) was 2.

2.4. AC Impedance Measurements. A CHI electrochemical impedance analyzer (model 660 A) was used for AC impedance measurements. A time interval of 5 to 10 minutes was given for the system to attain its open circuit potential. The real part Z' and imaginary part Z'' of the cell impedance were measured in ohms at various frequencies. The values

TABLE 1: Physicochemical parameters of well water.

Parameters	Value
pH	8
Conductivity	1770 $\mu\text{mhos/cm}$
Total dissolved solids	1204 ppm
Total hardness	402 ppm
Total alkalinity	390 ppm
Magnesium	63 ppm
Calcium	88 ppm
Sodium	172 ppm
Potassium	55 ppm
Chloride	665 ppm
Sulphate	214 ppm

SCHEME 1: Circuit diagram of three-electrode cell assembly.

SCHEME 2: Equivalent circuit diagram: R_s is solution resistance, R_{ct} is charge transfer resistance, C_{dl} is double layer capacitance.

of the charge transfer resistance R_t , double-layer capacitance C_{dl} , and impedance value were calculated. The equivalent circuit diagram is shown in Scheme 2.

2.5. Scanning Electron Microscopic Studies (SEMs). The carbon steel specimen immersed in blank and in the inhibitor solution for a period of seven days was removed, rinsed with double-distilled water, dried, and observed in a scanning electron microscope to examine the surface morphology. The surface morphology measurements of the carbon steel were examined using JOEL-6390 computer-controlled scanning electron microscope.

2.6. Energy Dispersive Analysis of X-Rays (EDAXs). The carbon steel specimen immersed in blank and in the inhibitor solution for a period of seven days was removed, rinsed with

TABLE 2: Corrosion rates (CRs) of carbon steel immersed in well water in the presence and absence of inhibitor system at various concentrations and the inhibition efficiencies (IEs) obtained by weight loss method.

DL-Phe ppm	Zn ²⁺ ppm	CR mm/y	IE %
0	0	0.0874	—
50	0	0.0515	41
100	0	0.0550	37
150	0	0.0585	33
200	0	0.0629	28
250	0	0.0664	24

Inhibitor system: DL-phenylalanine-Zn²⁺ (0 ppm), immersion period: 7 days, pH = 8.

TABLE 3: Corrosion rates (CRs) of carbon steel immersed in well water in the presence and absence of inhibitor system at various concentrations and the inhibition efficiencies (IEs) obtained by weight loss method.

DL-Phe ppm	Zn ²⁺ ppm	CR mm/y	IE %
0	0	0.0874	—
0	5	0.0743	15
50	5	0.0306	65
100	5	0.0183	79
150	5	0.00874	90
200	5	0.0139	84
250	5	0.0174	80

Inhibitor system: DL-phenylalanine-Zn²⁺ (5 ppm), immersion period: 7 days, pH = 8.

double-distilled water, dried, and observed in an Energy Dispersive Analysis of X-Rays (EDAXs) to examine the elements present on the metal surface. The elements present on the metal surface were examined using JOEL-6390 computer-controlled Energy Dispersive Analysis of X-Rays.

3. Result and Discussion

3.1. Analysis of the Weight Loss Method. Corrosion rates (CRs) of carbon steel immersed in well water in the absence and presence of inhibitor (DL-phenylalanine) are given in Tables 2 and 3. The inhibition efficiencies (IE) are also given in these Tables.

It is observed from Table 2 that DL-phenylalanine shows some inhibition efficiencies. 50 ppm of DL-phenylalanine has 41 percent IE. As the concentration of DL-phenylalanine increases, the IE decreases. This is due to the fact that as the concentration of DL-phenylalanine increases, the protective film (probably iron DL-phenylalanine complex) formed on the metal surface goes into solution. That is, the system passes from passive region to active region [9].

3.2. Influence of Zn²⁺ on the Inhibition Efficiencies of DL-Phenylalanine. The influence of Zn²⁺ on the inhibition efficiencies of DL-phenylalanine is given in Table 3. It is observed that as the concentration of DL-phenylalanine increases the

FIGURE 1: Polarization curves of carbon steel immersed in test solutions (pH = 8). (a) Well water (blank). (b) Well water + DL-phenylalanine (150 ppm) + Zn²⁺ (5 ppm).

IE increases. Similarly, for a given concentration of DL-phenylalanine the IE increases as the concentration of Zn²⁺ increases. It is also observed that a synergistic effect exists between DL-phenylalanine and Zn²⁺. For example, 5 ppm of Zn²⁺ has 15 percent IE; 150 ppm of DL-phenylalanine has 33 percent IE. Interestingly their combination has a high IE, namely, 90 percent.

In presence of Zn²⁺ more amount of DL-phenylalanine is transported towards the metal surface. On the metal surface Fe-DL-phenylalanine complex is formed on the anodic sites of the metal surface. Thus the anodic reaction is controlled. The cathodic reaction is the generation of OH⁻, which is controlled by the formation of Zn(OH)₂ on the cathodic sites of the metal surface. Thus, the anodic reaction and cathodic reaction are controlled effectively. This accounts for the synergistic effect existing between Zn²⁺ and DL-phenylalanine:

3.3. Synergism Parameters (S_I). Synergism parameter (S_I) has been used to know the synergistic effect existing between two inhibitors [10–15]. Synergism parameter (S_I) can be calculated using the following relationship:

$$\text{synergism parameters } (S_I) = \frac{1 - \theta_{1+2}}{1 - \theta'_{1+2}}, \quad (4)$$

TABLE 4: Inhibition efficiencies and synergism parameters for various concentrations of DL-Phe-Zn²⁺ (5 ppm) system, when carbon steel is immersed in well water.

DL-phenylalanine ppm	Inhibition efficiency IE (%)	Surface coverage θ_1	Zn ²⁺ ppm	Inhibition efficiency IE (%)	Surface coverage θ_2	Combined IE % I'_{1+2}	Combined surface coverage θ'_{1+2}	Synergism parameters S_I
50	41	0.41	5	15	0.15	65	0.65	1.4328
100	37	0.37	5	15	0.15	79	0.79	2.55
150	33	0.33	5	15	0.15	90	0.90	5.695
200	28	0.28	5	15	0.15	84	0.84	3.825
250	24	0.24	5	15	0.15	80	0.80	3.23

Immersion period: 7 days, pH = 8.

TABLE 5: Corrosion parameters of carbon steel immersed in well water in the absence and presence of inhibitor system obtained from potentiodynamic polarization study (pH = 8).

System	E_{corr} mV versus SCE	b_c mV/decade	b_a mV/decade	I_{corr} A/cm ²	LPR ohm cm ²
Well water	-668	268	104	5.775×10^{-7}	5.630×10^4
Well water + DL-Phe (150 ppm) + Zn ²⁺ (5 ppm)	-658	242	151	4.993×10^{-7}	8.075×10^4

where

$$\theta_{1+2} = (\theta_1 + \theta_2) - (\theta_1 \theta_2) \quad (5)$$

θ_1 = surface coverage by DL-phenylalanine,

θ_2 = surface coverage by Zn²⁺,

θ'_{1+2} = surface coverage by both DL-phenylalanine and Zn²⁺,

where θ = surface coverage = (IE%)/100.

The synergism parameters of DL-phenylalanine-Zn²⁺ system are given in Table 4. For different concentrations of inhibitors, S_I approaches 1 when no interaction between the inhibitor compounds exists. When $S_I > 1$, it points to synergistic effects. In the case of $S_I < 1$, it is an indication that the synergistic effect is not significant [14]. From Table 3, it is observed that values of synergism parameters (S_I) calculated from surface coverage were found to be one and above. This indicates that a synergistic effect exists between DL-phenylalanine and Zn²⁺ [12, 13, 15]. Thus, the enhancement of the inhibition efficiency caused by the addition of Zn²⁺ ions to DL-phenylalanine is due to the synergistic effect.

3.4. Analysis of Potentiodynamic Polarization Study (pH = 8). Polarization study has been used to confirm the formation of protective film formed on the metal surface during corrosion inhibition process [16–21]. If a protective film is formed on the metal surface, the linear polarization resistance value (LPR) increases and the corrosion current value (I_{corr}) decreases.

The potentiodynamic polarization curves of carbon steel immersed in well water in the absence and presence of inhibitors are shown in Figure 1, the corrosion parameters are given in Table 5. When carbon steel was immersed in

well water the corrosion potential was -668 mV versus SCE. When DL-phenylalanine (150 ppm) and Zn²⁺ (5 ppm) were added to the above system, the corrosion potential shifted to the noble side -658 mV versus SCE. This indicates that a film is formed on the anodic sites of the metal surface. This film controls the anodic reaction of metal dissolution by forming Fe²⁺-DL-Phe complex on the anodic sites of the metal surface. The formation of protective film on the metal surface is further supported by the fact that the anodic Tafel slope (b_a) increases from 104 to 151 mV.

Further, the LPR value increases from 5.630×10^4 ohm cm² to 8.075×10^4 ohm cm²; the corrosion current decreases from 5.775×10^{-7} A/cm² to 4.993×10^{-7} A/cm². Thus, polarization study confirms the formation of a protective film on the metal surface.

3.5. Analysis of AC Impedance Spectra. AC impedance spectra (electrochemical impedance spectra) have been used to confirm the formation of protective film on the metal surface [22–24]. If a protective film is formed on the metal surface, charge transfer resistance (R_t) increases, double-layer capacitance value (C_{dl}) decreases, and the impedance log (z/ohm) value increases. The AC impedance spectra of carbon steel immersed in well water in the absence and presence of inhibitors (DL-phenylalanine-Zn²⁺) are shown in Figures 2(a) and 2(b) (Nyquist plots) and Figures 3(a) and 3(b) and Figures 4(a) and 4(b) (Bode plots). The AC impedance parameters, namely, charge transfer resistance (R_t) and double-layer capacitance (C_{dl}) derived from Nyquist plots are given in Table 6. The impedance log(z/ohm) values derived from Bode plots are also given in Table 6.

It is observed that when the inhibitors [DL-Phe(150 ppm) + Zn²⁺ (5 ppm)] are added, the charge transfer resistance (R_t) increases from $1212 \Omega \text{ cm}^2$ to $12711 \Omega \text{ cm}^2$. The C_{dl} value decreases from $3.8424 \times 10^9 \text{ F/cm}^2$ to $4.0083 \times 10^{-10} \text{ F/cm}^2$. The impedance value [log (z/ohm)] increases from 3.120 to

TABLE 6: Corrosion parameters of carbon steel immersed in well water in the absence and presence of inhibitor system obtained from AC impedance spectra (pH = 8).

System	Nyquist plot		Bode plot
	R_t ohm cm^2	C_{dl} F/ cm^2	Impedance value $\log(z/\text{ohm})$
Well water	1212	3.8424×10^{-9}	3.120
Well water + DL-Phe (150 ppm) + Zn^{2+} (5 ppm)	12711	4.0083×10^{-10}	4.181

(a)

(a)

(b)

(b)

FIGURE 2: AC impedance spectra of carbon steel immersed in test solution (Nyquist plot) (pH = 8). (a) Well water (blank). (b) Well water + DL-phenylalanine (150 ppm) + Zn^{2+} (5 ppm).

FIGURE 3: AC impedance spectra of carbon steel immersed in test solution (impedance-Bode plot) (pH = 8). (a) Well water (blank). (b) Well water + DL-phenylalanine (150 ppm) + Zn^{2+} (5 ppm).

4.181. These results lead to the conclusion that a protective film is formed on the metal surface.

3.6. SEM Analysis of Metal Surface. SEM provides a pictorial representation of the surface. To understand the nature of the surface film in the absence and presence of inhibitors and the extent of corrosion of carbon steel, the SEM micrographs of the surface are examined [25–27].

The SEM images of different magnification ($\times 500$, $\times 1000$) of carbon steel specimen immersed in well water for 7 days in the absence and presence of inhibitor system are shown in Figures 5(a), 5(b), and 5(c), respectively.

The SEM micrographs of polished carbon steel surface (control) in Figure 5(a) show the smooth surface of the metal. This shows the absence of any corrosion products (or) inhibitor complex formed on the metal surface.

FIGURE 4: AC impedance spectra of carbon steel immersed in test solution (phase-Bode plot) (pH = 8). (a) Well water (blank). (b) Well water + DL-phenylalanine (150 ppm) + Zn^{2+} (5 ppm).

The SEM micrographs of carbon steel surface immersed in well water (Figure 5(b)) show the roughness of the metal surface which indicates the highly corroded area of carbon steel in well water. However, Figure 5(c) indicates that in the presence of inhibitor (150 ppm DL-Phe and 5 ppm Zn^{2+}) the rate of corrosion is suppressed, as can be seen from the decrease of corroded areas. The metal surface is almost free from corrosion due to the formation of insoluble complex on the surface of the metal [25]. In the presence of DL-Phe and Zn^{2+} , the surface is covered by a thin layer of inhibitors which effectively controls the dissolution of carbon steel.

3.7. Energy Dispersive Analysis of X-Rays (EDAXs). The EDAXs survey spectra were used to determine the elements present on the metal surface before and after exposure to the inhibitor solution [26–29]. The objective of this section was to confirm the results obtained from chemical and electrochemical measurements that a protective surface film of inhibitor is formed on the metal surface. To achieve this,

FIGURE 5: SEM analysis of carbon steel; magnification $\times 1000$ (control). (b) Carbon steel immersed in well water, magnification $\times 1000$ (blank). (c) Carbon steel immersed in well water + 150 ppm DL-phenylalanine + 5 ppm of Zn^{2+} magnification $\times 1000$.

EDAX examinations of the metal surface were performed in the absence and presence of inhibitors system [26–29].

EDAX spectrum of carbon steel immersed in well water is shown in Figure 6(a). They show the characteristic peaks of some of the elements constituting the carbon steel sample. The EDAX spectrum of carbon steel immersed in well water containing 150 ppm of DL-Phe and 5 ppm of Zn^{2+} is shown in Figure 6(b). It shows the additional line characteristic for the existence of N and Zn. In addition, the intensity of C and O signals is enhanced. The appearance of the N and Zn signal and this enhancement in C and O signal is due to the presence of inhibitor. These data show that metal surface covered the N, O, C, and Zn atoms.

FIGURE 6: EDAX spectra of (a) carbon steel sample after immersion in well water blank. (b) carbon steel sample after immersion in solution containing well water + DL-phe (150 ppm) + Zn^{2+} (5 ppm).

This layer is undoubtedly due to the inhibitor system. The N, Zn signals and this high contribution of O and C are not present on the metal surface exposed in well water.

Figure 6(b) shows that the Fe peaks observed in the presence of inhibitor are considerably suppressed relative to those observed in well water (blank solution). The suppression of the Fe peaks occurs because of the overlying inhibitor film. This observation indicates the existence of an adsorbed layer of inhibitor that protects steel against corrosion. These results suggest that N, O, and C atoms of DL-phenylalanine have coordinated with Fe^{2+} , resulting in the formation of Fe^{2+} -DL-Phe complex on the anodic sites of metal surface and presence of Zn atoms is precipitated as $\text{Zn}(\text{OH})_2$ on the cathodic sites of metal surface.

4. Conclusion

Present study leads to the following conclusions. The formulation consisting of 150 ppm of DL-Phenylalanine and 5 ppm

of Zn^{2+} offers good inhibition efficiency of 90%. Polarization study reveals that this formulation functions as an anodic inhibitor. AC impedance spectra reveal that a protective film is formed on the metal surface. SEM and EDAX confirm the presence of a protective film on the metal surface.

Acknowledgments

The authors are thankful to their respective management and UGC for their encouragement.

References

- [1] N. Hackerman, "The theory and practice of corrosion and its control in industry," *Langmuir*, vol. 3, no. 6, pp. 922–924, 1987.
- [2] A. Nestle, "Corrosion inhibitors in petroleum production primary recovery," in *Corrosion Inhibitors*, C. C. Nathan, Ed., NACE, Houston, Tex, USA, 1973.
- [3] E. W. Flick, *Corrosion Inhibitors: An Industrial Guide*, William Andrew, 2nd edition, 1993.
- [4] G. Moretti, F. Guidi, and G. Grion, "Tryptamine as a green iron corrosion inhibitor in 0.5 M deaerated sulphuric acid," *Corrosion Science*, vol. 46, no. 2, pp. 387–403, 2004.
- [5] H. Ashassi-Sorkhabi, M. R. Majidi, and K. Seyyedi, "Investigation of inhibition effect of some amino acids against steel corrosion in HCl solution," *Applied Surface Science*, vol. 225, no. 1–4, pp. 176–185, 2004.
- [6] S. Bilgic and A. A. Aksut, "Effect of amino acids on corrosion of cobalt in H_2SO_4 ," *British Corrosion Journal*, vol. 28, no. 1, pp. 59–62, 1993.
- [7] G. Moretti and F. Guidi, "Tryptophan as copper corrosion inhibitor in 0.5 M aerated sulfuric acid," *Corrosion Science*, vol. 44, no. 9, pp. 1995–2011, 2002.
- [8] N. O. Eddy, U. J. Ibok, and B. I. Ita, "QSAR and quantum chemical studies on the inhibition potentials of some amino acids for the corrosion of mild steel in H_2SO_4 ," *Journal of Computational Methods in Sciences and Engineering*, vol. 11, no. 1–2, pp. 25–43, 2011.
- [9] B. V. A. Rao, M. V. Rao, S. S. Rao, and B. Sreedhar, "Synergistic effect of N,N-Bis(phosphonomethyl) glycine and zinc ions in corrosion control of carbon steel in cooling water systems," *Chemical Engineering Communications*, vol. 198, no. 12, pp. 1505–1529, 2011.
- [10] N. A. Abdel Ghany, A. E. El-Shenawy, and W. A. M. Hussien, "The inhibitive effect of some amino acids on the corrosion behaviour of 316L stainless steel in sulfuric acid solution," *Modern Applied Science*, vol. 5, no. 4, pp. 19–29, 2011.
- [11] S. Varvara, I. Rotaru, M. Popa, and L. M. Mureşan, "Inhibition of bronze corrosion in aerated acidic solution using amino acids as environmentally friendly inhibitors," *Revue Roumaine de Chimie*, vol. 56, no. 8, pp. 793–801, 2011.
- [12] D.-Q. Zhang, B. Xie, L.-X. Gao, Q.-R. Cai, H. G. Joo, and K. Y. Lee, "Intramolecular synergistic effect of glutamic acid, cysteine and glycine against copper corrosion in hydrochloric acid solution," *Thin Solid Films*, vol. 520, no. 1, pp. 356–361, 2011.
- [13] J. Wu, Q. Wang, S. Zhang, and L. Yin, "Methionine as corrosion inhibitor of brass in O_2 -free 1M NaOH solution," *Advanced Materials Research*, vol. 308–310, pp. 241–245, 2011.
- [14] J. Wilson Sahayaraj, J. Amalraj, and S. Rajendran, "Eco-friendly inhibitor L-valine - Zn^{2+} -SG system controlling the corrosion

- of carbon steel in rain water," in *Proceedings of the International Conference on "Recent Advances in Space Technology Services and Climate Change" (RSTS and CC'10)*, pp. 247–251, November 2010.
- [15] M. A. Amin, "A newly synthesized glycine derivative to control uniform and pitting corrosion processes of Al induced by SCN⁻ anions—chemical, electrochemical and morphological studies," *Corrosion Science*, vol. 52, no. 10, pp. 3243–3257, 2010.
- [16] M. Ormellese, F. Bolzoni, L. Lazzari, A. Brenna, and M. Pedferri, "Organic substances as inhibitors for chloride-induced corrosion in reinforced concrete," *Materials and Corrosion*, vol. 62, no. 2, pp. 170–177, 2011.
- [17] N. H. Helal and W. A. Badawy, "Environmentally safe corrosion inhibition of Mg-Al-Zn alloy in chloride free neutral solutions by amino acids," *Electrochimica Acta*, vol. 56, no. 19, pp. 6581–6587, 2011.
- [18] G. Wranglen, *An Introduction to Corrosion and Protection of Metals*, Chapman & Hall, New York, NY, USA, 1985.
- [19] A. Baral and R. D. Engelken, "Chromium-based regulations and greening in metal finishing industries in the USA," *Environmental Science and Policy*, vol. 5, no. 2, pp. 121–133, 2002.
- [20] A. Y. El-Etre, "Inhibition of aluminum corrosion using *Opuntia* extract," *Corrosion Science*, vol. 45, no. 11, pp. 2485–2495, 2003.
- [21] A. Y. El-Etre, "Natural honey as corrosion inhibitor for metals and alloys. I. Copper in neutral aqueous solution," *Corrosion Science*, vol. 40, no. 11, pp. 1845–1850, 1998.
- [22] H. Ashassi-Sorkhabi, M. R. Majidi, and K. Seyyedi, "Investigation of inhibition effect of some amino acids against steel corrosion in HCl solution," *Applied Surface Science*, vol. 225, no. 1–4, pp. 176–185, 2004.
- [23] Z. Ghasemi and A. Tizpar, "The inhibition effect of some amino acids towards Pb-Sb-Se-As alloy corrosion in sulfuric acid solution," *Applied Surface Science*, vol. 252, no. 10, pp. 3667–3672, 2006.
- [24] D.-Q. Zhang, L.-X. Gao, and G.-D. Zhou, "Inhibition of copper corrosion in aerated hydrochloric acid solution by amino-acid compounds," *Journal of Applied Electrochemistry*, vol. 35, no. 11, pp. 1081–1085, 2005.
- [25] D. Gopi, S. Manimozhi, K. M. Govindaraju, P. Manisankar, and S. Rajeswari, "Surface and electrochemical characterization of pitting corrosion behaviour of 304 stainless steel in ground water media," *Journal of Applied Electrochemistry*, vol. 37, no. 4, pp. 439–449, 2007.
- [26] 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," *Electrochimica Acta*, vol. 52, no. 11, pp. 3588–3600, 2007.
- [27] M. A. Amin, S. S. Abd El-Rehim, and H. T. M. Abdel-Fatah, "Electrochemical frequency modulation and inductively coupled plasma atomic emission spectroscopy methods for monitoring corrosion rates and inhibition of low alloy steel corrosion in HCl solutions and a test for validity of the Tafel extrapolation method," *Corrosion Science*, vol. 51, no. 4, pp. 882–894, 2009.
- [28] S. S. A. Rehim, O. A. Hazzazi, M. A. Amin, and K. F. Khaled, "On the corrosion inhibition of low carbon steel in concentrated sulphuric acid solutions. Part I: chemical and electrochemical (AC and DC) studies," *Corrosion Science*, vol. 50, no. 8, pp. 2258–2271, 2008.
- [29] M. A. Migahed, E. M. S. Azzam, and S. M. I. Morsy, "Electrochemical behaviour of carbon steel in acid chloride solution in the presence of dodecyl cysteine hydrochloride self-assembled on gold nanoparticles," *Corrosion Science*, vol. 51, no. 8, pp. 1636–1644, 2009.