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Anti-Corrosive Behavior of Senna Aqueous Extract to Aluminum in Alkaline Solutions

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ABSTRACT

Electrochemical measurements (EIS and PDP) were used to evaluate the anti-corrosive behaviour of SAE on Al in 0.25 M NaOH solutions. The results showed that the inhibition efficiency increases with increasing SAE concentration. PDP measurements revealed that SAE acts as a mixed type inhibitor against the corrosion of Al in the studied solution. EIS measurements indicated the formation of a compact adsorbed layer by inhibitor species on Al surface. Different adsorption isotherm models were tested and paramount fitting was obtained by Langmuir isotherm model. The analysis of FTIR spectra confirmed the formation of a strong interaction between inhibitor species and Al surface.

Keywords: Aluminum, Corrosion, Senna, Polarization, Impedance, Inhibition, FTIR

INTRODUCTION

In the past, the term "oxidation" was consistently used in place of the term "corrosion". Nevertheless, the latter is the right term because corrosion is also an electrochemical reaction, during which the metal is oxidized, and indicates its conversion into an oxide, i.e. the form in which it existed in the natural ores [1]. Aluminum is actually a very effective reactive metal, and one of its important features is the tendency to undergo oxidation relatively quickly. The resultant aluminum oxide covers the metal surface, and protects the interior aluminum from any further reaction [2]. However, if anything corrodes this layer, then the attack becomes rapid until the aluminum is consumed [3]. The dissolution rate of aluminum oxide depends on the pH value. It is higher at acidic and alkaline pH values, which reveals the amphoteric properties of aluminum oxide [1]. In general, aluminum surfaces corrode in higher alkaline solutions by forming soluble species (AlO_2^-) and generating hydrogen molecules (H₂), according to the following redox reaction [4]:

(1)

$$Al + OH^- + H_2O \rightarrow AlO_2^- + \frac{3}{2}H_2$$

One strategy of reducing aluminum corrosion is the use of inhibitors that decrease the dissolution rate of the corroded metal to a recommended level with little environmental impact [5]. The research field of corrosion inhibitors is going through extraordinary changes the ecological concern point of view. Ecological rules require corrosion inhibitors to be green, environmentally friendly and safe [5]. Some current studies have used of green inhibitors acquired from plant sources, to control the deterioration of aluminum in alkaline solutions. These inhibitors include Gum Arabic [6], *Sansevieria trifasciata* extract [7], Damsissa (*Ambrosia maritime* L.) extract [8], *Gossipium hirsutum* L. extracts [9], *Hibiscus sabdariffa* leaves extract [4], Azwain (*Trachyspermum copticum*) seed extract [10] and *Euphorbia hirta and Dialium guineense* leave extracts [11], *Senna auriculata* leaves extract [12] and *Neolamarkia cadamba* bark extact [13]. It is worth noting that most of the literature agree well that the inhibitors for aluminum corrosion in alkaline solutions [14-20]. Generally, the core mechanism of inhibiton is no different, whether using pure organic compounds or natural products, which is built mainly on physical adsorption and/or chemical adsorption for the inhibitor species on the metal surface. The resultant adsorbed layer reduces the surface area that is available for the attack of aggressive ions in the test solution. Valuable information on adsorption can be derived from the adsorption isotherms. Langmiur [10,21], Temkin [22,23], Frumkin [24,25], Freundlich [7,26] and Flory-Huggins [27] adsorption isotherms are the most common models used to fit the adsorption data of

various corrosion inhibitors. Recently, the Dubinin-Radushkevich adsorption isotherm was used successfully to distinguish the type of inhibitor adsorption, whether chemical or physical adsorption [4,28].

Senna leaves are one of the medicinal herbs, which have been used for a long time in the Eastern and Western countries for the treatment of constipation. It is commercially available and consists of dried leaflets of Alexandria senna (Cassia acutifolia Delile) or Tinnevelly senna (Cassia angustifoliaVahl) belonging to the plant family Leguminosae [29,30]. The active constituents of Senna are known to be sennosides A, B, C and D, while 1,8-dihydroxyanthraquinone derivatives such as chrysophanol, aloe-emodine, rhein and their glycosides are also present [31]. This work is aimed

(i) to study the effect of Senna Aqueous Extract (SAE) on the Al corrosion rate in 0.25 M NaOH using electrochemical impedance spectroscopy (EIS) and potentiodynamic polarization (PDP) measurements,

(ii) to analyze the adsorption data using various adsorption isotherm models, and

(iii) to analyze the protective layer formed on Al by using Fourier transform infrared (FTIR) spectroscopy.

EXPERIMENTAL

Inhibitor preparation

SAE was prepared as follows: 25 g of dried senna leaves (Figure 1) were crushed and mixed with 250 mL of deionized water in suitable round bottom flask. The mixture was heated for 1 h on a boiling water bath. After filtration, the water was evaporated from the extract in an oven at controlled temperature (50-60°C) to yield a dark brown crystalline precipitate (Figure 2b). Accordingly, the concentration of SAE was expressed as w/v.

Working electrode preparation

The chemical composition of the commercially pure aluminum used in the present study was (wt%): 0.002% Cu, 0.003% Zn, 0.100% Pb, 0.050% Co, 0.011% Ni, 0.179% Fe, 0.082% Cr and 99.574% Al. A rod of 5 cm in length and 1 cm in diameter was used as the working electrode, after inserting into a Teflon tube just larger than the specimen and fixed with an adhesive. In this case, the cross-sectional area exposed to the solution was 0.785 cm². Surface preparation of the specimens was carried out using SiC abrasive papers ranging from 80 to 1000 grit. Afterwards, the abraded aluminum surface was washed with deionized water, degreased with acetone and finally dried at room temperature before immersion in the tested solution.

Test solutions preparation

1 M NaOH stock solution was prepared by dissolving the appropriate amount of NaOH (analytical grade) in 2 L of deionized water. Alkaline solutions for each test (0.25 M) were newly prepared by dilution, either in the absence or in the presence of a certain concentration of inhibitor. The inhibitor concentrations (0.25-3.5 g.L⁻¹) were prepared by adding an appropriate amount of SAE to the aggressive solution. The volume of test solution for each experiment was 100 mL. All test solutions were stagnant and not deaerated before use and maintained at 30° C.

PROCEDURES

Electrochemical methods

Electrochemical Impedance Spectroscopy (EIS) and potentiodynamic polarization (PDP) were used to assess the Al corrosion rates, in the absence and presence of inhibitor using ACM Gill AC Potentiostat/Galvanostat model 655. These techniques enable the scientist to determine corrosion rate with high sensitivity, assess rate controlling mechanisms, and in some cases make life predictions [32]. EIS and PDP were carried out using a three-electrode cell design consisting of Al as the working electrode, a platinum wire as auxiliary electrode, and Ag/AgCl/KCl_{sat} electrode was used as a reference. EIS measurements were carried out in the frequency range of 30 kHz–0.1 Hz, at the steady state potential, by applying 30 mV sine wave ac voltage. EIS spectra were



Figure 1: (a) The dried senna leaves and (b) The dark brown crystalline precipitate of SAE

plotted in the Nyquist and Bode formats. For PDP measurements, the potential was scanned at a scan rate of 1 mV s⁻¹ from the cathodic (-1,700 mV) to anodic (-1,300 mV) potentials. Electrochemical parameters were extracted using ACM software analysis version 4 based on Randle equivalent circuit for EIS spectra and Tafel ruler extrapolation method for PDP curves.

FTIR method

FTIR spectra were recorded in a Perkin- Elmer spectrophotometer model Frontier (USA), which extended from 400 to 4000 cm⁻¹ using the KBr disk technique. The first sample of FTIR characterization is the SAE powder, which mixed with KBr and compressed as a disk. The second sample was the skinny film adsorbed on asteel surface after immersion for 72 h in 0.25 M NaOH solution containing 1.5 g.L⁻¹ SAE, which was first cleaned, well dried, rubbed with a small amount of KBr and compressed as a desk.

RESULTS AND DISCUSSION

Analysis of PDP curves

Figure 2 shows the PDP curves for pure Al in 0.25 M NaOH in the absence and presence of different concentrations of SAE. The electrochemical parameters derived from these curves (E_{corr} , i_{corr} and IE%) are listed in Table 1. In this case the inhibition efficiency percentage, IE%, is calculated as follows:

$$IE\% = \left(1 - \frac{i_{corr}}{i_{corr}^0}\right) \times 100 \tag{2}$$

Where i_{corr}^{o} and i_{corr} are the corrosion current density values in the absence and presence of SAE, respectively. Inspection of Table 1 reveals that the presence of increasing amount of SAE leads to irregular displacement for the E_{corr} value of pure Al, compared to the free solution. Since this displacement is less than 85 mV, the studied inhibitor can be classified as a mixed type inhibitor [33-35]. It was observed that the addition of SAE affected both the anodic and cathodic curves (Figure 2) and caused a remarkable decrease in the value of i_{corr} with increasing the concentration of SAE (Table 1). In the light of this, the effective constituents of SAE were expected to adsorb on the Al|solution interface, thus blocking the action of the aggressive solution and slow down both the cathodic and the anodic reactions. The results in Table 1 revealed positive correlation between inhibitor concentration and the value of, *I.E.*, increasing inhibitor concentration enhances more species of SAE to adsorb on the Al surface leading to higher surface coverage.



Figure 2: Potentiodynamic polarization curves of Al in 0.25 M NaOH in the absence and presence of different concentrations of SAE

Table 1: PDP parameters of Al in 0.25 M NaOH in the absence and presence of different concentrations of SAE

C _{inh.} (g.L ⁻¹)	- E _{corr.} (mV)	i _{corr.} (mA.cm ⁻²)	IE%
0	1519.5	1.98	0
0.25	1471.4	1.27	36
0.5	1484.4	0.87	56
1.5	1482.2	0.69	65
2.5	1512.1	0.56	72
3	1522.4	0.43	78
3.5	1516.5	0.31	84

Analysis of EIS spectra

Figure 3 shows the EIS spectra of pure Al in 0.25 M NaOH in the absence and presence of different concentrations of SAE presented as Nyquist (Figure 3a) and Bode (Figure 3b and 3c) plots. These spectra are similar, indicating that the addition of SAE does not modify the reaction mechanism of aluminum in the studied solution. The Nyquist plots (Figure 3a) are apparently characterized by two depressed capacitive semicircles separated by an inductive loop. The plots indicated that increasing SAE concentration in the aggressive medium leads to increase the size of the capacitive semicircles and hence the electrode impedance (Figure 3b), indicating suppression of corrosion rate with inhibitor addition. While the continuous increase in the phase angle shift with inhibitor concentration, Figure 3c, reflects the formation of a compact and stable adsorbed layer on the metal surface [36,37].

The EIS parameters such as R_{cl} and C_{dl} were estimated and listed in Table 2 with the corresponding value of *IE*% The value of *IE*% is calculated by the following equation:

$$IE\% = \left(\frac{R_{ct} - R_{ct}^{0}}{R_{ct}}\right) \times 100$$
(3)

Where R_{cl}^{o} and R_{cl} are the charge transfer resistance in the absence and presence of SAE, respectively. Table 2 revealed that the addition of SAE improves R_{cl} values and get down the C_{dl} values. The decrease in C_{dl} may be attributed to the formation of an adsorbed film on the Al surface from the alkaline inhibited solution and the film thickness is inversely proportional to the C_{dl} value [4], i.e. directly proportional with inhibitor concentration which in good agreement with increasing *IE*% in the same direction.



Figure 3: EIS spectra, (a) Nyquist and (b),(c) bode plots, of Al in 0.25 M in the absence and presence of different concentrations of SAE

Table 2: EIS parameters of Al in 0.25 M NaOH in the absence and presence of different concentrations of SAE

C_{inh} , (g.L ⁻¹)	$R_{ct}(ohm.cm^2)$	C_{dl} ($\mu F.cm^{-2}$)	IE%
Ó	8.22	81.98	0
0.25	20.5	41.44	60
0.5	29.91	35.5	73
1.5	37.81	29.36	78
2.5	46.81	16.94	82
3	60.06	14.27	86
3.5	82.57	13.34	90

Analysis of adsorption data

Assuming that the surface coverage θ , is proportional to *IE*% and given as: θ =*IE*%/*100*. Hence, the simple relationship between θ values and SAE concentration is called adsorption isotherm as illustrated in Figure 4. The adsorption isotherm is one of the most important data used in identifying the mechanism of adsorption systems. Analysis of adsorption data is essential to develop an equation which precisely represents the results. Therefore, the values of θ at certain temperature can be introduced into several isotherm equations, in order to obtain the one that best fitted the adsorption data. In this study, adsorption data were fitted by four adsorption isotherm models namely: Langmuir, Temkin, Freundlich and Dubinin–Radushkevich (Table 3). Figure 5 displays the linear fitting of θ values obtained at different concentrations of SAE, to the previous adsorption isotherm models. Various adsorption parameters were derived based on the relationships shown in Figure 5 and are listed in Table 4. According to the regression coefficients (r²), the order for data fitting to the various adsorption isotherms can be given as:

Langmuir>Temkin=Dubinin-Radushkevich>Freundlich

It can be concluded that the Langmuir model presented the best fit to experimental data with regression coefficient superior to 0.99. This implies that SAE species form a monolayer on the Al surface by physical adsorption mechanism [4,38]. Furthermore, the mean adsorption energy, *E*, obtained from the Dubinin–Radushkevich adsorption isotherm is less than 8 kJ mol⁻¹ which indicates that SAE species may adsorb physically onto the Al surface [4,39]. However, the spontaneity of the adsorption process can be discussed on the basis of the free energy change of adsorption (ΔG_{ads}). ΔG_{ads} can be calculated by using the following equation:

$$\log K_L = -\log[H_2O] - \frac{\Delta G_{ads}}{2.303RT} \tag{4}$$

Where $[H_2O]$ is the concentration of water molecules in g.L⁻¹, R is the molar gas constant in kJ.mol⁻¹.K⁻¹ and T is the absolute temperature. The obtained values of ΔG_{ads} from techniques, PDP and EIS, are -19.33 kJ mol⁻¹ and -21.63 kJ mol⁻¹, respectively. The negative sign for ΔG_{ads} values indicates that SAE species are adsorbed spontaneously on the Al surface [40].



Figure 4: Variation of Al surface coverage (β) with concentration of SAE

Table 3:	The studied adsor	ption isotherm models
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Adsorption isotherm model	Linear expression	Plot	Parameters
Langmuir [10,21]	$C_{inh}\theta^{-1} = K_L^{-1} + C_{inh}$	$C_{inh} \theta^{-1}$ vs. C_{inh}	$K_L = (\text{intercept})^{-1}$, where K_L is the Langmuir constant of adsorption
Temkin [22,23]	$\theta = f^{-1} \ln K_T + f^{-1} \ln C_{inh}$	θ vs. $\ln C_{inh}$	$f = (\text{slope})^{-1}$ and $K_T = e^{(\text{intercept /slope})}$, where K_T is the Temkin constant of adsorption and f is the Temkin heterogeneity factor
Freundlich [7,26]	$\log \theta = \log K_F + n \log C_{inh}$	$\log \theta$ vs. $\log C_{inh}$	$K_F = 10^{\text{(intercept)}}$ and $n = \text{slope}$, where K_F is the Freundlich constant of adsorption and $0 < n < 1$ is the adsorption intensity
Dubinin- Radushkevich [4]	$\ln\theta = \ln\theta_{\rm max} - B\sigma^2$	$\ln\theta vs. \sigma^2$	$\theta_{\max} = e^{(\text{intercept})}, -B = \text{slope and } \sigma = RT \ln(1 + C_{inh}^{-1})$, where θ_{\max} is the maximum surface coverage, <i>B</i> is a constant related to the mean adsorption energy $E(E = \sqrt{1/2B})$ needed to adsorb one mole of inhibitor from bulk solution to metal surface.



Figure 5: Fitting of θ values obtained at different concentrations of SAE to various adsorption isotherm models

Table 4: Isotherm parameters for	SAE adsorption on Al surface from	n 0.25 M NaOH estimated from	various adsorption isotherm models
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Adsorption isotherm	Method of measurements		
model	PDP	EIS	
Langmuir			
$K_{L}(L.g^{-1})$	2.15	5.35	
slope	1.12	1.09	
r ²	0.99	1	
Temkin			
$K_T(\mathrm{L.g}^{-1})$	49.28	1939.14	
f	6.25	10.00	
r ²	0.95	0.95	
Freundlich			
$K_{\rm F}({\rm L.g^{-1}})$ 0.58 0.75			
n	0.27	0.14	
r ²	0.92	0.93	
Dubinin-Radushkevich			
θ_{max}	0.77	0.86	
B (mol ² .kJ ⁻²)	0.05	0.02	
E (kJ.mol ⁻¹)	3.16	5	
r ²	0.95	0.95	

Analysis of FTIR spectra

As was mentioned previously, the principal active constituents of Senna are dimeric glycosides called Sennosides A, B, C, and D [31]. The aglycones are composed of Aloe-Emodin+Rhein for A and B and Rhein+Rhein for C and D as shown in Figures 6 and 7 [41]. In order to confirm the adsorption of SAE on the metal surface, FTIR spectra analysis was carried out for the SAE powder and the corrosion products formed on the metal surface after immersion for 72 h in 0.25 M NaOH containing 1.5 g.L⁻¹ of SAE (Figure 8). Figure 8a showed the FTIR spectrum of the SAE powder where a broad band was recorded at 3401 cm⁻¹, due to hydrogen bond formation between OH and carbonyl groups of inhibitor. The stretching vibrations of both aliphatic and aromatic C-H vibrations were recognized at 2925 and 2854 cm⁻¹, respectively. The carbonyl group was located at a lower frequency of 1599 cm⁻¹, confirming its involvement in hydrogen bonding. Furthermore, the v(C=C) was located at 1413 cm⁻¹ while v (C-O) was observed at 1075 cm⁻¹. Two absorption frequencies of out of plane pending of both OH and C-H were recorded at 919 and 603 cm⁻¹, respectively. So, FTIR spectrum recorded in Figure 8a agrees with the function groups of the active constituents of SAE (Figures 6 and 7).

Figure 8b represents the FTIR of corrosion products formed on the metal surface after immersion in 0.25 M NaOH solution containing 1.5 g.L⁻¹ of SAE where a sharp intense absorption band at 3436 cm⁻¹ was observed confirming the formation of aluminum



Figure 8: FTIR spectra of (a) SAE powder and (b) corrosion products formed on Al surface after immersion for 72 h in 0.25M NaOH solution containing 1.5 g.L⁻¹ SAE

hydroxide between the metal and the adsorbed layer. It also confirms the disappearance of hydrogen bonding between the OH and carbonyl groups of the inhibitor species. Small shifts of both aliphatic and aromatic C-H vibrations of adsorbed inhibitor were compared with the inhibitor alone, confirming the interaction between inhibitor species and the Al surface. An important finding from Figure 8b is the blue shift of the carbonyl group v (C=O) to 1637 cm⁻¹ compared with 1599 cm⁻¹, for the inhibitor itself (Figure 8a). Once again, this finding confirms the absence of hydrogen bonding between inhibitor molecules due to the interaction between the inhibitor and Al surface. The disappearance of some inhibitor vibrations after adsorption, especially v(C=C), γ (OH) and γ (C-H), powerfully confirms the strong interaction between the inhibitor species and Al surface.

GENERAL REMARKS

- SAE was found to be an effective inhibitor against the corrosion of Al in an alkaline solution.
- The inhibition efficiency increases with increase in SAE concentration.
- PDP measurements revealed that SAE acts as a mixed type inhibitor for the corrosion of pure Al in 0.25 M NaOH.
- EIS measurements indicates the formation of an adsorbed film on the Al surface from the alkaline inhibited solution.
- Different adsorption isotherm models were tested and paramount fitting was obtained by the Langmuir isotherm model.
- Based on the negative values of ΔG_{ads} obtained from both EIS and PDP measurements, SAE species were adsorbed spontaneously on Al surface from 0.25 M NaOH.
- Good agreement between results obtained from EIS and PDP measurements was observed.
- Analysis of FTIR spectra confirms the adsorption of SAE species on Al surface.

REFERENCES

- [1] C. Vargel, M. Jacques, M.P. Schmidt, Elsevier, Netherland, 2004.
- [2] http://www.cmiengineer.com/whitepapers/aluminum_corrosion.pdf
- [3] R.B. Spacht, J. Chem. Educ., 1946, 23(5), 253.
- [4] E.A. Noor, J. Appl. Electrochem., 2009, 39, 1465.
- [5] V.S. Sastri, Winston Revie, Series Editor, 2011.
- [6] S.A. Umoren, I.B. Obot, E.E. Ebenso, P.C. Okafor, O. Ogbobe, Anti-Corros. Method M., 2006, 53(5), 77.
- [7] E.E. Oguzie, Corros. Sci., 2007, 49(3), 1527.
- [8] A.M. Abdel-Gaber, E. Khamis, H. Abo-El Dahab, Sh. Adeel, Mater. Chem. Phys., 2008, 109 (2-3), 297.
- [9] O.K. Abiola, J.O.E. Otaigbe, O.J. Kio, Corros. Sci., 2009, 51, 1879.
- [10] A. Singh, M.A. Quraishi, Res. J. Recent. Sci., 2012, 1, 57.
- [11] L.A. Nnanna, I.U. Anozie, C.S. Akoma, I.M. Mejeha, K.B. Okeoma, K.I. Mejeh, Amer. J. Mater. Sci., 2011, 1(2), 76.
- [12] A. Sirajunnisa, M.I. Fazal Mohamed, A. Subramania, B.R. Venkatraman, IJSEAT, 2014, 2, 58.
- [13] N. Chaubey, V.K. Singh, M.A. Quraishi, E.E. Ebenso, Int. J. Electrochem. Sci., 2015, 10, 504.
- [14] B. Müller, Pigm. Resin Technol., 2002, 31(2), 84.
- [15] B. Müller, Corros. Sci., 2004, 46, 159.
- [16] D. Mercier, M.G. Barthés-Labrousse, Corros. Sci., 2009, 51, 339.
- [17] S. Edrah, S.K. Hasan, J. Appl. Sci. Res., 2011, 6(8), 1045.
- [18] H.N. Soliman, Corros. Sci., 2011, 53, 2994.
- [19] M. Lashgari, Electrochim. Acta., 2011, 56, 3322.
- [20] P.D.R. Kumari, J. Nayak, A.N. Shetty, J. Coat. Technol. Res., 2011, 8(6), 685.
- [21] A.M. Al-Turkustani, S.T. Arab, L.S.S. Al-Qarni, J. Saudi Chem. Soc., 2011, 15, 73.
- [22] S.A. Umoren, I.B. Obot, E.E. Ebenso, N. Obi-Egbedi, Portu. Electrochim. Acta., 2008, 26, 199.
- [23] E.A. Noor, Mater. Chem. Phys., 2011, 131, 160.
- [24] A. Chetouani, B. Hammouti, M. Benkaddour, Pigm. Resin Technol., 2004, 33(1), 26.
- [25] L. Valek, S. Martinez, Mater. Lett., 2007, 61, 148.
- [26] U.M. Eduok, S.A. Umoren, A.P. Udoh, Arab. J. Chem., 2012, 5, 325.
- [27] N.O. Eddy, P.A.P. Mamza, Portu. Electrochim. Acta., 2009, 27(4), 443.
- [28] M.M. Solomon, S.A. Umoren, I.I. Udosoro and A.P. Udoh, Corros. Sci., 2010, 52, 1317.
- [29] United States pharmacopoeia 27. Rockville, MD.U.S pharmacopoeia convention: 1686, 2004.

- [30] T.E. Wallis, Ed. Text book of pharmacognosy, 5th Edn., CBS publishers, New Delhi, 2004, 136-138.
- [31] S. Hayashi, A. Yoshida, H. Tanaka, Y. Mitani, K. Yoshizawa, Chem. Pharm. Bull., 1980, 28, 406.
- [32] G.S. Frankel, JASTM Int., 2008, 5(2), 1.
- [33] Y. Yan, W. Li, L. Cai, B. Hou, *Electrochim. Acta.*, 2008, 53(20), 5953.
- [34] A.K. Satapathy, G. Gunasekaran, S.C. Sahoo, K. Amit, P.V. Rodrigues, Corros. Sci., 2009, 51, 2848.
- [35] H.B. Shao, J.M. Wang, Z. Zhang, J.Q. Zhang, C.N. Cao, Corrosion (NACE)., 2001, 57(7), 577.
- [36] A.A. Mazhar, S.T. Arab, E.A. Noor, Bull. Electrochem., 2001, 17(10), 449.
- [37] K.F. Khaled, Electrochim. Acta, 2009, 54, 4345.
- [38] A.Y. El-Etre, Corros. Sci., 2003, 45, 2485.
- [39] S. Karahan, M. Yurdakoc, Y. Seki, K. Yurdakoc, J. Colloid. Interface. Sci., 2006, 293 (1), 36.
- [40] S. Eid, M. Abdallah, E.M. Kamar, A.Y. El-Etre, J. Mater. Environ. Sci., 2015, 6(3), 892.
- [41] http://www.mdidea.com/products/new/new04005.html