INHIBITION OF CORROSION OF α -BRASS (Cu-Zn, 67/33) IN HNO_3 SOLUTIONS BY SOME ARYLAZO INDOLE DERIVATIVES.

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ABSTRACT

The influence of some arylazo indole derivatives on the corrosion rate of 70/30 α -brass in 2 mol l⁻¹ HNO_3 was investigated using weight loss and galvanostatic polarization techniques. It was found that the investigated compounds behave as inhibitors. The inhibition efficiency increases with increasing the inhibitor concentration, but decreases with increasing the temperature. The adsorption of these compounds on the α -brass surface follows a Frumkin's adsorption isotherm. The electrochemical results indicated that all the investigated compounds act as mixed-type inhibitors. The influence of the substituent group on the inhibition efficiency of the inhibitor was explained in terms of the density of the electron cloud on arylazo indole moiety. Some thermodynamic parameters for corrosion and adsorption processes were determined and discussed.

Keywords: corrosion inhibition; α -brass; synergistic effect; HNO_3 ; arylazo indole derivatives.

INTRODUCTION

Copper and its alloys, because of their excellent resistance to corrosion in neutral aggressive media and their ease of processing, they are widely used in industries, particularly as condensers and heat exchangers in power plants [1]. Electrochemical techniques are powerful tools to study brass since they offer valuable information about the phase and chemical composition [2]. Such techniques have also proved to be useful to study the evolution of brass in the environment [3] to understand the degeneration process and to prevent oxidation of the alloy better [4-6].

A number of studies have recently appeared in the literature [7-9] on the topic of the corrosion inhibition of α -brass in acidic medium. But little work appears to have been done on the inhibition of α -brass alloys in HNO_3 using arylazo indole derivatives.

The aim of this paper is to describe an investigation of the inhibition of corrosion of commercial 67/33 brass in 2 mol l⁻¹ HNO_3 solutions by some arylazo indole derivatives using weight-loss and galvanostatic polarization measurements.

2. Experimental technique

2.1. Materials

The experiments were performed with local commercial α -brass (Helwan Company of Non-Ferrous Industries, Egypt) with the following composition (weight %) Cu 67.28, Pb 0.029, Fe 0.002, Zn 32.689. Brass specimens were cooled and annealed in an electric oven maintained at 600 °C. After annealing the specimens were quenched in air to reach the ambient temperature. The inhibitors used were selected from arylazo indole derivatives with chemical structures shown in scheme 1. The organic compounds were prepared, purified and identified according to the recommended method [10].

Where: R = OCH_3 (c)
 = CH_3 (b)
 = H (a)
 = NO_2 (d)

2.1.1. Preparation of inhibitors used

Arylazo indole derivatives (a-d) were prepared by adding a mixture of isatin (0.01 moles), p-aminoazobenzene derivatives (0.01 moles) was heated in an oil bath at 170°C for 2h in the presence of freshly fused sodium acetate. After cooling, the solid product was washed with water, dried and recrystallized from ethanol to give 3-arylaazoindol-2-one (a-d) derivatives. Formations of

these compounds were established by both elemental and spectral analyses. In general, the IR spectra gave an absorption bands at 1730, 1658 and 1614 cm⁻¹ due to the CON, C=N and N=N functions, respectively. Moreover, the mass spectrum of compounds (a, b, d) showed the molecular ion peaks at 427 (M⁺, 25%), 356 (M⁺, 100%) and 371 (M⁺, 100%), respectively. Finally, the ¹H-NMR of compound (c) reveals bands at δ 4.1 (s, 3H, OCH_3), 7.2-8.3 (m, 12H, Ar-H), 9.9 (s, 1H, NH).

100 ml stock solutions (10⁻³ mol l⁻¹) of compounds (a-d) were prepared by dissolving an accurately weighed quantity of each material in an appropriate volume of absolute ethanol, then the required concentrations (1×10⁻⁶ - 11×10⁻⁶ mol l⁻¹) were prepared by dilution with bidistilled water.

HNO_3 solution was prepared by diluting the appropriate volume of the concentrated chemically pure acid (BDH grade), with bidistilled water and its concentration was checked by standard solution of Na_2CO_3 .

100 ml stock solution (10⁻² mol l⁻¹) of KSCN (BDH grade) is prepared by dissolving an accurately weighed quantity of this material in an appropriate volume of bidistilled water.

2.2. Chemical technique (weight-loss method)

The reaction basin used in this method was graduated glass vessel 6 cm inner diameter and having a total volume of 250 ml. 100 ml of the test solution were employed in each experiment. The test pieces were cut into 20 x 20 x 2 mm. They were mechanically polished with emery paper (a coarse paper was used initially and then progressively finer grades were employed), ultrasonically degreased in methanol, rinsed in doubly distilled water and finally dried between two filter papers and weighed. The test pieces were suspended by suitable glass hooks at the edge of the basin, and under the surface of the test solution by about 1cm. After specified periods of time, 3 test pieces were taken out of the test solution, rinsed in doubly distilled water, dried as before and weighed again. The average weight loss at a certain time for each set of three samples was taken. The weight loss recorded to the nearest 0.0001g. Solutions were not deaerated.

2.3. Electrochemical technique (galvanostatic polarization method):

Three different types of electrodes were used during polarization measurements, the working electrode was α -brass electrode, which cut from the α -brass sheets, of thickness 0.2 cm. The electrode was of dimensions 1cm x 1cm and was weld from one side to a copper wire used for electric connection. The samples were embedded in glass tube using epoxy resin [11] the electrode was prepared before immersion in the test solution as in the case of weight loss. Saturated calomel electrode and a platinum coil as reference and auxiliary electrodes, respectively, were used. A constant quantity of the test solution (100 ml) was taken in the polarization cell. A time interval of about 30 min was given for the system to attain steady state. Both cathodic and anodic polarization curves were recorded galvanostatically using Amel galvanostat (Model 549) and digital multimeters (Fluke-73) were used for accurate measurements of the potentials and current density. All the experiments were carried out at 30 ±1°C by using an ultra circulating thermostat. The potential at any given current under similar experimental conditions was reproducible within ± 4%. Solutions were not deaerated to make the conditions identical to weight loss measurements.

RESULTS AND DISCUSSION

3.1. Weight-loss measurements

Figure (1) shows the weight loss-time curves for α -brass in 2 mol l^{-1} nitric acid in the presence and absence of different concentrations of compound (c) at 30 °C. These curves are characterized by a sharp rise in weight loss from the beginning. Curves for additives containing system fall below that of the free acid. These curves indicated that, the weight loss of α -brass depends on both the type and concentration of these additives. Increase in bulk concentration and consequently increase of surface coverage by the additive increases their inhibition efficiencies towards α -brass dissolution. The results of the Table (1) show that the inhibition efficiency of all additives increases with the increase of their concentrations in the corrosive medium. It is thus obvious that increase of bulk concentration and consequently, increase of surface area coverage by the additive retards the dissolution of α -brass. The order of the inhibition efficiency of the additive compounds in 2 mol l^{-1} HNO_3 solution over most of the concentration ranges used after is: $c > b > a > d$.

Fig.(1): Weight loss-time curves for α -brass in 2 mol l^{-1} HNO_3 in the presence and absence of different concentrations of compound (c) at 30 °C.

Table 1: Variation of the inhibition efficiency (In %) of the studied compounds with their molar concentrations after 120 min.; immersion at 30 °C.

Concentration mol l^{-1}	In %			
	c	b	a	d
1×10^{-6}	16.7	13.5	11.4	7.2
3×10^{-6}	19.8	17.2	15.7	12.3
5×10^{-6}	23.7	20.6	18.2	14.5
7×10^{-6}	27.4	23.3	21.6	17.9
9×10^{-6}	32.0	28.5	26.8	22.8
11×10^{-6}	33.9	31.6	28.7	26.6

3.2. Adsorption isotherm

To understand the mechanism of corrosion inhibition, the adsorption behavior of the organic adsorbate on the metal surface must be known [12]. The degree of surface coverage (θ) which represents the part of metal surface covered by inhibitor molecules was calculated using the following equation:

$$\theta = [1 - (W_{\text{inh}} / W_{\text{free}})] \quad (1)$$

where W_{free} and W_{inh} are the weight losses in the absence and in presence of inhibitors, respectively.

The degree of surface coverage was found to increase with increasing the concentration of the used additives. Attempts were made to fit θ values to various isotherms including Frumkin, Freundlich, Langmuir and Temkin. By far, the best fit was obtained with Frumkin's isotherm which has the following equation:

$$\theta = \text{Const} + (2.303 / f) \log C \quad (2)$$

$$\text{where, } f = 1/RT [d(\Delta G_a^\circ / d\theta)] \quad (3)$$

where C is the inhibitor concentration and ΔG_a° is the free energy of adsorption. Fig. (2) represents the relation between θ and $\log C$ for the inhibitors (a-d). The Frumkin's adsorption isotherm is obeyed.

Fig.(2):Frumkin isotherm for the adsorption of investigated compounds α brass surface at 30 °C, from weight loss method

3.3. Effect of temperature on the corrosion inhibition of α -brass

The dissolution of α -brass in 2 M nitric acid increases by increasing temperatures Figure (3), the dissolution of α -brass in 2 mol l⁻¹ HNO₃ in the presence of compound c at 11x10⁻⁶ mol l⁻¹ was studied by weight loss method over a temperature range 30-50°C. The weight loss-time curves obtained (Figure 4) in the presence of compound c indicate that the rate of α -brass dissolution increases as the temperature increases, but at lower rate than in uninhibited solutions. The inhibition efficiency of the additives decreases with rising the temperature which proves that the adsorption of these compounds on the surface of α -brass occurs through physical adsorption of the additives on the metal surface. Desorption is aided by increasing the reaction temperature. The apparent activation energy (E_a^*), the enthalpy of activation (ΔH^*) and the entropy of activation (ΔS^*) for the corrosion of α -brass in 2 mol l⁻¹ nitric acid solution in the absence and presence of different concentrations of arylazo indole compounds were calculated from Arrhenius-type equation:

$$\text{Rate (k)} = A \exp(-E_a^*/RT) \quad (4)$$

and transition-state equation:

$$\text{Rate (k)} = RT/Nh \exp(\Delta S^*/R) \exp(-\Delta H^*/RT) \quad (5)$$

where (A) is the frequency factor, (h) is the Planck's constant, (N) is Avogadro's number and (R) is the universal gas constant. Kinetic parameters obtained from plots of log Rate vs. (1/T) [Fig. 5] and log (Rate/T) vs. (1/T) [Fig. 6] graphs for the studied arylazo indole derivatives are given in Table (2). Inspection of Table 2 shows that higher values were obtained for (E_a^*) and (ΔH^*) in the presence of inhibitors indicating the higher protection efficiency observed for these inhibitors. There is also a parallelism between increases in inhibition efficiency and increases in (E_a^*) and (ΔH^*) values. The positive values of (ΔH^*) suggest that the dissolution process is an exothermic phenomenon and that the dissolution of α -brass is difficult. Also, the entropy ΔS^* widely decreases with the content of the inhibitor. This means the formation of an ordered stable layer of inhibitor on α -brass surface [13].

Fig.(3).- Weight loss-time curves for α -brass dissolution in 2 mol l⁻¹ HNO₃ at different temperatures.

Fig.(4).- Weight loss-time curves for α -brass dissolution in 2 mol l⁻¹ HNO₃ in the presence of (11x10⁻⁶ mol l⁻¹) of compound (c) at different temperatures.

Fig.(5): Arrhenius plot for the corrosion of the α -brass in 2 mol l⁻¹ HNO₃ in the presence and absence of investigated compounds.

Table 2: Activation energy (E_a^*), enthalpy change (ΔH_a^*) and entropy change (ΔS_a^*) for the α -brass in 2 mol l⁻¹ nitric acid in absence and presence of different inhibitors.

$-\Delta S_a^*$ J mol ⁻¹ K ⁻¹	ΔH_a^* kJ mol ⁻¹	$-E_a^*$ kJ mol ⁻¹	Compound
161.9	30.2	32.7	Blank
158.9	31.5	34.0	c
158.5	31.7	34.2	b
158.3	31.8	34.3	a
157.2	32.3	34.8	d

Fig. (6): $\log k/T$ vs. $1/T$ for the corrosion of the α -brass in $2 \text{ mol l}^{-1} \text{ HNO}_3$ in presence and absence of investigated compounds.

3.4. Synergistic effect

Some anions are found to enhance the inhibitive effect of several nitrogen containing organic compounds in acid solutions [14-17]. In the present paper the influence of SCN^- ions on the inhibitive performance of arylazo indole compounds has been studied using weight loss technique. Figure (7) represents the weight loss-time curves for α -brass dissolution in 2 mol l^{-1} nitric acid for various concentrations of compound (c) at a concentration $1 \times 10^{-2} \text{ mol l}^{-1}$ SCN^- . The values of inhibition efficiency (In %) for various concentrations of inhibitors in the presence of specific concentration of KSCN are given in Table (3). The synergistic inhibition effect was evaluated using a parameter, S_θ , obtained from the surface coverage values (θ) of the anion, cation and both. Aramiki and Heckerman [18] calculated the synergism parameter S_θ using the following equation:

$$S_\theta = 1 - \theta_{1+2} / (1 - \theta_{1+2}) \quad (6)$$

Fig.(7).- Weight loss-Time curves for α -brass in 2 M HNO_3 in the presence and absence of various concentrations of compound (c) and in presence of ($1 \times 10^{-2} \text{ M}$) of KSCN at 30°C .

Table 3: Values of inhibition efficiencies (In %) of different arylazo indole compounds in the presence of ($1 \times 10^{-2} \text{ mol l}^{-1}$) KSCN for the corrosion of α -brass in $2 \text{ mol l}^{-1} \text{ HNO}_3$ at 30°C . Duration of the experiment: 120 min., immersion.

Conc., mol l^{-1}	In %			
	c	b	a	d
1×10^{-6}	77.7	76.7	75.9	74.1
3×10^{-6}	80.1	78.4	77.3	75.7
5×10^{-6}	82.4	80.4	79.2	77.1
7×10^{-6}	84.4	82.9	80.9	78.4
9×10^{-6}	86.34	85.16	82.72	80.04
11×10^{-6}	88.29	86.73	84.32	81.57

where $\theta_{1+2} = (\theta_1 + \theta_2) - (\theta_1 \theta_2)$; θ_1 = surface coverage by anion; θ_2 = surface coverage by cation; θ_{1+2} = measured surface coverage by both the anion and cation. Table (4) shows the synergism parameter (S_θ) for constant KSCN concentration added to different concentrations of arylazo indole compounds. As can be seen from this Table, values nearly equal to unity were obtained, which suggests that the enhanced inhibition efficiencies caused by the addition of SCN^- to arylazo indole compounds is due mainly to the synergistic effect [19].

The synergistic effect of this SCN^- anion has been observed by other authors [20]. Adsorption of arylazo indole compounds at the α -brass/solution interface occurs through physical adsorption via electron rich centers, i.e. benzene ring through its π -electrons and nitrogen atoms through their lone pairs of electrons by donation of electrons to the empty d-orbital of the metal [21]. It is known that SCN^- anions have strong interactions with α -brass surfaces owing to chemisorptions [22, 23]. The strong chemisorptions of SCN^- anions on the metal surface are responsible for the synergistic effect of SCN^- anions in combination with cation of the inhibitor. The cation is then adsorbed by columbic attraction on the metal surface where SCN^- anions are already adsorbed by chemisorptions. Stabilization of adsorbed SCN^- anions with cations leads to greater surface coverage and therefore greater inhibition.

Table (4): Synergism parameter (S_θ) for various concentrations of different arylazo indole compounds in the presence of (1×10^{-2} mol l⁻¹) KSCN. Duration of the experiment: 120 min., immersion.

Concentration mol l ⁻¹	Synergism parameter (S_θ)			
	c	b	a	d
1×10^{-6}	0.8	1.0	1.0	1.0
3×10^{-6}	1.1	1.0	1.0	1.0
5×10^{-6}	1.2	1.1	1.1	1.0
7×10^{-6}	1.2	1.1	1.1	1.0
9×10^{-6}	1.3	1.1	1.1	1.0
11×10^{-6}	1.5	1.2	1.2	1.0

3.5. Galvanostatic polarization technique

The cathodic and anodic polarization curves of α -brass in 2 mol l⁻¹ nitric acid solution in the absence and presence of different concentrations of compound (c) at 30°C are shown in Figure (8). In the presence of inhibitor, the cathodic and anodic curves are shifted and the shift is dependent on inhibitor concentration. The polarization parameters such as corrosion current density (i_{corr}) obtained by extrapolation of Tafel lines, corrosion potential (E_{corr}), Tafel slopes (β_a and β_c), percentage inhibition efficiency (In %) and degree of surface coverage (θ) are listed in Table (5). As the concentration of the inhibitors increase, there is a marginal shift in E_{corr} and a decrease in i_{corr} . The addition of inhibitors hinders acid attack on the compound α -brass and a comparison of curves in both cases, shows that, with respect to the blank, increasing the inhibitor concentration gives rise to a consistent decrease in anodic and cathodic current densities, indicating that the arylazo indole derivatives act as mixed type inhibitors.

Fig.(8):- Galvanostatic polarization curves of α -brass in 2 mol l⁻¹ HNO₃ alone and containing different concentrations of compound (c) at 30°C.**Table 5:** The effect of concentration of compound (c) on the free corrosion potential (E_{corr}), corrosion current density (i_{corr}), Tafel slopes (β_a & β_c), In % and degree of surface coverage (θ) for α -brass in 2 mol l⁻¹ HNO₃ at 30 °C.

[inh.] mol l ⁻¹	- E_{corr} mV	i_{corr} $\mu\text{A cm}^{-2}$	β_a mV dec ⁻¹	$-\beta_c$ mV dec ⁻¹	θ	In %
00.	720	168.6	55	57	-	-
1×10^{-6}	724	132.6	80	68	0.214	21.4
3×10^{-6}	724	126.6	86	77	0.249	24.9
5×10^{-6}	725	119.1	90	87	0.293	29.3
7×10^{-6}	726	112.8	97	97	0.331	33.1
9×10^{-6}	726	104.6	105	100	0.380	38.0
11×10^{-6}	727	100.9	122	110	0.402	40.2

The values of cathodic Tafel slope β_c for arylazo indole derivatives are found to change with inhibitor concentration, which clearly indicates that arylazo indole derivatives influence the kinetics of hydrogen evolution reaction. However, the values of the anodic Tafel slope β_a , increases only to small extent, as these compounds do not influence anodic dissolution. This indicates an increase in the energy barrier for proton discharge, leading to less gas evolution. The values of In % increase with increase in inhibitor concentration, indicating that a higher surface coverage was obtained in a solution with maximum concentration of inhibitor. The order of decreased inhibition efficiency of arylazo indole compounds is: $c > b > a > d$ (Table 6). This is also in agreement with the observed order of percentage inhibition efficiency calculated from weight loss method. Fig. (9) represents the relation between θ and log C for the inhibitors (a-d). The Frumkin's adsorption isotherm is obeyed.

Table 6: Percent inhibition efficiency from galvanostatic polarization of α -brass containing various concentrations of all compounds used in 2 mol l⁻¹ HNO₃ at 30 °C.

Concentration (mol l ⁻¹)	In %			
	c	b	a	d
1×10^{-6}	21.4	18.4	16.3	12.4
3×10^{-6}	24.9	23.1	20.8	18.1
5×10^{-6}	29.4	26.3	23.7	20.3
7×10^{-6}	33.1	29.0	25.9	23.7
9×10^{-6}	38.0	34.2	31.3	28.9
11×10^{-6}	40.0	37.2	33.8	31.1

Fig.(9):Frumkin isotherm for the adsorption of investigated compounds on brass surface at 30°C, from polarization method

3.6. Chemical structure and corrosion inhibition of α -brass

Inhibition of the corrosion of α -brass in 2 mol l⁻¹ HNO₃ solution by some arylazo indole derivatives as determined by weight loss and galvanostatic polarization measurements was found to depend on concentration, nature of metal, the mode of adsorption of the inhibitors and surface conditions. Skeletal representation of the proposed mode of adsorption of the investigated arylazo indole derivatives as shown in Fig.(10) and clearly indicates the active adsorption centers in the arylazo indole derivatives. These compounds can be adsorbed through the N-atom of the pyridine ring. The surface coordination is through the nitrogen atoms. It was concluded that the mode of adsorption depends on the affinity of the metal towards the π -electron clouds of the ring system [24]. Metals such as Cu and Fe, which have a greater affinity towards aromatic moieties, were found to adsorb benzene rings in a flat orientation. Thus, it is reasonable to assume that the tested inhibitors are adsorbed in a flat orientation through the N- atom of the pyridine ring and O- atom of the OCH₃ group as shown in Fig. (11). The order of decreasing the inhibition efficiency of the investigated compounds in the corrosive solutions was as follow: c > b > a > d. This behavior can be rationalized on the basis of the structure-corrosion inhibition relationship of organic compounds. Linear Free Energy Relationships (LFER) has previously been used to correlate the inhibition efficiency of organic compounds with their Hammett constituent constants (σ) [25]. The LFER or Hammett relation is given by [26-28]:

Fig.(10).- Skeletal representation of the mode of adsorption of indole compounds.

$$\text{Log } R \text{ (rate of corrosion)} = -\rho \sigma \quad (7)$$

where ρ is the reaction constant, those constituents which attract electrons from the reaction center are assigned positive σ values and those which are electron donating have negative σ values. Thus, σ is a relative measure of the electron density at the reaction center. The slope of the plot of log (rate) vs. σ is ρ , and its sign indicates whether the process is inhibited by an increase or decrease of the electron density at the reaction center. The magnitude of ρ indicates the relative sensitivity of the inhibition process to electronic effects. Figure (11) shows that indole derivatives (a-d) give a good correlation. The large positive slope of the correlation line ($\rho = +0.994$) shows a strong dependence of the adsorption character of the reaction center on the electron density of the ring. The strong dependence of the adsorption character of the reaction center on the electron density of the ring may be due to the fact that in this type of derivatives the center of adsorption is conjugated to the ring. Compound (c) has the highest percentage inhibition efficiency, this due to the presence of p -OCH₃ group which is an electron repelling group with negative Hammett constant ($\sigma = -0.27$) this group will increase the electron charge density on the molecule. Compound (b) comes after compound (c), this is due to the presence of p -CH₃ group which is an electron donating group with negative Hammett constant ($\sigma = -0.17$). Also this group will increase the electron charge density on the molecule but with lesser amount than p -OCH₃ group in compound (c). Compound (a) with Hammett constant ($\sigma = 0.0$) comes after compound (b) in percentage inhibition efficiency, because H- atom in p -position has no effect on the charge density on the molecules. Compound (d) comes after compound (a) in percentage inhibition efficiencies. This is due to p -NO₂ groups is electron withdrawing group with positive Hammett constants ($\sigma = +0.78$) and its order of inhibition depends on the magnitude of its withdrawing character.

Fig. 11.-Relation between log corrosion current density, $\log i_{corr}$, and Hammett constants, σ_p of the substituent from polarization measurements.

4. REFERENCES

- Li, S.L., Ma, H.Y., Lei, S.B., Yu, R., Chen, S.H., and Liu, D.X., Corrosion 54, 947, (1998).
- Stevanovic J., Skibina L. J., Stefanovic M., Despic A., Jovic V. D., J. Appl Electrochem. 22, 172, (1992).
- Habib K., Amin A. Desalination 85, 275, (1992)
- Elrehim S. A., Assaf F. H., Elsayed A., Zaky A. M. Brit Corros J. 30, 247, (1995).
- Morales J., Fernandez G. T., Esparza P., Gonzalez S., Sa R. C. Corros. Sci. 37, 211, (1995).
- Badawy W. A., Al-Kharafi F. M. Corros. Sci. 5, 268, (1999)
- Rehan H. H., Al-Moubarak N. A., Al-Rafai H. A., Port Electrochim. Acta 21 (2), 99, (2003).
- Haqea M. M. and Faris Ismailb A., Adv Mater Res. 33-37, 7-12, (2008).
- Mihit M., El Issami S., Bouklah M., Bazzi L., Hammouti B., Ait Addi E., Salghi R. and Kertit S. Appl Surf Sci. 252 (6), 2389, (2006).
- H.Mahfouz, M.Sc. Thesis, Mansoura University, Egypt, 2008.
- Otieno-Alego V., Hope G. A., Flitt H. J., Cash G. A., and Schweinsberg D. P. Corros. Sci. 33, 1719, (1992).
- N.Al-Andis, E.Khamis, A.Al-Mayouf and H.Aboul-Enein, Corros Prevent Contr. 42, 13, (1995).
- M.M.Osman, Anti-Corros Meth Mater. 45, 176, (1998).
- Hackerman, N.; Snively, E. S. Jr. and Payne, J. S. Jr., J Electrochem Soc. 113 (7), 677, (1966).
- Murakawa T.; Kato T.; Naguara S. and Hackerman N. Corros. Sci. 8 (7), 483, (1968).
- Rawat N. S. and Udayabhanu G., Proceedings of 10th International Congress on Metallic Corrosion organized by CECRI in Madras, India Vol.III, 2963, (1987).
- Chatterjee P.; Banerjee, M. K. and Mukherjee P., Indian J Technol. 29 (5), 191, (1991)
- Aramaki K. and Hackerman N., J Electrochem Soc. 116, 568, (1969)
- Cahskan N.; Bilgic S., Appl Surf Sci. 153, 128, (2000)
- Khamis E., El-Ashary E. S. H. and Ibrahim A. K. Brit Corros J. 35 (2), 599, (2000)
- Hang J., Yao L., Ruang E., and Zou J., J.Chim Soc Corros Prot. 8, 189, (1988)
- Ammar I. A., Darwish S., and Etman M., Electrochim Acta. 13, 485, (1968)
- Jestonek M. and Szklarska Z. Smialowska, Corros Sci. 23, 183, (1983)
- Samkarapapaavinasam S. and Ahmed M. F., J Appl Electrochem. 22, 390, (1992)
- Madkour L. H., Elmorsi M. A., and Ghoneim M. M., Monatsh Chem.126 (10), 1087, (1995)
- Donahu F. M., and Nobe K., J Electrochem Soc. 112, 886, (1965)
- Vasseghi S. and Nobe K., Corrosion 35, 300, (1979)
- Szklavska Z. Smialowska and Kaminski M. Corros. Sci. 13, 1, (1973).