Corrosion Behaviour Of Aluminium Under The Influence of Superimposed Magnetic Field

by

M.A. Ghabashy

Department of Engineering Mathematics and Physics
Faculty of Engineering, Alexandria University, Egypt.

Abstract

The present experimental study concerns both the magnetic induction and the solution concentration effects on the corrosion rate of aluminium in sodium hydroxide solution using the loss in weight tecnique. Two chief findings are reported. First, it is found that till a certain critical value "B_{cr}" for the magnetic field induction   the corrosion rate decreased to a value which is much lower than that at zero magnetic field. The second finding is that for $B > B_{cr}$ the corrosion rate increases a rapidly inning and then gradually with a tendency to a saturation value. The results were explained on the basis of the existence of two opposing forces affecting the solution flow at the corroding surface, a boundary force acting downward as a result of the density difference between the bulk solution and the interfacial solution, and a magnetohydrodynamic force which acts in the upward direction as a result of the interaction between the magnetic field and the electrical field induced by the galvanic cells through which corrosion takes place.

Introduction

The use of aluminium as a material of construction is increasing because of its strength and light weight in industrial atmospheres. Structures made of aluminium may be subjected

to alkaline attack due to the presence of ammonia [3]. Besides, the use of aluminium in cathodic protection of steel structures is also growing. In this case aluminium may be subjected to alkaline attack whose rate may be influenced by surrounding magnetic field of electrical equipments such as motors, generators and transformers. Corrosion of aluminium in sodium hydroxide is known to be a diffusion-controlled reaction [4] at a rate depending on the rate of removal of corrosion products away from the corroding surface. It is hoped that the results of the present study will throw more light on the effect of magnetic field on the rate of diffusion-controlled corrosion of metals where the rate of corrosion is determined by the transfer of the corrosion products away from the corroding surface. Some work has been done [5-7] on the role of magnetic field on the rate of diffusion-controlled corrosion of metals where the rate of corrosion is controlled by the transfer of the corrosive agent to the metal surface. It was found that the rate of corrosion decreases at relatively low magnetic field intensities but may increase at relatively high intensities.

Mathematical Background

The following fundamental equations characterize a magnetohydrodymanic system [1],

$$div \ \vec{v} = 0, \tag{1}$$

$$div \ \vec{B} = 0, \tag{2}$$

$$u_o \vec{j} = curl \ \vec{B} \quad \text{(Ampere's law)}, \tag{3}$$

$$\vec{j} = \sigma(\vec{E} + \vec{v} \wedge \vec{B}) \quad \text{(Ohm's law)}, \tag{4}$$

$$d\vec{B}/dt + (\vec{v}.grad) \ \vec{B} = (\vec{B}.grad) \ \vec{v} + \ div \ grad \ \vec{B}, \tag{5}$$

$$\rho \ d\vec{v}/dt + (\vec{v}.grad) \ \vec{v} + grad \ p^* = (\vec{B}.grad) \ \vec{B}/u_o + \vec{F} + \gamma \ div \ grad \ \vec{v}. \tag{6}$$

In aqueous solutions, owing to low electrical conductivity, induced magnetic fields and electric currents may usually be neglected; in MHD (magnetohydrodymanic) theory this is

called the low magnetic Reynolds number (Re_m) approximation. Accordingly, $\vec{B}$ is replaced by the imposed uniform magnetic induction B_o, and $\vec{j}$ by the uniform electric current density j_o. Equations (3) and (5) can be ignored and equation (6) is considerably simplified. In the steady state, equation (6) takes the form,

$$(\vec{v}.grad)\,\vec{v} + grad\,p^* = (1/\rho)\,\vec{j}_\wedge\vec{B} + \gamma\,div\,grad\,\vec{v} + \vec{F} \tag{7}$$

From the theory of diffusional flow in natural convection [2] the concentration distribution across the two-dimensional boundary layer is given as,

$$D\,d^2c/dy^2 = v_x\,dc/dx + v_y\,dc/dy \tag{8}$$

Thus, in the low Re_m case, equations (1), (7) and (8) together with appropriate boundary conditions, completely characterize the mass transfer behaviour.

The MHD body force is a source of augmentation of the natural convection. It is important to note that if j_o and B_o are uniform, then the generated force will be rotational only in the boundary layer where the density is space dependent; in the bulk of the solution, $curl\,\vec{j}_\wedge\vec{B}/\rho$ = 0 and the irrotational force effect has no particular consequence.

Figure (1) indicates that the MHD body force, generated by the transverse coupling of B_o and j_o, points upwards (or downwards, if B_o is rotated by $180°$) in parallel with natural onvection at the electrodes. Hence, the gravitational and MHD forces are completely aligned in the x-direction. The above equations can, therefore, be further simplified to [2],

$$v_x\,dv_x/dx + v_y\,dv_x/dy = \gamma\,d^2v_x/dy^2 + g\alpha\varphi + j_o\,B_o/\rho \tag{9}$$

$$v_x\,d\varphi/dx + v_y\,d\varphi/dy = D\,d^2\varphi/dy^2 \tag{10}$$

with boundary conditions

$$y = 0\,;\ v_x = v_y\,;\ \varphi = 1$$

$$y \rightarrow \infty\,;\ v_x = 0\,;\ \varphi = 0$$

is the fractional solution concentration, defined as $(c_o - c)/c_o$, and α is the densification coefficient.

called the low magnetic Reynolds number (Re_m) approximation. Accordingly, $\vec{B}$ is replaced by the imposed uniform magnetic induction B_o, and $\vec{j}$ by the uniform electric current density j_o. Equations (3) and (5) can be ignored and equation (6) is considerably simplified. In the steady state, equation (6) takes the form,

$$(\vec{v}.grad)\,\vec{v} + grad\,p^* = (1/\rho)\,\vec{j}\wedge\vec{B} + \nu\,div\,grad\,\vec{v} + \vec{F} \tag{7}$$

From the theory of diffusional flow in natural convection [2] the concentration distribution across the two-dimensional boundary layer is given as,

$$D\,d^2c/dy^2 = v_x\,dc/dx + v_y\,dc/dy \tag{8}$$

Thus, in the low Re_m case, equations (1), (7) and (8) together with appropriate boundary conditions, completely characterize the mass transfer behaviour.

The MHD body force is a source of augmentation of the natural convection. It is important to note that if j_o and B_o are uniform, then the generated force will be rotational only in the boundary layer where the density is space dependent; in the bulk of the solution, $curl\,\vec{j}\wedge\vec{B}/\rho$ = 0 and the irrotational force effect has no particular consequence.

Figure (1) indicates that the MHD body force, generated by the transverse coupling of B_o and j_o, points upwards (or downwards, if B_o is rotated by $180°$) in parallel with natural onvection at the electrodes. Hence, the gravitational and MHD forces are completely aligned in the x-direction. The above equations can, therefore, be further simplified to [2],

$$v_x\,dv_x/dx + v_y\,dv_x/dy = \nu\,d^2v_x/dy^2 + g\alpha\varphi + j_o\,B_o/\rho \tag{9}$$

$$v_x\,d\varphi/dx + v_y\,d\varphi/dy = D\,d^2\varphi/dy^2 \tag{10}$$

with boundary conditions

$$y = 0\,;\ v_x = v_y\,;\ \varphi = 1$$

$$y\rightarrow\infty\,;\ v_x = 0\,;\ \varphi = 0$$

is the fractional solution concentration, defined as $(c_o - c)/c_o$, and α is the densification coefficient.
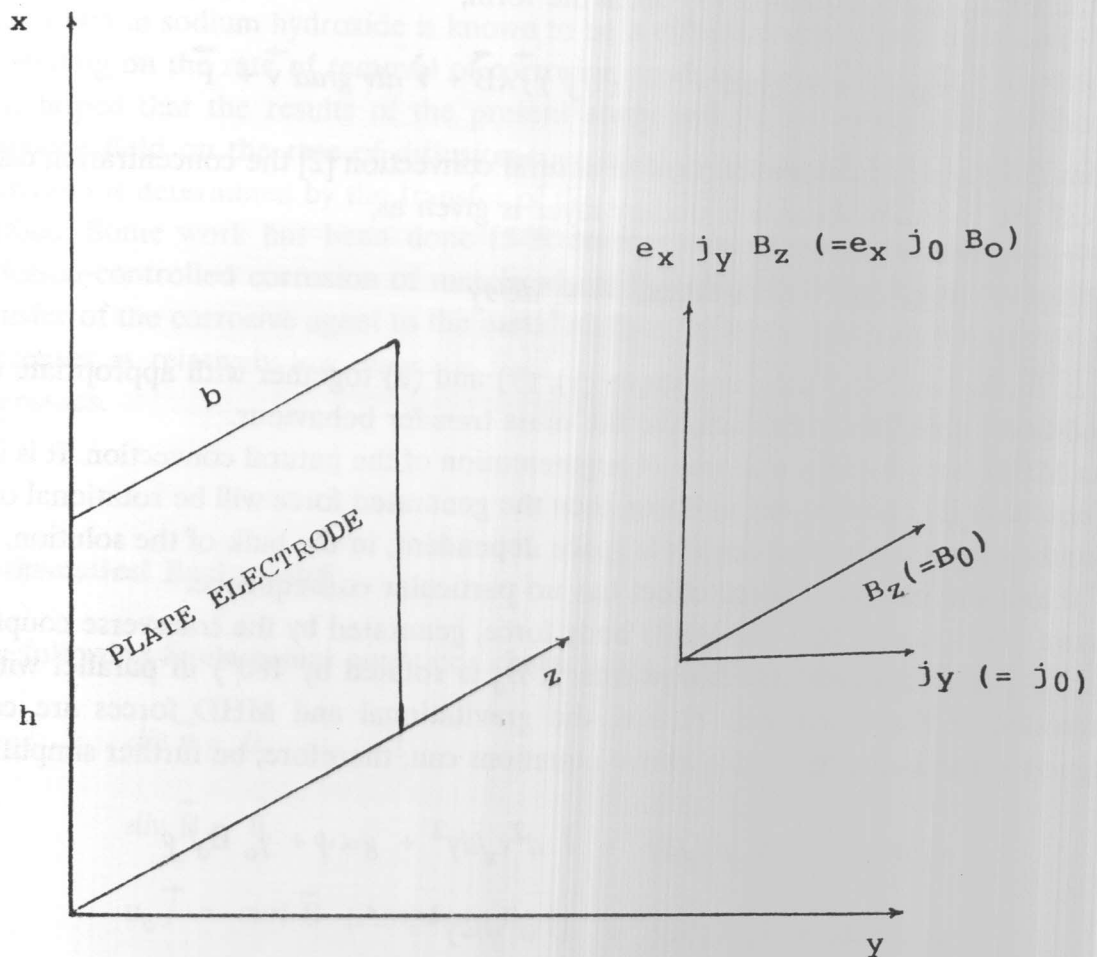
Fig.(1) Electric Field and Magnetic
Induction Configuration in the Cell

Experimental Technique

The apparatus consisted of 500 c.c. glass beaker containing 400 c.c. sodium hydroxide in which vertical aluminium rectangular sheet of 8 cm height and 3 cm width was dipped. The glass beaker was surrounded with a long magnetic coil connected in series with 12 Vdc power supply, a rheostat and a multirange ammeter. The strength of the magnetic field was varied by changing the current passing through the circuit. The magnetic flux density was measured by Tesla meter and found to agree with the known formula.

$$B_o = u_o \, n_o \, I$$

where B is the magnetic flux density in Tesla, u_o is the magnetic permeability constant (4 . 10^{-7} weber/A.m), n_o is the number of turns per unit length and I is the current passing through the circuit in amperes.

The rate of aluminium corrosion, R, in NaOH was determined from the loss in weight of the aluminium sheet using the formula

$$R = \text{loss in weight/area.time}$$

Each run was repeated twice using a fresh solution and a new metal specimen. The time of each experiment was 300 min. Temperature was 23+1 C. Pure aluminium was used in the present work. A.R. sodium hydroxide and distilled water were used in preparing all solutions. Before each run, the metal specimen was polished using fine emery paper, decreased with trichloroethylene and washed with alcohol and ether respectively before weighing.

Results and Discussion

Figures (2), (3) and (4) show the effect of magnetic flux density B_o on the rate of corrosion of aluminium in sodium hydroxide. At low magnetic flux density the rate of corrosion decreases below the value measured in the absence of magnetic flux density. With increasing magnetic flux density, the rate of corrosion increases. To explain this result, the
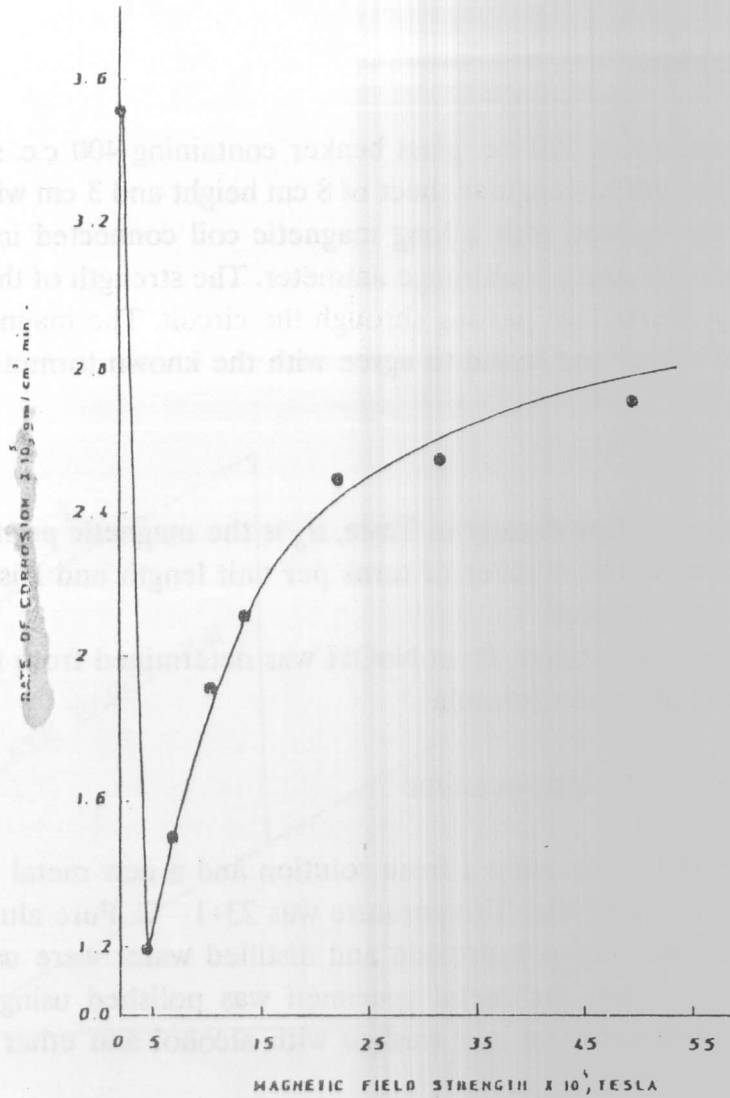
FIGURE 2, EFFECT OF MAGNETIC FIELD ON THE
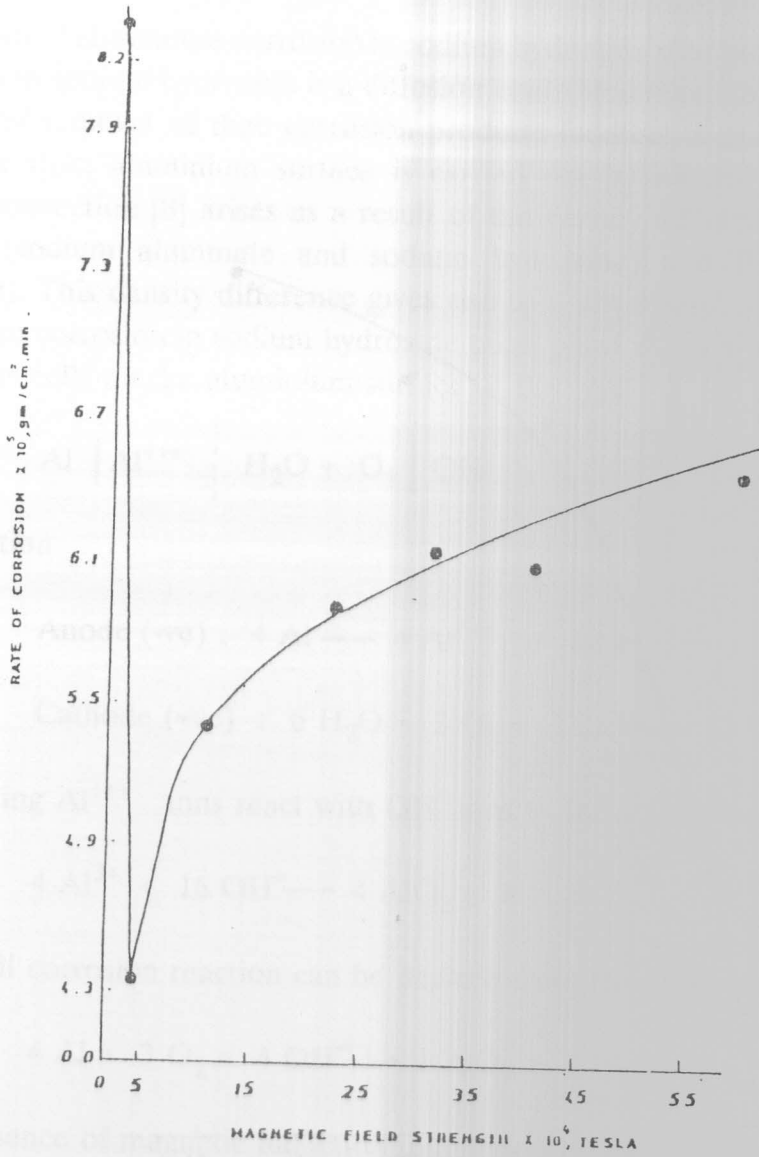RATE OF CORROSION OF ALUMINIUM IN
0.1N Na OH

FIGURE 3, EFFECT OF MAGNETIC FIELD ON THE
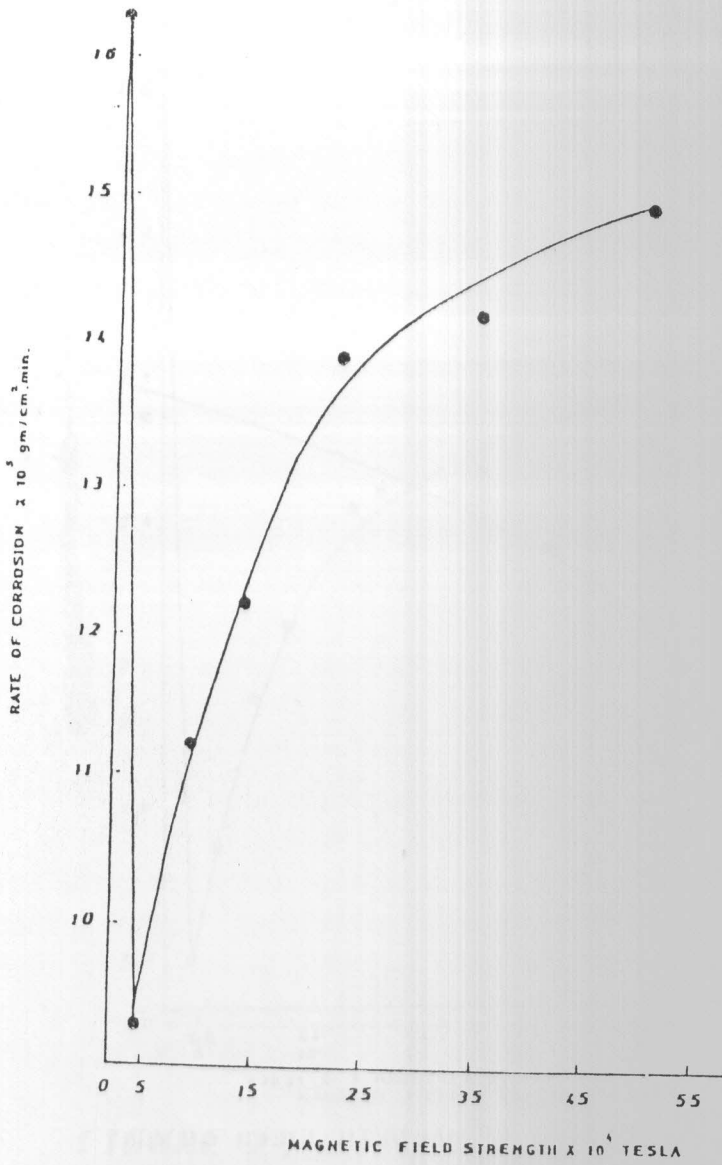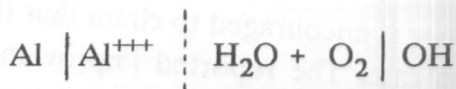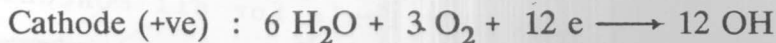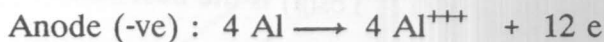RATE OF CORROSION OF ALUMINIUM IN
IN Na OH

FIGURE 4, EFFECT OF MAGNETIC FIELD ON THE RATE OF CORROSION OF ALUMINIUM IN 2N Na.OH.

mechanism of aluminium corrosion in sodium hydroxide should be recalled first. Aluminum corrosion in sodium hydroxide is a diffusion controlled reaction [4] whose rate depends on the rate of removal of thee corrosion products (sodium aluminate). Transfer of sodium aluminate from aluminium surface is carried out by natural convection and diffusion. Natural convection [8] arises as a result of the density difference between the interfacial solution (sodium aluminate and sodium hydroxide) and the bulk solution (sodium hydroxide). This density difference gives rise to a downward flow.

Aluminium corrosion in sodium hydroxide takes place through the formation of multitude of galvanic cells on the aluminium surface of the type
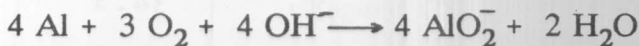
$$Al \left| Al^{+++} \right. \vdots \left. H_2O + O_2 \right| OH$$

Cell Reaction

$$\text{Anode (-ve)}: \quad 4\,Al \longrightarrow 4\,Al^{+++} + 12\,e$$

$$\text{Cathode (+ve)}: \quad 6\,H_2O + 3\,O_2 + 12\,e \longrightarrow 12\,OH$$

The resulting Al^{+++} ions react with OH^- ions to form aluminate.

$$4\,Al^{3+} + 16\,OH^- \longrightarrow 4\,AlO_2^- + 8\,H_2O$$

The overall corrosion reaction can be derived from the above three reactions giving

$$4\,Al + 3\,O_2 + 4\,OH^- \longrightarrow 4\,AlO_2^- + 2\,H_2O$$

In the presence of magnetic induction interaction takes place between the magnetic field and the electrical field of the galvanic cells present on the aluminium surface, giving rise to an upward magnetohydrodynamic flow [3-12] which opposes the downward natural flow arising from the density difference.

It seems that at low magnetic induction intensities the upward magnetohydrodynamic flow weakens the downward natural convection in such a manner that the difference in concentration between the metal surface and the bulk of solution decreases with the increase of magnetic induction intensity. As a consequence of this decrease, the rate of corrosion decreases.

As the magnetic induction strength increases the upward magnetohydrodynamic flow becomes strong enough to overcome the downward natural convection and to increase the upward flow of the corrosion product (aluminate). This results in an increase in the concentration difference between the metal surface and the bulk of solution with increase of magnetic induction, and consequently, the corrosion rate increases. The present finding that low magnetic induction intensities decrease the corrosion is consistent with the results of Chiba et al. [12], who found that magnetic induction decreases the anode efficiency of tin dissolution during tin electro-plating. Figures (2) to (4) show that the rate of corrosion increases with increasing NaOH concentration.

Conclusion

On the basis of the present findings the author is encouraged to claim that the effect of the magnetic field is to decrease the corrosion rate. The reported improvement percentage values in the corrosion rate under the magnetic field relative to the corresponding values in the absence of magnetic field ar represented in the following table. This table shows that the critical magnetic field induction ($B_{cr}=5 \times 10^{-4}$ Tesla) is the best value for minimizing the corrosion rate.

Table (1) , $B_{cr} = 5 \times 10^{-4}$ Tesla for all concentrations

Normality	Corrosion rate$\times 10^5$ gm.cm^{-2}.min^{-1}			Improved corrosion percentage value	
	$B=0$	$B=B_{cr}$	$B=B_{sat}$	at B_{cr}%	at B_{sat}%
0.1 N	3.5	1.2	2.7	34.3	77
1 N	8.4	4.3	6.4	51.1	76
2 N	16.3	9.3	14.8	57 0	91

From the table we can conclude that the relation between the rate of corrosion and the normality of the solution tends to be linear. Unfortunately the present work concerned with three concentrations only because the stress was done on the study of the magnetic field. This is enough reason to prevent the author from definitly judging the above mentioned linearity. Owing to this reason an extension research work might be done to study in more details the effect of normality on the corrosion behaviour as a magnetic field dependence. Figure(5) shows this linear tendency and this is the mair purpose of it.
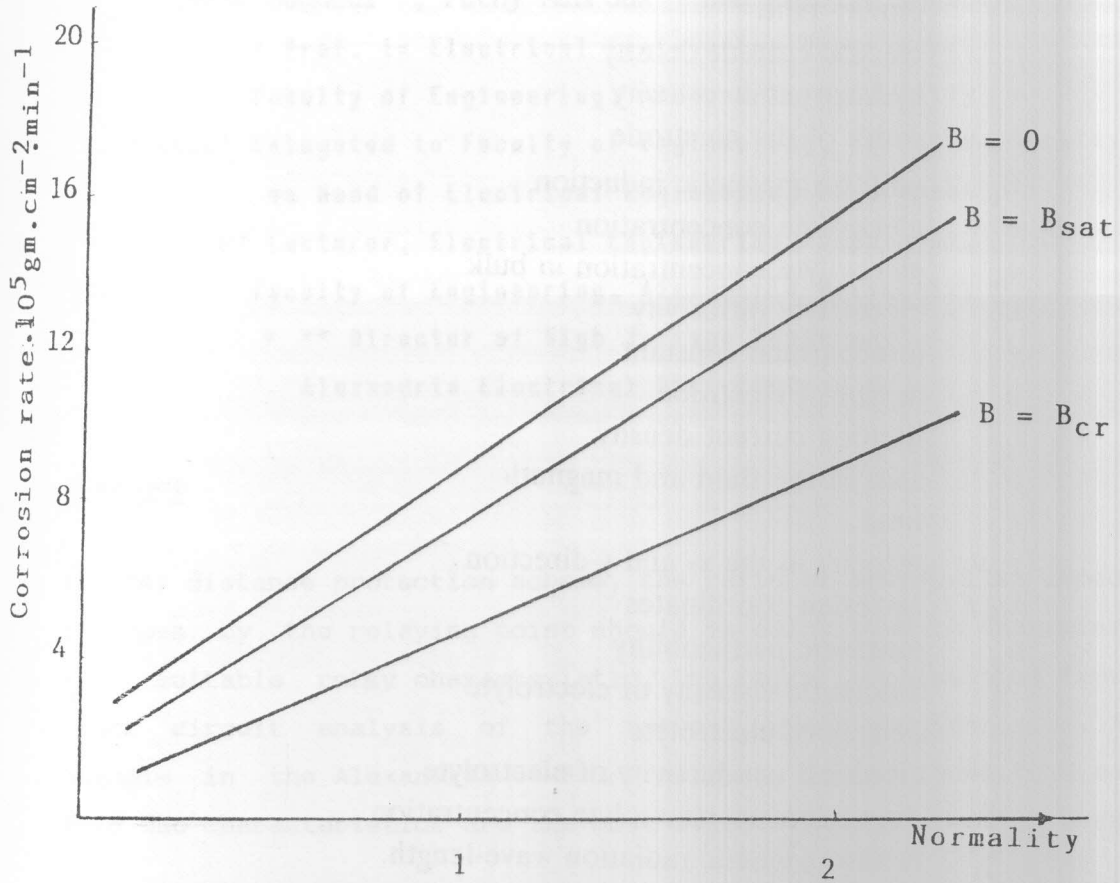
Figure (5).

Nomenclature

B	magnetic induction
E	electric field
F	gravity field
j	electric current density
v	hydrodynamic velocity
b	width of the electrode
B_o	uniform magnetic induction
c	electrolyte concentration
c_o	electrolyte concentration in bulk
D	electrolyte diffusivity
g	gravitational constant
h	height of electrode
j_{Q_L}	limiting current density
p	sum of the fluid and magnetic
t	time
v_x, v_y	velocity in the x- and y-direction
x,y,z	cartesian coordinates
u_o	magnetic permeability
γ	kinematic viscosity of electrolyte
ρ	density of electrolyte
σ	electrical conductivity of electrolyte
φ	dimensionless electrolyte concentration
λ	electromagnetic radiation wave-length.

References

[1]   Shercliff J.A., *A Textbook of Magnetohydrodynamics*, Pergamon Press, Oxford, 1965.

[2]   Levich V., *Physical Chemistry Thermodynamics*, Prentice-Hall, Englewood Cliffs, N.J., 1962.

[3]   Uhlig H., *Corrosion and Corrosion Control*, John Wiley & Sons Inc., N.Y., 1963.

[4]   Ellison B.T. and Wen C.J., *AIchE Symposium series 77*, No. 204, p. 161, 1981.

[5]   Ghabashy M.A. and Fawzy M.A., *J.Electrochem. Soc.*, 132,94c, 1985.

[6]   Ghabashy M.A., Sedahmed G.H. and Mansour I.A.S., *British Corrosion J.*, 17 36, 1982

[7]   Ghabashy M.A. and Fawzy M.A., *Bulletin of Electrochem.*, vol.2,1986, India.

[8]   Ibl N., *Advances in Electrochemistry and Electrochemical Engineering*, 2, 49, 1962.

[9]   Frary F.C., *J.Am.Chem. Soc.*, 29m, 1592, 1970.

[10]   Kelly E.J., *J. Electrochem. Soc.*, 124, 987, 1977.

[11]   Fahidy T.Z., *J. Appl. Electrochem.*, 13, 533, 1983.

[12]   Chiba A., Hosokawa A. and Ogawa T., *Surface and Coating Technology*, 27, 13, 1986.