

Ihebrodike Maurice Mejeha<sup>1\*</sup>, Kelechukwu Bierechi Okeoma<sup>1</sup>, Uchechi Agoh<sup>1</sup>, Daniel Chukwuebuka Igweze<sup>1</sup>, Jasper Tamadu Obi<sup>1,2</sup>

<sup>1</sup> Federal University of Technology, Materials Research Group, Department of Physics, Owerri, Owerri, Nigeria, <sup>1,2</sup> Isaac Jasper Boro College of Education, Department of Physics, Sagbama, Yenagoa, Nigeria

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## The protective effect of magnetic fields on the corrosion of aluminium alloys in hydrochloric acid solutions

### ABSTRACT

The effect of applied magnetic fields on the corrosion of aluminium alloys AA3003 and AA8011 in hydrochloric acid solutions at room temperature has been investigated by using the gravimetric technique. The magnetic fields were generated from a locally made electromagnet with variable outputs. They were applied at right angles to the surfaces of the aluminium alloy samples when completely immersed in the test solutions. The corrosion rates of the aluminium alloys AA3003 and AA8011 in 0.5M HCl acid solutions were monitored at different applied magnetic fields. Results show that the corrosion rates of the aluminium alloy samples studied decrease with increase in the applied magnetic field. This implies that the presence of magnetic field inhibits the corrosion of the aluminium alloy AA3003 and AA8011 samples. With applied magnetic fields in the range of 254.3 - 1040.6 mG [0.0254 – 0.1041 mT], the protection efficiency of the magnetic field observed for AA3003 in 0.5M HCl acid solutions ranges from 19.3 – 94.1% while for aluminium alloy AA8011 in identical test solutions, the protection efficiency ranges from 11.5 – 78.0%. The protection mechanism is attributed partly to the phenomenon of transverse magnetoresistance and partly to effect of the magnetic fields on the mass transport pattern of constituent ions in the electrochemical system.

**Keywords:** Magnetic field, aluminium alloys, gravimetric technique, corrosion rate, protection efficiency, transverse magnetoresistance.

### 1. INTRODUCTION

The corrosion of metals and their alloys when in service causes a lot of deterioration of the properties the metals and alloys. It also causes damage to components of engineering structures such as buildings, bridges, dams, ships, aircraft, oil pipelines and even electrical and electronic components of man-made systems. The damages caused to these systems not only constitute safety hazards, they may lead to catastrophic failures of moving and static components of systems in industrial and engineering productions and in environments. Indeed, it is on record that very devastating accidents have in the past occurred as a result of neglect of corroding parts of engineering systems or to failure to identify or observe the corroding parts, leading possibly to human and material losses, environmental pollution, as well as

consequential economic losses [1-4]. This explains why considerable amount of research and development efforts and resources are often devoted to finding ways of ameliorating metal and metallic alloy corrosion. Many corrosion control and prevention techniques have been developed over time. Among these include: well – thought out engineering design and materials selection procedures, environmental alteration, painting and spraying including electroplating, cathodic protection, addition of corrosion inhibitors – which could be inorganic or organic inhibitors including plant extracts - to the corrodent [3-14]. Nevertheless, there is still an on-going search for other novel techniques which could most suitably apply to specific environments and situations.

It happened that when two of the authors were reviewing the corrosion behaviour of two aluminium alloys in acidic media sometime in 2010, they were led to compare the corrosion data for aluminium alloys on one hand and those of mild steel on the other. One thing common to the two sets of data obtained in the Corrosion Laboratory at the Federal University of Technology, Owerri, FUTO, was that they were obtained by using such electrochemical

\*Corresponding author: Ihebrodike Maurice Mejeha

E-mail: micmejeha@gmail.com

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techniques as potentiodynamic polarization (PDP) and electrochemical impedance spectroscopy (EIS) techniques. The striking differences in the observed EIS spectra of the two metallic systems rightly or wrongly lead to the suspicion that magnetic field effects might have affected the data being scrutinised. Nevertheless, the authors have since been better educated on the possible explanation of the observed differences. Somehow, the haunch that magnetic fields could affect the corrosion behaviour of metals and their alloys still persisted in their minds. In 2012, this idea was tested in experiments in which aluminium alloy AA3003 coupons immersed completely in hydrochloric acid solutions were exposed to a magnetic field. One major finding in that study, which employed the gravimetric technique, was that the presence of a magnetic field could inhibit the corrosion of the aluminium alloys in an acidic environment [15]. It was also established that when an aluminium alloy sample completely immersed in an acidic solution containing a given concentration of an inhibiting plant extract was exposed to a magnetic field for a few hours, the inhibition efficiency of the added plant extract was observed to further increase above the value observed for the inhibitor alone.

Follow up studies in which other metal systems were investigated have since confirmed the outcomes of the studies cited above [16,17]. *It was not long before it came to light that some journal articles* had earlier been published on the effect of magnetic fields on the corrosion of metals and metal alloys in corrosive environments [18–23]. These cited studies were done at single fixed values of applied magnetic fields. Costa and co-workers [19] show that the corrosion rate of a magnetized metal alloy is considerably larger than that of the same alloy when unmagnetized but which is immersed in identical corrosive environments. But Maatya co-workers [21,22] obtained results similar to those obtained in the studies carried out in the FUTO laboratory, already cited.

In their investigation of the effect of magnetic fields on the dissolution and passivation of iron in sulphuric,  $H_2SO_4$ , acid solutions, Lu, and co-workers [18] used such electrochemical methods as scanning potentiodynamic polarization (PDP) and potentiostatic polarization (PSP) techniques to show that the presence of a magnetic field during the electrochemical process rendered the metal electrode (iron) prone to active dissolution in  $H_2SO_4$  acid solutions. The results of the studies cited above [18–23] show that the presence of magnetic

fields do indeed affect the corrosion behaviour of the metals and alloys in different corrosive environments.

Some research workers [19,22,23] have sought to develop a theory that can explain the effect of magnetic field on metal corrosion. Incidentally, practically all the formulations so far made focus on the effect of applied magnetic field on the motion of the ionic species in the electrolyte, the reactants and reaction products in the electrochemical system. Usually, a charged particle moving in a magnetic field will experience a sideways deflecting force called the Lorentz force,  $F$ , given by:

$$F = q(\mathbf{v} \times \mathbf{B}) \quad (1)$$

where  $q$  is the charge on the particle,  $\mathbf{v}$  and  $\mathbf{B}$  are the velocity of the particle and the applied magnetic field respectively. The magnetohydrodynamic (MHD) theory so far formulated based on the effect of the Lorentz force on the ionic constituents of the electrochemical system with the magnetic gradient force plays an important role in the mass transport model formulated to explain metal corrosion in the presence of magnetic fields. The model suggests that the limiting currents of reaction that go on in the electrochemical system depend, among other factors, on the strength of the magnetic field [23].

Nevertheless, it is known that the electrochemical process leading to metal corrosion in an aqueous solution involves an oxidation reaction at anodic sites which results in the release of metal ions and electrons as well as a reduction reaction at cathodic sites at which metal ions take on electrons to get neutralized [2–4]. The process implicitly requires the conduction of the electrons released during oxidation through a metallic pathway from the anodic to cathodic sites. The motion of electrons from the anodic to cathodic sites constitute a current flow through a metallic path [4,22]. In the existing theory of metal corrosion in the presence of a magnetic field, the effect of the magnetic field on the flow of electrons conducted through the metallic pathway has been completely ignored. This renders the theory incomplete.

In those studies, carried out at the FUTO Corrosion Laboratory, two main issues bothered the minds of the investigators. Firstly, the value of the magnetic field produced by the electromagnet could not be ascertained because no magnetic field meter (or gaussmeter) was available to measure its value **at the time**. Secondly, the electromagnet could only produce a fixed value magnetic field. But the researchers considered it desirable for the magnetic field source to have variable output. In this study, the corrosion behaviour of aluminium

alloys AA3003 and AA8011 in 0.5M HCl acid solutions when exposed to different magnetic fields are investigated at room temperature. It is hoped that the results of the study could yield information that will be helpful in developing a clearer understanding of how magnetic fields affect the corrosion of metals and their alloys in acidic environments.

## 2. MATERIALS AND METHODS

### 2.1. Materials and handling

The aluminium alloys AA3003 and AA8011 used in this study were obtained in form of sheets from First Aluminium Company Limited, Port Harcourt, Nigeria. The certified elemental compositions of the alloys are given in Table 1. The sheets were mechanically press – cut into coupons of dimensions 30 x 30 x 0.9 mm. A hole of diameter 2.00 mm was drilled on the middle of the upper edge of each coupon. The hydrochloric acid and reagents used in the study were of BDH analytical grade and were supplied by FINLAB Nigeria Limited, Owerri. The acid solutions of molarity 0.5 M were prepared by using double distilled water.

Table 1. Certified elemental compositions of aluminium alloys AA3003 and AA8011

Tabela 1. Sertifikovani elementarni sastavi aluminijumskih legura AA3003 i AA8011

Alloy - Element	AA3003 (wt %)	AA8011 (wt %)
Mn	1.2196	0.1022
Fe	0.5498	0.980
Si	0.3629	0.2408
Cu	0.0771	0.0346
Pb	0.0637	0.014
Ti	0.0262	0.019
Zn	0.0042	0.0435
Mg	0.0055	0.009
V	0.0087	0.0
Cr	0.0068	0.0
Ni	0.0015	0.0
Al	97.672	98.525
Other trace elements	0.002	0.0641

The magnetic fields used were produced by an electromagnet powered by a direct current source that could supply up to 40.0 volts. The electromagnet has a variable output and could produce magnetic fields of up to 1041 mG (0.1041 mT). It was made locally and was fully characterized and calibrated. The magnetic field measurements were carried out by using a digital gaussmeter with a trade mark: Magnetic Field Meter TM 191 with a least count of 0.01 mG (or 1.0

nT). Coupons of aluminium alloys AA3003 and AA8011 were wet-polished with the aid of different grades of emery clothe, 200 – 800. They were then degreased in absolute ethanol, washed in double distilled water, rinsed in acetone and allowed to dry before weighing by means of a digital electronic weighing balance, OHAUS, model AR 2140, with a least count of 0.05 mg. They were stored away in a moisture free desiccator after labeling until required for use.

### 2.2. Experimental procedure

A previously weighed coupon of AA3003 or AA8011 was suspended by means of a polystyrene thread and completely immersed in a 0.5M HCl acid solution in a beaker and left at room temperature. After a two – hour exposure time, the coupon was dropped into a nitric acid solution in order to quench further corrosion attack. The coupon was then washed in double distilled several times, degreased in ethanol and dried in acetone. It was further dried by means of a hand - held electric dryer and reweighed on cooling in order to determine the weight loss of the coupon. The procedure was repeated with two other coupons. The corrosion rate of each coupon was calculated by using Eq. 1 and the mean value taken. This gives the mean corrosion rate,  $\rho$ , of the aluminium alloy in 0.5M HCl acid solution for a 2 – hour exposure time without the magnetic field at room temperature.

The experiment was repeated but this time with the beaker containing the test solution and the coupons placed between the poles of the electromagnet and the magnetic field applied onto the coupons perpendicularly at a chosen setting of source voltage for a 2–hour duration. The procedure for cleaning and drying the coupon then followed before reweighing it to determine the weight loss in the presence of magnetic field. The experiment was repeated at different voltage settings within the range 10.0 – 40.0 volts while maintaining the exposure time of 2 hours. Triplicate experiments were done for each setting of applied voltage and the mean corrosion rate of each alloy sample for each voltage setting determined.

## 3. RESULTS AND DISCUSSION.

### 3.1. Corrosion rate of aluminium alloys in magnetic fields.

The corrosion rate of a coupon of an alloy of aluminium in a test solution can be calculated by using the expression [3,12-14,24]:

$$\rho = \frac{k\Delta W}{DAT} \quad (2)$$

where

$k$  = rate constant, whose value is 534 if the system of units used is mils per year (mpy) or 87.6 if the system of units chosen is millimeter per year (mmpy), as used in this study,

$\Delta W$  - weight loss in milligrams (mg),

$D$  - density of metal or alloy coupon in grams per cubic centimeter ( $\text{gcm}^{-3}$ ),

$A$  - exposed surface area of the coupon in square centimeter ( $\text{cm}^{-2}$ ) for mmpy unit system,

$T$  - exposure time in hours.

In Tables 2a and 2b are shown the values of the direct current voltages applied to the electromagnet and the corresponding magnetic fields produced. It can be noticed that at zero volts,

a value of magnetic field of 37.86 mG (0.003786 mT) was recorded. This value corresponds to the background magnetic field ever pervading the environment. In those tables, the corrosion rates corresponding to zero volt is regarded as the zero - field corrosion rate and is designated as,  $\rho_0$ .

The corrosion rates,  $\rho$ , of aluminium alloys AA3003 and AA8011 are recorded in columns 3 of both tables respectively. It can be seen from the results that the corrosion rates of the aluminium alloys in 0.5M HCl acid solutions decrease as the applied magnetic field increases. The implication of this finding is that the presence of the magnetic field inhibits the corrosion of the aluminium alloys in the 0.5M HCl acid solutions.

*Table 2a. Corrosion rate, fractional decrease in corrosion rate and protection efficiency of the magnetic field for aluminium alloy AA3003 immersed in 0.5M HCl acid solutions in the presence of applied magnetic fields for an exposure time of 2 hours at room temperature*

*Tabela 2a. Brzina korozije, frakciono smanjenje brzine korozije i efikasnost zaštite magnetnog polja za leguru aluminijuma AA3003 potopljenu u 0,5M HCl kiseline u prisustvu primenjenih magnetnih polja tokom vremena izlaganja od 2 sata na sobnoj temperaturi*

Applied voltage V, (volts)	Magnetic field B, (mT)	Corrosion rate $\rho$ (mmpy)	Fractional decrease in corrosion rate, $\Delta\rho/\rho_0$	Protection efficiency $\eta$ (%)
0	0.003786	21.88	0.0	-
10	0.025429	17.65	0.193	19.3
15	0.044286	13.49	0.383	38.3
20	0.059129	5.07	0.768	76.8
25	0.076429	3.17	0.855	85.5
30	0.088934	2.14	0.902	90.2
35	0.104062	1.28	0.941	94.1

*Table 2b. Corrosion rate, fractional decrease in corrosion rate and protection efficiency of magnetic field for aluminium alloy AA8011 immersed in 0.5M HCl acid solutions in the presence of applied magnetic fields for a 2- hour exposure time at room temperature*

*Tabela 2b. Brzina korozije, frakciono smanjenje brzine korozije i efikasnost zaštite magnetnog polja za leguru aluminijuma AA8011 potopljenu u 0,5M HCl kiseline u prisustvu primenjenih magnetnih polja tokom 2-časovnog izlaganja na sobnoj temperaturi*

Applied voltage V (volts)	Magnetic field B (mT)	Corrosion rate P (mmpy)	Fractional decrease in corrosion rate, $\Delta\rho/\rho_0$	Protection efficiency $\eta$ (%)
0	0.003786	24.44	0.0	-
10	0.025429	21.63	0.115	11.5
15	0.044286	17.74	0.274	27.4
20	0.059129	15.79	0.354	35.4
25	0.076429	10.89	0.554	55.4
30	0.088934	8.50	0.652	65.2
35	0.104062	5.38	0.780	78.0

A close look at Tables 2a and 2b also reveal that the zero - field corrosion rate,  $\rho_0$ , for the aluminium alloy, AA3003, sample is lower than that

for aluminium alloy, AA8011, sample. Moreover, at any given applied magnetic field, the corrosion rate,  $\rho$ , is lower for AA3003 than for AA8011. In

other words, the corrosion behaviour of the two alloys in the test solutions in the absence and presence of the applied magnetic field are noticeably different. The observed difference in the corrosion behaviour of the two alloys, AA3003 and AA8011 in the absence and presence of applied magnetic field may be as a result of the elemental composition of the alloys.

Table 1 shows that apart from the host metal, aluminium, both alloys contain different quantities of some key added alloying metals including Mn, Fe, Si, Cu and other metals in less significant amounts. X-Ray Diffraction, XRD, studies of these alloy samples by Okeoma and co-workers yield XRD spectra which reveal that samples of AA3003 and AA8011 which have not been subjected to any form of heat treatment since after production contain some well-defined crystallites with identifiable compositions [25,26]. For example, AA3003 samples contain a large density of crystallites of the intermetallic compound Al(Fe,Mn) and small densities of crystallites of intermetallic compounds AlFe, and MnFe dispersed in the matrix of the aluminium host [25]. The studies also reveal that the AA8011 samples contain crystallites most of which consists of intermetallic compound, AlFe with much smaller densities of crystallites of intermetallic compound, MnFe, as well as manganese and silicon crystallites [26].

The findings of these studies are considered to be significant since it is thought that the presence of these intermetallic compounds, their sizes and densities profoundly affect the electrochemical properties of the alloys and hence their corrosion behaviour [26,27]. It is hereby speculated that the observed difference in the corrosion behaviour of the aluminium alloys AA3003 and AA8011 may in part be due to the presence of the intermetallic particles.

### 3.2. The protection efficiency of the magnetic field

In each of Tables 2a and 2b is given the fractional decrease of the corrosion rates of the aluminium alloys AA3003 and AA8011 for each of the applied magnetic fields. One can deduce from the results that the corrosion rates of the alloy AA3003 samples in the test solutions decrease more than the corrosion rates of the AA8011 alloy samples in identical test solutions for the same applied magnetic fields. The protective efficiency,  $\eta$  %, of the magnetic field (which is analogous to inhibition efficiency in the case of the use of additive inhibitors in a test solution) can be defined [12 – 14, 24] as:

$$\eta = \frac{\rho_o - \rho_B}{\rho_o} \times 100\% \quad (3a)$$

$$= \frac{\Delta\rho}{\rho_o} \times 100\% \quad (3b)$$

where

$\rho_B$  - corrosion rate in the presence of applied magnetic field

$\rho_o$  - corrosion rate without applied magnetic field or zero – field corrosion rate

$\Delta\rho$  - decrease in corrosion rate relative to the zero – field corrosion rate.

The computed protection efficiencies of the applied magnetic fields for the aluminium alloys AA3003 and AA8011 are given in Tables 2a and 2b respectively. Magnetic field protection efficiencies as high as 94.1% for AA3003 and 78.0% for AA8011 were achieved with applied magnetic field of 0.10406 mT at an applied direct current voltage of 35 volts.

Figure 1 shows the variation of the fractional decrease in corrosion rate with magnetic field for aluminium alloys AA3003 and AA8011 in 0.5 M HCl acid solutions for exposure time of 2 hours at room temperature. It is curious that the fractional decrease in the corrosion rate of AA3003 increases linearly at first before tending towards saturation at higher applied magnetic fields. In the case of the alloy AA8011, however,  $\Delta\rho/\rho_o$  shows a slightly different trend from that of the alloy AA3003, with no apparent sign of saturation within the magnetic field range available in this work.

Overall, the fitting curves for the two sets of corrosion data are polynomials of the form:

$$\frac{\Delta\rho}{\rho_o} = aB^2 + bB + c \quad (4)$$

where  $a$ ,  $b$  and  $c$  are constants parameters listed in Table 3. Also contained in Table 3 are the value of the square of the coefficients of correlation,  $R^2$ , between the fitting curves and the corrosion data.

Nevertheless, by considering the trend depicted in Fig.1 for the AA3003 corrosion data, it would be possible to deduce that the curve would plateau at much higher applied magnetic fields in the order of 0.15 mT. This is so because the empirical parameters  $a$  and  $b$ , which respectively are the coefficients of  $B^2$  and  $B$  in the fitting polynomial curve of Eq. 4 are of opposite tendencies, one being negative while the other is positive. This characteristics of the two parameters will ensure that as long as the magnetic field remains within the low magnetic field regime (as in this work), the polynomial of Eq. 4 will saturate as the applied magnetic field is increased well beyond that used in this study.

Table 3. Predicted values of the constants  $a$ ,  $b$ , and  $c$  appearing in the polynomial equation, Eq. 4, and the square of the coefficient of correlation,  $R^2$  between the fitting polynomial curves and the corrosion data for aluminium alloys AA3003 and AA8011 in 0.5M HCl acid solutions in the presence of applied magnetic fields

Tabela 3. Predviđene vrednosti konstantnih parametara  $a$ ,  $b$  i  $c$  koji se pojavljuju u polinomskoj jednačini, jednačina 4, i kvadrata koeficijenta korelacije, za legure aluminijuma AA3003 i AA8011 u 0,5M HCl kiseline u prisustvu primenjenih magnetnih polja

Parameters of fit	$a$	$b$	$c$	$R^2$
AA3003	$-1 \times 10^8$	$2.6454 \times 10^4$	-0.4325	0.9597
AA8011	$3 \times 10^7$	$4.6725 \times 10^3$	0.0	0.9925

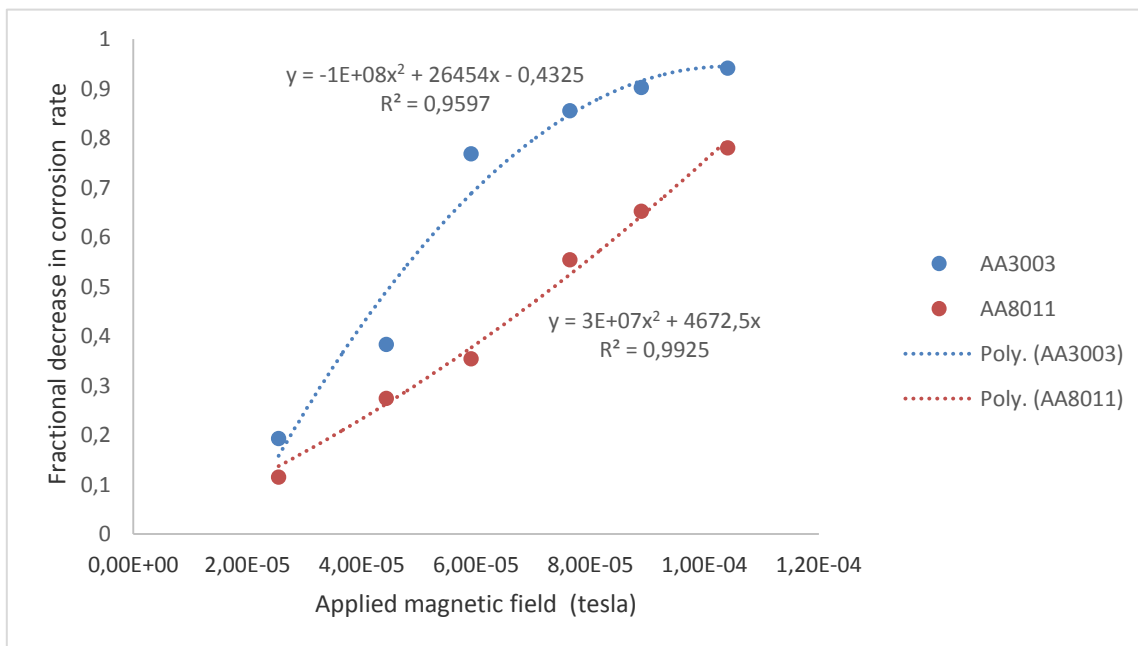


Figure 1. Variation of the fractional decrease in the corrosion rates of aluminium alloys AA3003 and AA8011 in 0.5M HCl acid solutions with applied magnetic field for a 2 - hour exposure time at room temperature

Slika 1. Varijacija frakcionog smanjenja u stopama korozije legura aluminijuma AA3003 i AA8011 u 0,5M HCl kiseline sa primenjenim magnetnim poljem za vreme izlaganja od 2 sata na sobnoj temperaturi

In the case of the aluminium alloy AA8011, the character of the fitting curve suggests that the fractional decrease,  $\Delta\rho/\rho_0$  will continue to increase as long as the applied magnetic field increases. Both empirical parameters  $a$  and  $b$  are positive. As a result, both terms,  $aB^2$  and  $bB$ , on the right-hand side of Eq. 4 are positive quantities for aluminium alloy AA8011.

In fact, the trends depicted in Fig. 1 evoke an insightful connection between the corrosion behaviour of the aluminium alloys under study and the behaviour of some metals, their alloys and some semiconductors when exposed to applied magnetic fields. For such materials, their electrical resistances change with increase in applied magnetic field. The phenomenon is known as magnetoresistance. In the case where the direction of applied magnetic field is at right angles to the direction of the current flowing in the metal, alloy or

semiconductor, the phenomenon is known as transverse magnetoresistance [28].

As regards transverse magnetoresistance and in the case of low applied magnetic field, the fractional change in the electrical resistance of the material depends on the applied magnetic field through a relation of the form [28 – 30]:

$$\frac{R(B) - R(0)}{R(0)} = \beta f(B) \quad (5a)$$

or

$$\frac{\Delta R(B)}{R(0)} = \beta f(B) \quad (5b)$$

implying that the fractional change of the resistance,  $R(B)$ , of the material in the presence of the magnetic field relative to resistance,  $R(0)$ , in the absence of the magnetic field, is some function,  $f(B)$ , of the magnetic field,  $B$ . The parameter,  $\beta$ , in

Eqs. (5) is a constant. The functional form of the function,  $f(B)$ , depends on the material being investigated, the relative concentration of charge carriers and the details of the Fermi surfaces of the material [28 – 29].

However, materials in which transverse magnetoresistance occurs fall into three categories, namely:

**Category I:** Materials for which  $\Delta R(B)/R(0)$  increases quadratically with  $B$  at first, then increasing more slowly before saturating at higher values of magnetic field, exhibiting independence of  $B$  [28,29]. Materials in this category have unequal concentration of electrons and holes and are therefore uncompensated with all electron and hole orbits on the Fermi surface being closed [29]. Pure aluminium metal falls into this category of materials [28].

**Category II:** Materials for which  $\Delta R(B)/R(0) = \alpha B^2$  with  $\alpha$  being a constant. For such a material, the fractional change in resistance varies quadratically with  $B$ , increasing without limit as long as  $B$  increases. Materials in this category are compensated, having equal concentrations of electrons and holes but like Category I materials, all electron and hole orbits are closed [29].

**Category III:** Materials for which the quantity  $\Delta R(B)/R(0)$  is anisotropic, its dependence on  $B$  being determined by the crystallographic direction along which the magnetic field is applied. In some crystallographic directions of such a material,  $\Delta R(B)/R(0)$  may behave as for Category I materials. In such directions, electron and hole orbits on the Fermi surface are closed. But there are some other crystallographic directions in this category of materials which contain open electron and hole orbits on the Fermi surface. In such directions, the fractional change,  $\Delta R(B)/R(0)$ , in resistance may increase without saturation as  $B$  increases [28].

The above exposition can be connected with the observed behaviour of the corrosion rate of aluminium alloy AA3003 as the applied magnetic field is increased in this study. All in all, it appears that the presence of the applied magnetic field causes an increase in the electrical resistance of the aluminium alloy AA3003 samples leading to increased limiting of the flow of corrosion currents on the surfaces of the alloy samples. This results in reduced corrosion rates since corrosion currents are directly connected to corrosion rates and can be used as a measure of corrosion rate [31]. It is quite intriguing that the variation of the fractional decrease in corrosion rates  $\Delta\rho/\rho_0$  with magnetic field for aluminium alloy, AA3003, samples almost mimics the behaviour of the fractional increase of electrical resistance  $\Delta R(B)/R(0)$  of Category I materials with magnetic field increase.

It is pertinent at this stage to comment that in metal corrosion studies which employ such

electrochemical techniques as potentiodynamic polarization (PDP) and electrochemical impedance spectroscopy (EIS), such observed parameters as polarization resistance,  $R_p$  (as in the case of PDP) and charge transfer resistance,  $R_{ct}$  (as in the case of EIS), all have inverse relationships with corrosion currents and hence with corrosion rates. For example, in a PDP experiment, corrosion currents which are directly proportional to corrosion rates are observed to decrease with increasing polarization resistance,  $R_p$  [11,25,31–33]. Again, in an EIS experiment, increased charge transfer resistance,  $R_{ct}$ , of the electrochemical process leads to decrease in the corrosion current of the metal or alloy involved in the corrosion process [7, 11,25,31–33]. The remarks made above are consistent with the suggestion that the large reduction in the corrosion rates of the aluminium alloy AA3003 may be largely attributed to the increase in the electrical resistance of the alloy specimens in the presence of applied magnetic field, a phenomenon called transverse magnetoresistance.

One therefore considers the following scenario. The presence of a perpendicularly applied magnetic field causes an increase in the electrical resistance of the alloy sample (transverse magnetoresistance effect). This causes the limiting (or decrease) in the corrosion current flow. Further increase in the applied magnetic field results in a further increase in the electrical resistance of the alloy sample, hence leading to a further lowering of the corrosion current. Since corrosion current (or more precisely, corrosion current density) is directly proportional to corrosion rate of the sample [3], one can now understand how the application of magnetic field causes a reduction in the corrosion rate of the alloy sample.

In the case of the aluminium alloy AA8011, the fitting curve for the corrosion data suggests that the material is a Category II material since  $\Delta\rho/\rho_0$  tends to increase without limit so long as the applied magnetic field increases. In the low magnetic field regime (as being used in this work), a Category II material is expected to exhibit a quadratic relationship between  $\Delta R(B)/R(0)$  and  $B$ . But what is being observed in this study is that  $\Delta\rho/\rho_0$  is connected to  $B$  through a polynomial function of order 2, with both linear and quadratic components. This means that although the transverse magnetoresistance model largely explains the observed corrosion data for AA8011, there exists some deviations from the prediction of the model that are yet to be accounted for.

One would however seek an explanation by considering the fact that the model envisages the corrosion current pathway to be linear [28–29]. But the corrosion current pathway is not necessarily linear. It could be curved. This could introduce some deviation from the predictions of the model.

Moreover, one cannot ignore the effects of the magnetic field on the ionic constituents of the electrochemical system such as  $H^+$ ,  $Cl^-$ ,  $O^{2-}$  and metallic ions resulting from the electrochemical processes connected with the corrosion of the aluminium alloys [18,22–23]. What this means is that the observed reduction in the corrosion rates of the aluminium alloys AA3003 and AA8011 in the test solutions as the applied magnetic field is increased may be largely due to the transverse magnetoresistance phenomenon. Some other magnetic field effects may however contribute to the observed corrosion rate reductions [18,23].

#### 4. CONCLUSIONS

In this study, the corrosion behaviour of aluminium alloys AA3003 and AA8011 in 0.5M HCl acid solutions in the absence and presence of applied magnetic fields for exposure time of 2 hours at room temperature have been investigated by using the gravimetric technique. Results show that magnetic fields inhibit the corrosion of the aluminium alloys AA3003 and AA8011 in the 0.5M HCl acid solutions. This means that the presence of the magnetic field actually protects, to some degree, the aluminium alloys from corrosion. The observed protection efficiencies are higher for AA3003 alloy than for AA8011 alloy. This may be attributed to the differences in the elemental compositions of the alloys and the consequential differences in the electronic structure of the alloys.

It was established that the functional dependence of the fractional decrease in corrosion rates of the aluminium alloys on the applied magnetic field,  $B$ , strongly suggest that the corrosion inhibition mechanism can largely be attributed to the transverse magnetoresistance phenomenon. However, it is thought that the effects of the magnetic field on the ionic components of the electrochemical system only make a secondary contribution to the observed reduction in the corrosion rates of the aluminium alloys.

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## IZVOD

### ZAŠTITNO DEJSTVO MAGNETNOG POLJA NA KOROZIJU ALUMINIJUMSKIH LEGURA U RASTVORIMA HLOROVODONIČNE KISELINE

Gravimetrijskom tehnikom ispitan je uticaj primenjenih magnetnih polja na koroziju legura aluminijuma AA3003 i AA8011 u rastvorima hlorovodonične kiseline na sobnoj temperaturi. Magnetno polje je generisano od lokalno napravljenog elektromagneta sa promenljivim izlazima. Naneti su pod pravim uglom na površine uzoraka legure aluminijuma kada su potpuno uronjeni u ispitne rastvore. Praćene su brzine korozije legura aluminijuma AA3003 i AA8011 u 0,5M rastvorima HCl kiseline pri različitim primenjenim magnetnim poljima. Rezultati pokazuju da se brzine korozije ispitivanih uzoraka legure aluminijuma smanjuju sa povećanjem primenjenog magnetnog polja. Ovo implicira da prisustvo magnetnog polja inhibira koroziju uzoraka legure aluminijuma AA3003 i AA8011. Sa primenjenim magnetnim poljima u opsegu od 254,3 - 1040,6 mG [0,0254 – 0,1041 mT], zaštitna efikasnost magnetnog polja primećena za AA3003 u 0,5M rastvorima HCl kiseline kreće se od 19,3 – 94,1% dok je za identičan rastvor aluminijuma AA8011 test , efikasnost zaštite se kreće od 11,5 – 78,0%. Mehanizam zaštite se delom pripisuje fenomenu poprečne magnetootpornosti, a delom uticaju magnetnih polja na obrazac transporta mase konstitutivnih jona u elektrohemijskom sistemu.

**Ključne reči:** Magnetno polje, legure aluminijuma, gravimetrijska tehnika, brzina korozije, efikasnost zaštite, poprečna magnetootpornost.

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