



Data article

Evaluation of cathodic protection of mild steel with magnesium anodes in 0.5 M HCl

Cleophas Akintoye Loto^{a,b,*}, Roland Tolulope Loto^a, Patricia Abimbola Popoola^b^a Department of Mechanical Engineering, Covenant University, Ota, Ogun State, Nigeria^b Department of Chemical, Metallurgical and Materials Engineering, Tshwane University of Technology, Pretoria, South Africa

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ABSTRACT

The performance of two different sizes of galvanic magnesium anodes on the cathodic protection of mild steel in 0.5 M hydrochloric acid was evaluated at room and elevated temperatures. The cathodic protection reactions process was observed by weight-loss method's corrosion rate calculation and potential and current measurement methods. The magnesium anodes were observed to be effective as sacrificial anode in the tested environments. The results obtained for the potential and current measurements bear close correlation with the corrosion rate method in the hydrochloric acid environment. The varying anode cross-sectional areas used showed the anode size effects. The varied percentage protection of magnesium anodes ranged between 5.88 and 59.81% (Mg 1); and, 16.80 and 48.65% (Mg 2) respectively at 27 °C. At 60 °C, the percent change ranged between 22.49 and 61.46 (Mg 1); and 21.7 and 68.95 for Mg anode 2.

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Specifications Table

Subject area	Electrochemistry, Materials Science and Engineering, Corrosion Science
Compounds	Hydrochloric acid, Magnesium anodes, Mild steel.
Data category	Coupon specimens measurement
Data acquisition format	Weight loss measurement/corrosion rate, analytic calculations
Data type	Filtered, analyzed, graphical data presentations
Procedure	Weighed test pieces of mild steel were fully and separately immersed for 21 days in each of the different beakers containing 0.5 M HCl at both the room temperature of 27 °C and at the elevated temperature of 60 °C in which the test pieces were separately protected by wire connection to each of the magnesium anodes. Corrosion rate was calculated from the weight loss data and used. The prepared specimens were also separately tested for the potential and current measurements. The potential was recorded at every 3-day interval using a digital voltmeter and saturated calomel electrode as the reference electrode.
Data accessibility	Data are with the article in graphical presentations

1. Rationale

The effect of corrosive degradation and deterioration of materials by electrochemical reactions is tremendous both economically and technologically and hence corrosion is one of the biggest challenges facing the aging infrastructure today

* Corresponding author at: Covenant University, Km. 10, Idiroko Rd., Canaan Land, Ota, Nigeria.

E-mail address: cleophas.loto@covenantuniversity.edu.ng (C.A. Loto).

world-wide. In the US alone, many government studies indicate that costs due to corrosion loss is more than \$276 billion annually [1]; and according to recent NACE studies [2], the global cost is estimated to be US\$2.5 trillion which is equivalent to 3.4% of the global GDP (2013). This tremendous cost could be drastically reduced or minimized by using available corrosion control practices of which cathodic protection is a major part.

The technique is a procedure used to protect an object from corrosion by making it a cathode. It is an electrochemical means of corrosion control in which the oxidation reaction in a galvanic cell is concentrated at the anode and suppresses corrosion of the cathode in the same cell. This is achieved by placing a more easily corroded metal to act as the anode of the electrochemical cell in contact with the metal to be protected. This technique was first used in 1824 by Davy [3]. This method is a widely used method for controlling the corrosion of metallic structures in contact with many types of conducting environments. This method of protection essentially reduces the corrosion rate of a metallic structure by reducing its corrosion potential, bringing the metal closer to an immune state.

The protection systems are most commonly used to protect steel, water/fuel pipelines and storage tanks; ships, offshore oil platforms and onshore oil well casings among others [4–6]. It can be an effective method of preventing stress corrosion cracking. There is still keen interest in research on cathodic protection by corrosion research scientist [4–9] due to its technological and economic importance. However, an improperly performed cathodic protection has the adverse effect of producing molecular hydrogen that could be absorbed in the protected metal and cause subsequent hydrogen embrittlement [10]. The galvanic or sacrificial anode method; and the impressed current cathodic protection (CP) are the two mostly used methods. Galvanic anode systems employ reactive metals as auxiliary anodes that are directly electrically connected to the steel to be protected. Impressed-current systems employ inert anodes and use an external source of DC power to impress a current from an external anode onto the cathode surface. Galvanic anodes system is cheap and simple, but there is usually no convenient way to monitor the amount of protection being given [11]. It is also usually applied to a large range of industrial equipment where the surfaces are in contact with corrosive electrolytes e.g. heat exchangers; pump impellers and vessel internals [12]. The impressed current cathodic protection is used for larger structures that galvanic anodes could not economically deliver current to provide complete protection.

This investigation focuses on continuous efforts being made to improve the efficiency of this method to mitigate the debilitating effect of corrosion, particularly in strong corrosive environment. This could enhance wider engineering applications and with consequent economic benefits.

This experimental work examines the performance of magnesium alloy as sacrificial anodes for the cathodic protection of mild steel in HCl. It aims at investigating the rate of corrosion of the test specimens and the corresponding protection effectiveness of the anodes used.

2. Procedure

The mild steel specimen used had a percent nominal chemical composition of 0.130 C, 0.147 Cu, 0.173 Si, 0.397 Mn, 0.017 P, 0.031 S, 0.010 Co, 0.0005 Ca, 0.021 Zn and the rest 99.2 Fe. The magnesium anode used had ~99.36% magnesium composition. The hydrochloric acid was of AnalaR grade. The concentration of the acid electrolyte was 0.5 M HCl. The metallic samples were specifically cut into dimensions of 200 mm × 350 mm × 3 mm. They were initially pickled in dilute HCl. These test specimens were then ground with silicon abrasive paper of 60, 120, 220, 320 grits, polished to 1 μm, cleaned thoroughly with distilled water/ethanol, dried and kept in a desiccator for further experimental tests. Some selected specimens were in turn, mounted in araldite resin after spot welding to the connecting insulated flexible wire and were used for potential and current measurements of the steel specimens. There were two types of magnesium anodes used with variables dimensions of: (i) 15 × 30 mm = 450 mm² (4.5 cm²) surface area and designated as 'magnesium anode 1' and (ii) 20 × 25 mm = 500 mm² (5 cm²) surface area and designated as 'magnesium anode 2'.

Weighed test pieces were fully and separately immersed for 21 days in each of the different beakers containing the 0.5 M HCl at both the temperature of 27°C and at the elevated temperature of 60 °C in which the test pieces were separately protected by wire connection to each of the magnesium anodes. Each of the test specimens and the anodes was taken out every three days, washed with distilled water, rinsed with methanol, dried, and re-weighed. Plots of corrosion rate vs. exposure time were made as presented in results and discussion Section 3. Corrosion rate was calculated from the formula in Eq. (1).

$$\text{C.R. (mm/y)} = 87.6 \times (W/\text{DAT}) \quad (1)$$

where: W = Weight loss in milligrams; D = Metal density in g /cm³; A = Exposed area of sample in cm²; T = Time of exposure of the specimens in hours.

Some prepared specimens were tested for potential measurements. They were immersed, in turns, in the test media after being connected to the magnesium anode. The potential was recorded at every 3-day interval using a digital voltmeter and saturated calomel electrode as the reference electrode. Plots of potential (vs. SCE) with the exposure time were made. Readings of current measurement was with the use of zero resistance ammeter (ZRA).

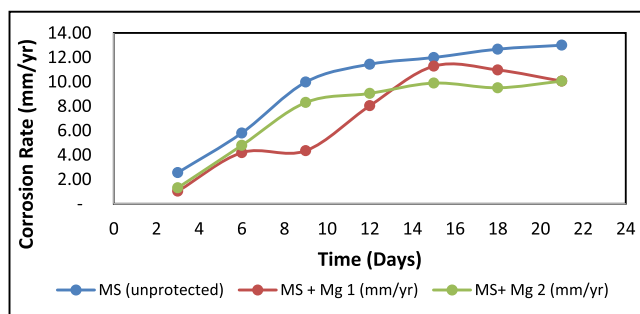


Fig. 1. Curves of corrosion rate with exposure time of mild steel in HCl (MS = mild steel).

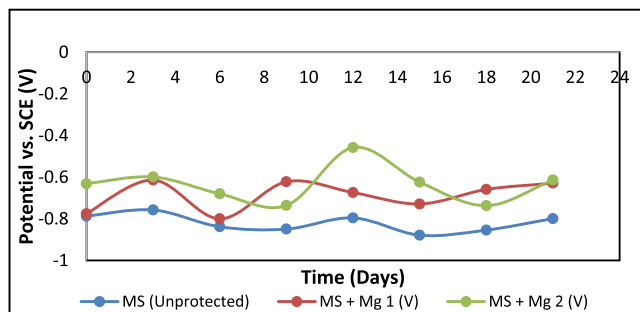


Fig. 2. Curves of potential with exposure time of mild steel in HCl (MS = mild steel).

Table 1

Per cent change in corrosion rate data - at 27 °C (MS = Mild Steel).

Time (Days)	MS (unprotected)	MS + Mg 1 (mm/yr)	% Change	MS+ Mg 2 (mm/yr)	% Change
0	-	-	-	-	-
3	2.5523	1.02566504	59.81	1.31057	48.6592
6	5.7985	4.1881322	27.7721	4.786436	17.45389
9	9.9768	4.34957	56.403155	8.300289	16.8040955
12	11.4352	8.034376	29.73996	9.045796	20.8951658
15	11.9883	11.282315	5.88895	9.891969	17.48647
18	12.6725	10.96891	13.44320	9.506395	24.9841
21	12.9967	10.053114	22.64872	10.05315	22.64844

3. Data, value and validation

In cathodic protection, anode, the more active metal supplies current and dissolves gradually into ions in the electrolyte; and at the same time produces electrons which the cathode (the less active) receives through the metallic connection (galvanic) with the anode. The cathode is thus negatively polarized and becomes protected from corrosion [13,14].

4. At room temperature (27 °C)

4.1. Corrosion rate of mild steel

Fig. 1 shows the results of the calculated corrosion rate obtained from the weight-loss of the specimens immersed in 0.5M HCl using separately two magnesium anodes of different sizes and surface areas for the cathodic protection of the mild steel specimens. It could be observed that the two anodes (Mg anode 1 and 2) performed well relatively without much apparent difference due to size effect. They both recorded a mild steel corrosion rate of 10.053 mm/y on the 21st day of experiment. The strong acid caused active corrosion reactions up to the 10th day. The results profile show a relative substrate protection due to the low corrosion rates recorded. The unprotected specimen showed increased and higher corrosion rates throughout the experiment. Magnesium is a reactive metal and its immersion in HCl to protect the steel will not endure for long as it will be susceptible to rapid dissolution in such a strong electrolyte. Its reactive tendency will enhance the production of current for effective cathodic protection. Table 1 shows the per cent change in corrosion rates recorded. No particular trend was followed as the obtained calculated results looked similar, though haphazardly.

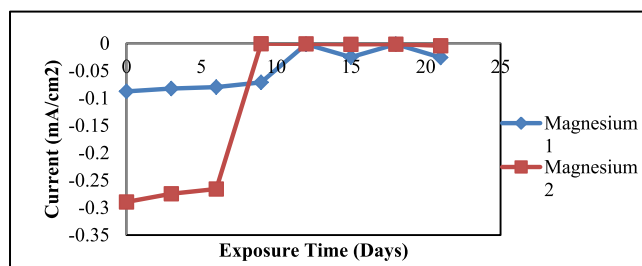


Fig. 3. Curves of current with exposure time of mild steel in HCl using magnesium anodes for CP.

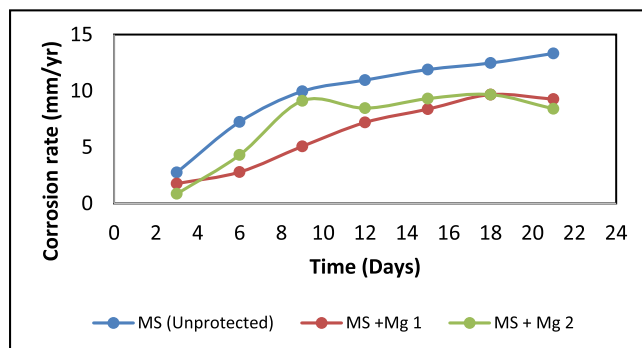


Fig. 4. Curves of corrosion rate with exposure time of mild steel in HCl at elevated temperature (60 °C).

4.2. Potential measurements

Fig. 2 shows the results obtained for the potential measurement of mild steel specimens protected by magnesium anodes in HCl. The mild steel specimens protected with the two magnesium anodes (different in size) had slightly fluctuating electrode potentials that put them in the protective passive range right from the start of the experiment to the end. The potentials recorded with the use of magnesium anode 2 (bigger size) ranged from the start with a value of -0.632 V (-632 mV) and ended with -0.614 V (-614 mV). Likewise with the use of magnesium anode 1 (slightly smaller size) the electrode potential started with -0.759 V (-759 mV) and ended on the 21st day of the experiment with the same recorded result as Mg anode 2. From the results, the curves crisscrossed each other, that is, their electrochemical corrosion reactions behavior were similar and very close indeed.

The current values generated show the initial reactive nature of the magnesium anode initially with some disparity between the two anode sizes used. However, the overall current results showed that the mild steel substrate was well protected due to the very low currents obtained. Increased current is an indication of increasing corrosion rate and this phenomenon was not observed in the experimental data as presented in Fig. 3.

The current value of the smaller magnesium anode size ranged from -0.877 from the start to -0.0257 (mA) on the 21st day of the experiment. With the slightly bigger Mg anode, mild steel protection seemed low in the first 5 days after which it recorded very low/negligible current that ranged between -0.0006 (mA) on the 9th day to -0.0043 (mA) on the 21st day. It indicates good results.

4.3. At elevated temperature (60 °C)

Data results obtained for the same experiments as above but at the temperature of 60 °C are presented graphically in Figs. 4–6. The elevated temperature was aimed at determining the magnesium anode protective efficiency on mild steel under harsher condition of corrosion reactions kinetics. The results obtained were almost similar in all the tested parameters/calculations. These include the corrosion rates, the potential and current measurements. The corrosion rate trend, Fig. 4, was similar here to that of 27 °C with values of 9.2635 and 8.4088 mm/yr respectively achieved for the relatively smaller Mg anode 1 and the bigger one (Mg anode 2) on the 21st day of the experiment. The size effect for the anodes was not pronounced here. The unprotected mild steel samples recorded the highest corrosion rates throughout the experiments. The percent change in corrosion rate calculated data, presented in Table 2, showed no apparent conformity to a particular trend.

In Fig. 5, though wider fluctuations could be observed with the use of slightly smaller Mg anode, the result still bear close similarity to that obtained at the room temperature of 27 °C. Relatively stable potentials were obtained from the 15th day (-0.574 V) and ended with -0.50 V on the 21st day of the experiment. The bigger Mg anode (2), gave slightly fluctuating results but more in a steady state than the former. It recorded -0.501 V at the beginning and ended with -0.52 V . These

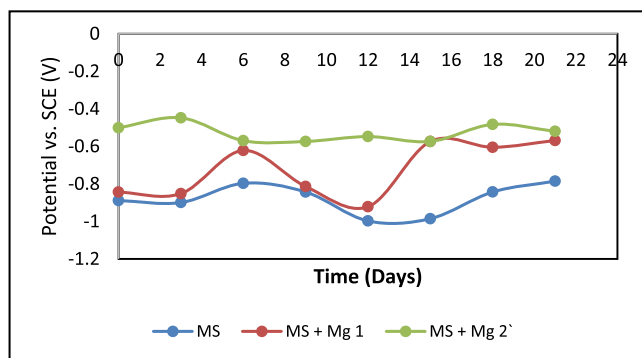


Fig. 5. Curves of potential with exposure time of mild steel in HCl at 60 °C (MS = mild steel).

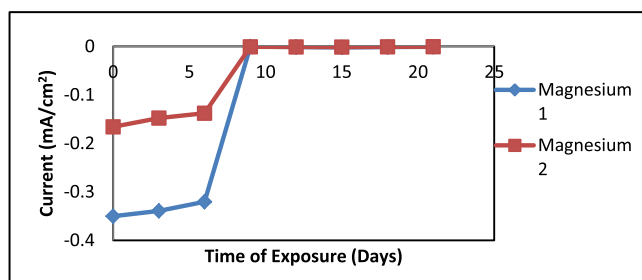


Fig. 6. Curves of current with exposure time of mild steel in HCl at elevated temperature (60 °C).

Table 2

Per cent change in corrosion rate data - at 60 °C (MS = Mild Steel).

Time (Days)	MS (Unprotected)	MS +Mg 1	% change	MS +Mg 2	% change
0	–	–	–	–	–
3	2.7536	1.766421	35.85049	0.854721	68.95987
6	7.2421	2.79088	61.46311	4.30209502	40.59603
9	9.9571	5.071343	49.06807	9.117022	8.43697
12	10.9573	7.193900	34.34605	8.46173	22.77541
15	11.8945	8.376264	29.5862457	9.310759	21.729715
18	12.4739	9.667884	22.49509776	9.66784	22.49545
21	13.3241	9.263546	30.475259	8.4088253	36.89010665

are values within the passivity range of good immunity for the mild steel substrate being protected with the galvanic magnesium anode. Here also, the influence of elevated temperature over the effective protection of mild steel with magnesium anode is insignificant.

The current data value in Fig. 6 also bear very close similarity with that of Fig. 3 and trend profile of the curves bear very close relationship. Excellent protective results of insignificant current values indicating negligible corrosion rates were exhibited particularly from the 9th day of the experiment with data values ranging for the two Mg anodes, from -0.0007 (9th day) to -0.0006 mA (21st day).

Declaration of Competing Interest

Authors declare no conflict of interest.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:[10.1016/j.cdc.2019.100246](https://doi.org/10.1016/j.cdc.2019.100246).

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