Materials and Design 93 (2016) 133–145

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Effect of alternating current on the performance of magnesium sacrificial anode

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ARTICLE INFO

Article history:
Received 30 October 2015
Received in revised form 17 December 2015
Accepted 19 December 2015
Available online 21 December 2015

Keywords:
Magnesium
Sacrificial anode cathodic protection
Alternating current
Polarity reversal
Instant effect
Time effect

ABSTRACT

Performance of magnesium sacrificial anode under alternating current was investigated in 4 g/L Na_2SO_4 simulated backfill solution by weight-loss measurements for 96 h, electrochemical measurements and surface examination. Alternating current increased the dissolution of magnesium, and at the same time, its DC potential shifted positively. The output cathodic protection current decreased at alternating current density of 50 A/m^2. Polarity reversal occurred to magnesium sacrificial anode as soon as alternating current interference of 100 A/m^2 (or larger) was applied. Besides the “instant effect”, the polarity reversal showed a “time effect”. It disappeared gradually at alternating current density of 100 A/m^2. When alternating current density was more than 200 A/m^2, the polarity reversal remained throughout the experiment (96 h). Based on the results of electrochemical measurements and surface examination, mechanism of polarity reversal was proposed.

1. Introduction

Nowadays it is unanimously accepted that buried metallic pipeline suffers from alternating current (AC) interference when it is close to power lines [1–5], i.e., high voltage AC transmission lines or rail transit systems. Magnesium (Mg) sacrificial anode has been widely used to protect buried metallic pipeline or other structures from corrosion because of its large driving voltage [6–8]. The reported work indicates that AC can exhibit significant effects on the performance of Mg sacrificial anode used to provide cathodic protection (CP) for buried pipeline [9–12].

As early as 1978, Pookote [13] pointed out that AC could lead to the potential shift of Mg sacrificial anode and accelerate its dissolution. Freiman [14] investigated the effect of AC on the performance of pipeline-Mg sacrificial anode CP system. Experimental results showed that both the DC potentials of Mg and pipeline shifted positively under AC. At the same time, the current efficiency of Mg sacrificial anode was decreased significantly. Besides, Bruchner [15] found that the polarity of pipeline-Mg sacrificial anode CP system could be changed under AC. When the applied AC current density reached 39 A/m^2 Mg sacrificial anode turned to be the cathode while the protected pipeline turned to be the anode. Pipeline provided cathodic protection to Mg. He called this fact as the “polarity reversal” of Mg sacrificial anode. And he thought that the so-called “polarity reversal” of Mg sacrificial anode could be attributed to the rectification between Mg substrate and corrosion film.

To date, there is no doubt that AC plays a significant role in the electrochemical performance of Mg sacrificial anode. Even so, most of the reported works were concentrated on the corrosion behavior of Mg under no AC [16–18]. Effects of AC on the service parameters of Mg sacrificial anode, i.e., the DC potential, the output CP current as well as the corrosion rate, are not well understood currently. Moreover, the conditions of polarity reversal of Mg sacrificial anode under AC and corresponding mechanism remain mysterious. In this work, effects of AC on the performance of Mg sacrificial anode were investigated by AC interference experiment. Combined with electrochemical measurements, the affecting mechanism of AC on the performance of Mg was explored.

2. Experimental

2.1. Electrodes and solution

Mg and Q235 steel were employed in this work. The Mg was fabricated from a Mg sacrificial anode with the chemical composition (wt.%): Al 0.0036, Zn 0.001, Mn 0.035, Fe 0.0047, Si 0.0095 and Mg balance. The chemical composition (in wt.%) of Q235 steel was Mn 0.42,C 0.16,Si 0.1, S 0.039, P 0.024 and Fe balance. Both Mg and Q235 steel were cut into 10 × 10 × 6 mm cubes, to each of which a copper wire was attached for electrical connection by welding. Then they were embedded in epoxy resin, leaving a working area of 10 × 10 mm. The specimen preparation process should be performed with caution to avoid any gaps and cracks generating at epoxy/metal interface. Subsequently, the working surfaces of the specimens were wet ground by increasingly finger SiC papers (up to 1200 grits), cleaned by deionized water and ethanol.

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http://dx.doi.org/10.1016/j.matdes.2015.12.112

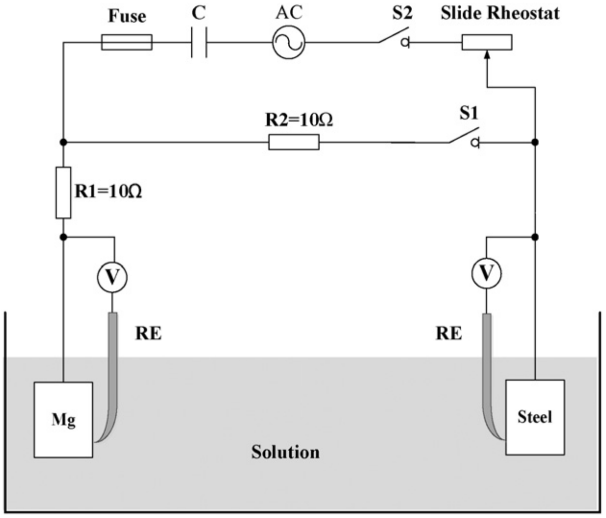

Fig. 1. Schematic diagram of experimental setup.

It is well-known that Mg sacrificial anode should be used with backfill, one of whose main composition is Na_2SO_4. Referenced with the reported work [1–2], a simulated backfill solution of 4 g/L Na_2SO_4 (1.98 Ω·m in resistivity and pH 6.4) was adopted as the aggressive solution, which was made from analytic grade reagents and deionized water (18 MΩ·cm in resistivity). All measurements were conducted at ambient temperature of 20 °C and open to air.

2.2. Weight-loss measurements

The experimental setup depicted in Fig. 1 was adopted to conduct the weight-loss measurements of Mg and Q235 steel under various AC current densities, from 0 to 300 A/m^2. The applied AC was a sine-waveform with 50 Hz in frequency. The AC current density was determined dividing the root-mean-square (RMS) value of AC voltage across resistor R1 by its resistance (10 Ω) and the working area (1 cm^2) of the Mg. Resistor R2 (10 Ω, 25 W) was used to simulate the direct current (DC) connection between Mg sacrificial anode and pipeline. The slide rheostat (10 kΩ, 2 W) was introduced to adjust AC current density to the preset value. The capacitor (50 V, 1000 μF) was used to protect AC power from DC signal and the fuse was missioned to make sure the security of circuit. Weight-loss measurements lasted for 96 h in this work.

After measurements, specimens were cleaned elaborately by both mechanical and chemical methods. For mechanical step, the slight scraping and brushing were used to remove the tightly adherent corrosion products. In chemical removal procedure, Mg specimen was bathed in a solution of 20% Cr_2O_3 at 25 °C for 1 min while Q235 steel specimen was cleaned by a descaling solution containing 500 mL HCl (special gravity 1.19), 3.5 g hexamethylenetetramine and 500 mL distilled water [19]. Subsequently, both specimens were rinsed by deionized water and ultrasonically bathed in acetone for 10 min. The cleaning process was repeated several times to remove corrosion products thoroughly. The weight-losses of specimens were measured by an electric balance with the accuracy of 0.1 mg.

2.3. Cathodic protection parameters measurements

The experimental setup for CP parameters measurements was identical to that used in weight-loss measurements. DC potentials of Mg and Q235 steel were measured by using a high impedance voltmeter (200 M Ω) with a suitable AC filtering and a saturated calomel electrode (SCE), with an acquisition frequency of 1 Hz. In order to minimize the ohmic drop, the reference electrode (SCE) was located at 1 mm away from the surface of specimen. The CP current (DC current) was calculated by measuring the DC voltage of R2 and then divided by its resistance (10 Ω). CP parameters measurements were conducted in two steps: (i) cathodic protection stage (CP): Turned switch S1 on and Mg provided cathodic protection to Q235 steel for 0.5 h; (ii) cathodic protection + AC interference stage (CP + AC): Both switch S2 and S1 were turned on, and AC with 50 Hz in frequency was applied to the CP system. The adopted AC current density ranged from 0 to 300 A/m^2. This stage lasted for 96 h.

2.4. Surface examination

The experimental setup shown in Fig. 1 was adopted to conduct the AC interference experiment of Q235 steel–Mg sacrificial anode CP system under AC of 100 and 300 A/m^2 for various time. After the experiment, the cross-section of Mg was examined by scanning electron microscope (SEM) and the chemical composition of corrosion film was analyzed by low angle X-rays diffraction.

2.5. Electrochemical impedance spectroscopy and potentiodynamic polarization measurements

The AC interference experiment of Q235 steel–Mg sacrificial anode CP system under AC of 100 and 300 A/m^2 for various time was conducted in 4 g/L Na_2SO_4 simulated backfill solution, using the experimental setup shown in Fig. 1. After experiment, electrochemical impedance spectroscopy (EIS) measurements of Mg, potentiodynamic polarization measurements of Mg and Q235 steel were performed. A traditional three-electrode system was employed for EIS and potentiodynamic polarization measurements, with Mg (or Q235 steel) as working electrode, SCE as reference electrode and Pt plate as counter electrode. EIS measurement of Mg was performed at open circuit potential (OCP) with the shift of OCP no more than 5 mV. The EIS measurement frequency was ranged from 10 mHz to 100 kHz with an applied AC perturbation of 10 mV. It should be noted that before the EIS measurements the specimens were allowed to reach a stable corrosion potential. After EIS measurements, potentiodynamic polarization measurements of Mg and Q235 steel were performed at a potential scan rate of 0.16 mV/s. Besides, the potentiodynamic polarization measurements of Mg and Q235 steel in 4 g/L Na_2SO_4 solution were performed respectively under no AC.

3. Results

3.1. Weight-loss measurements

Table 1 presented corrosion rates of Mg and Q235 steel as a function of AC current density (i_{ac}) determined by weight-loss measurements after 96 h of exposure in an aerated 4 g/L Na_2SO_4 simulated backfill solution. It could be seen that both corrosion rates of Mg and Q235 steel increased with increasing i_{ac}. The corrosion rate of Mg was 6.88 mm/y in the absence of AC. When AC was imposed to the system, the corrosion rate, however, was accelerated dramatically.

Table 1
Corrosion rate determined by weight-loss measurements of Q235 steel–Mg sacrificial anode CP system under various i_{ac} after 96 h of exposure in an aerated 4 g/L Na_2SO_4 simulated backfill solution.

The applied AC current density (A/m^2)	Corrosion rate (mm/y)	
	Mg	Q235 steel
0	6.88	0.0065
50	11.33	0.08
100	13.13	1.00
200	18.48	2.69
300	34.90	5.11