Corrosion Resistance of AA6063-Type Al-Mg-Si Alloy by Silicon Carbide in Sodium Chloride Solution for Marine Application

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Abstract: The present work focused on corrosion inhibition of AA6063 type Al-Mg-Si alloy in sodium chloride (NaCl) solution with a silicon carbide inhibitor, using the potentiodynamic electrochemical method. The aluminium alloy surface morphology was examined, in the as-received and as-corroded in the un-inhibited state, with scanning electron microscopy equipped with energy dispersive spectroscopy (SEM-EDS). The results obtained via linear polarization indicated a high corrosion potential for the unprotected as-received alloy. Equally, inhibition efficiency as high as 98.82% at 10.0 g/v silicon carbide addition was obtained with increased polarization resistance (R_p), while the current density reduced significantly for inhibited samples compared to the un-inhibited aluminium alloy. The adsorption mechanism of the inhibitor aluminium alloy follows the Langmuir adsorption isotherm. This shows that the corrosion rate of aluminium alloy with silicon carbide in NaCl environment decreased significantly with addition of the inhibitor.

Keywords: corrosion resistance; silicon carbide; sodium chloride (NaCl); aluminium alloy; interface; inhibition efficiency; thin film; adsorption isotherm; potentiodynamic electrochemical method; marine application

1 Introduction

Corrosion is believed to be one of the major problems affecting the durability, performance, safety, and appearance of materials in most service conditions. In these conditions and in various industries, such as chemical and construction, safely and cost reduction are of great priority. Corrosion affects all areas of the economy and it has been estimated that the cost of corrosion in an industrialized nations is more than 4% of Gross National Product, as reported by Suleiman *et al.* (2013), Mohammed *et al.* (2013) and Singh *et al.* (2012). Here for example, the physical properties of this aluminium alloy can be obtained easily, but the effects of corrosion deter its selection. Also, an increase in corrosion

resistance comes with an increase in cost. Aluminium alloys have considerable corrosion resistance in most environments; however, their resistance to corrosion in some aggressive environments like chloride is still a research concern. In the efforts toward identifying corrosion control method(s), the use of inhibitors often offers an alternative low cost way of combating corrosion, as stated by Fouda *et al.* (2009), Oguzie *et al.* (2004), Rahim and Kassim (2008), Rahim *et al.* (2007) and Amin and Khaled (2010). However, most inhibitors are considered to be toxic, expensive, and not eco-friendly. With increasing environmental awareness and the disadvantages of some chemicals, recent research is now tailored towards exploring some organic and non-toxic inhibitors. This leads to developing cheap and environmentally acceptable corrosion inhibitors, according to Obot *et al.* (2011) and Ogoko *et al.* (2009). In our previous studies: Abdulwahab *et al.* (2013), Fayomi *et al.* (2013) and Popoola *et al.* (2012a), various eco-friendly inhibitors have been used successfully for aluminium based alloy in different experimental conditions producing a high level of inhibition. This clearly showed that continued effort toward identifying new but promising corrosion inhibitors is important. This study, used polarization techniques to evaluate silicon carbide as a corrosion inhibitor for an aluminium alloy in sodium chloride solution.

2 Experimental procedures

2.1 Materials and methods

Aluminium alloy type AA6063, sized 20 mm×20 mm×3 mm with the chemical composition shown in Table 1, was sourced from the Surface Engineering Research Centre (SERC) of Tshwane University of Technology, Pretoria. The aluminium alloy was in the form of corrosion coupons to be immersed in 3.5% NaCl static solution with and without silicon carbide (SiC) inhibitor. In preparation, the coupons were abraded mechanically with 220, 400, 600, 800 and 1 000 grid emery paper, degreased with acetone and rinsed with distilled water. The initial weight of each sample coupon was then recorded. The silicon carbide was obtained in powdered form from the Technology Innovation Agency,

Chemical Station Ga-Rankuwa. It was dispersed onto a solution of 3.5 g NaCl in 100 mL distilled hot, 80 °C, water at 2.0, 5.0 and 10.0 g/v. The SiC was considered to be directly hydrolyzed to a silica solution rather than a slurry formation. Then the solution temperature was allowed to fall to 25 °C and mixed thoroughly by continuous agitation until a near homogeneous solution was observed.

Table 1 Nominal chemical composition of the aluminium alloy used   %

Element	Al	Si	Mn	Mg
Percentage	99.01	0.157	0.025	0.5
Element	Sr	Bi	Ca	Na
Percentage	0.0001	0.0024	0.0012	0.001
Element	Fe	Ti	P, Cr, Zr, Cu, Zn	B, Ni, Ag, Co
Percentage	0.281	0.0046	0.01	0.004

2.2 Polarization measurements

A conventional three electrode cylindrical glass cell, containing 100 mL of electrolyte at 25 °C was used for the electrochemical study. A platinum electrode was used as the counter electrode, and a saturated calomel electrode (SCE) as the reference electrode, with the aluminium alloy specimen as the working electrode. The polarization curves were plotted using an Autolab data acquisition system (Autolab model: AuT 71791 and PGSTAT 30). Both the corrosion rate and I_{corr} E_{corr} were estimated by the Tafel extrapolation method. Before recording the polarization curves, the solution was de-aerated for 10 min and the working electrode was maintained at its open circuit potential for 30 min until a steady state was obtained. The inhibition efficiencies (IE %) were obtained according to the equation reported by Lebrini *et al*. (2010):

$$\text{IE} = \frac{I_{corr} - I_{corr}^*}{I_{corr}} \times 100\% \qquad (1)$$

where I_{corr} and I_{corr}^* are the corrosion current densities of mild steel in the presence and absence of inhibitor, respectively.

2.3 Surface characterization of the coupons

The surface morphology and electron dispersive spectrometer (EDS) analysis of each aluminium alloy specimen, after corrosion measurement in 3.5% NaCl solution in the absence of silicon carbide, was assessed using scanning electron microscopy equipped with energy dispersive spectroscopy using model: JOEL 6100.

3 Results and discussion

3.1 Electrochemical corrosion of aluminium in SiC-NaCl solution

Potentiodynamic corrosion values obtained from the electrochemical study for the aluminium alloy in 3.5% NaCl/silicon carbide are presented in Table 2. The criterion under this method includes: potentiodynamic polarization-corrosion rate (PP-CR), potentiodynamic polarization-corrosion density (PP-I_{corr}), and linear polarization resistance (LPR), which were used for the evaluation of corrosion resistance of the aluminium alloy under investigation. Fig. 1 shows the polarization curves for 3.5% NaCl/silicon carbide at 25 °C. The use of silicon carbide as inhibitor in the 3.5% NaCl shows a decrease in corrosion rate and current density at all the concentrations of inhibitor used. In Table 2, the corrosion rate of the aluminium in NaCl solution without inhibitor, with 5.0 g/v SiC added, was the highest as expected. The lowest protection of the alloy was noticed (0.012 479 mm/yr) which corresponds to I_{corr} (4.48E-06 A/cm^2). Since the higher the corrosion rate, the more the current density value, and corrosion potential is expected to be lowered. Equally, the LPR (2 052.7 Ωcm^2) further justified such observation as it is next to the control value; without inhibitor addition (1 541.6 Ωcm^2). On the other hand, in Fig. 1, the least protected system was that of 'Al in NaCl +0g SiC', followed by curve 'Al in NaCl + 5 g SiC' with smaller corrosion potential value. However, it was expected that 'Al in NaCl + 10 g SiC' should have had higher potential, but obviously, its cathodic branch 'bc' is better stretched (passively).

Equally, corrosion potential (E_{corr}) and polarization resistance (R_p) increase with concentration of inhibitor. This is in line with other studies reported by Abdulwahab *et al*. (2013) and Rosliza *et al*. (2010). The inhibited aluminium alloy in 3.5% NaCl/silicon carbide indicated that corrosion resistance was improved significantly, with corrosion rate decreasing from 0.027 178 mm/yr to 0.000 480, 0.012 479 and 0.000 320 mm/yr at 2.0, 5.0 and 10.0 g/v silicon carbide concentration respectively. From the changes observed with the anodic and cathodic branches of the metal/inhibitor in the environment, a mixed-type corrosion inhibition was suggested for this study condition.

Table 2 Electrochemical corrosion data for AA6063-type Al-Mg-Si alloy in a static SiC/3.5% NaCl solution with and without silicon carbide addition obtained from polarization technique at 25 °C

S/N	$C/(\text{g·v}^{-1})$	$I_{corr}/(\text{A·cm}^{-2})$	$b_a/(\text{v·dec}^{-1})$	$b_c/(\text{vdec}^{-1})$	LPR $R_p/\Omega\text{cm}^2$	$-E_{corr}/\text{V}$	$CR/(\text{mm·yr}^{-1})$
1	0	9.75E-06	0.11851	0.11631	1541.6	1.3520	0.027178
2	2.0	1.72E-07	0.06170	0.05931	39431	0.7253	0.000480
3	5.0	4.48E-06	0.05028	0.05132	2052.7	1.3158	0.012479
4	10.0	1.15E-07	0.03836	0.02415	56051	0.9344	0.000320
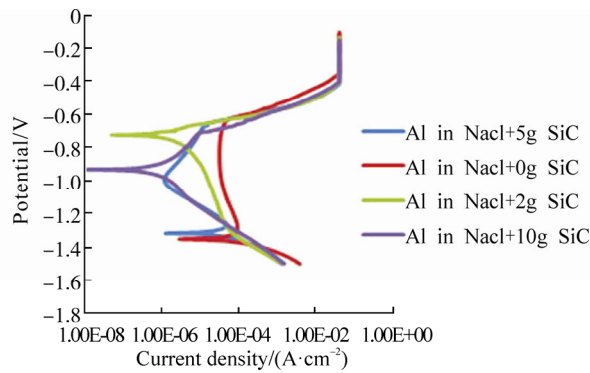
Fig. 1 Linear polarization of AA6063-type Al-Mg-Si alloy in a static SiC/3.5% NaCl solution with and without silicon carbide addition at 25 °C

3.2 Percentage inhibition efficiency, adsorption behaviour and evaluation of surface morphology

The percentage inhibition efficiency (IE%) of the silicon carbide inhibitor for aluminium alloy in 3.5% NaCl/silicon carbide solution was computed using the equation reported by Lebrini *et al*. (2010). Silicon carbide was used as inhibitor in varying concentrations for the study of the corrosion behaviour of aluminium alloy in NaCl at 25 °C. The results for the IE were used to compute the isotherm as presented in Fig. 2 for 3.5% NaCl/silicon carbide environment. This shows that % IE of the NaCl/silicon carbide environment increases with an increase in the inhibitor concentration. The reason might be that the surface area occupied by these inhibitors increased with concentration in the environment, hence higher % IE were obtained.
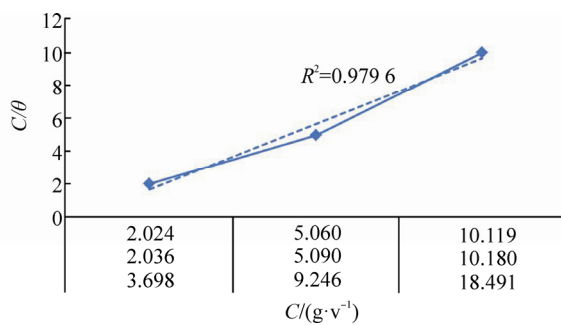

Fig. 2 Langmuir adsorption isotherm for the adsorption of silicon carbide compounds on the aluminium alloy surface in 3.5% NaCl/silicon carbide at 25 °C for PP-CR

It can be said that the silicon carbide provided a mixed-type inhibition since there are consistent variations in the branches (anodic and cathodic) during the corrosion study. These results were found to agree with other work by Lahhit *et al.* (2011), Haldar *et al.* (2012), Popoola *et al.* (2012b) and Abdulwahab *et al.* (2012). In order to assert the mechanism of adsorption of the inhibitor onto the aluminium surface, the Langmuir isotherm was used. The relationship between C/θ against C is linear at 25 °C (Fig. 2). Since the correction factor (R^2) for the aluminium alloy in

NaCl/inhibitor is almost unity; silicon carbide, PP-CR (0.979 6), the adsorption behavior can be assumed to have followed Langmuir adsorption isotherms in the studied conditions. However, it is important to note that the corrosion behavior is not the same with that for high-temperature or vapor-phase hydrothermal oxidation, since the oxidation rate is not controlled by oxidant diffusion through the protective silica surface layer that might have formed during the process.
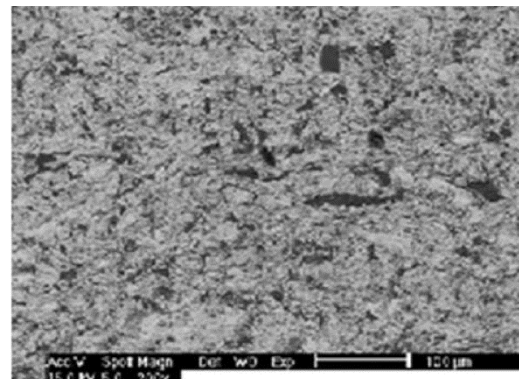
Fig. 3 SEM micrograph of AA6063-type Al-Mg-Si alloy as-received sample (x500)

(a) Micrograph

(b) Spectrum
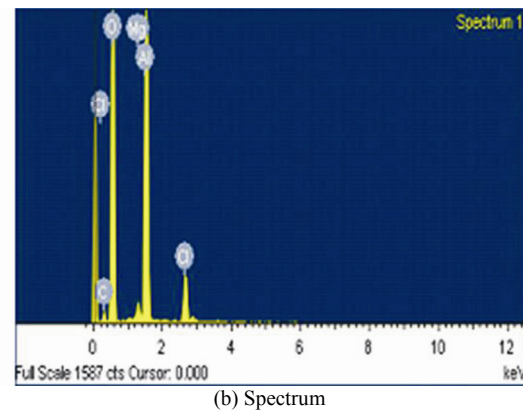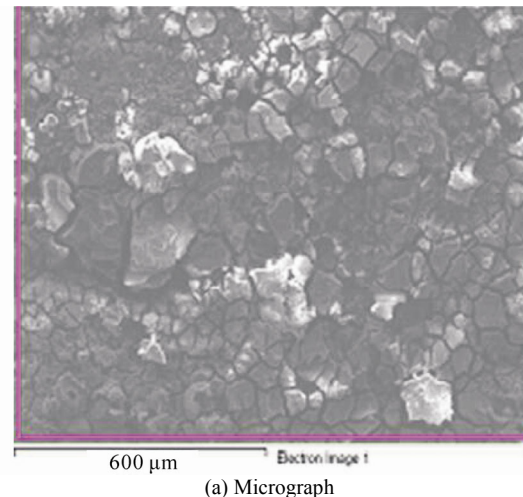
Fig. 4 SEM micrograph of uninhibited AA6063-type Al-Mg-Si alloy in NaCl solution (x500)

The microstructure of aluminium alloy surfaces is shown in Figs. 3 and 4. The as-received aluminium alloy can be seen in Fig. 3. An un-inhibited sample in 3.5% NaCl solution shows a severely pitted formation (Fig. 4). From the EDS in Fig. 4, the occurrence of O is a result of oxidation reaction and dissociation of the chloride ions in the solution.

4 Conclusions

The potential of silicon carbide as a corrosion inhibitor for Al-Mg-Si alloy has been evaluated, it is a good corrosion inhibitor in a simulated marine environment at 25 °C (sodium chloride solution). The corrosion resistance of the alloy increased with the addition of SiC into the NaCl solution. The SEM-EDS microstructures revealed that, without the application of this inhibitor, the alloy surface was damaged. This suggests that the addition of SiC as inhibitor might have formed a thin film layer on the surface of the alloy in the simulated marine environment. Also, the results obtained by linear polarization indicate a very high inhibition efficiency of 98.82% at 10.0 g/v silicon carbide in a static solution.

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