Evolution of physical and mechanical characteristics of deposited composite coatings on A356 mild steel

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Abstract
This research investigated the development of Zn-SnO2/Zn-Al2SiO5 thin film on A356 mild steel using the electrodeposition technique. The developed coating was attained in 2.0 V for 10 min at a constant current density of 1.5 A/cm2. The electroplating process was maintained at a constant stirring rate of 250 rpm, temperature of 45 °C, 10 g of SnO2 was used for the bath while Al2SiO5 was varied from 5 to 15 g. The surfaces of coated samples were characterized using a scanning electron microscope (SEM). The effects of 3.56% NaCl on the coated and uncoated sample were examined via the potentiodynamic polarization technique, employing Autolab PGSTAT 101 Metrohm potentiostat with NOVA software of version 2.1.2. The outcome of the experiment revealed that the electrodeposited Zn-SnO2/Zn-Al2SiO5 exhibits better stability, improved microhardness, excellent microstructural qualities, and outstanding corrosion resistance. The Zn-10SnO2-15Al2SiO5-coated steel exhibits the lowest corrosion rate of 0.0473 mm/year, representing 99.32% reduction in corrosion rate compared to the uncoated sample. Similarly, a corrosion current density (jcorr) value of 20.5 μA/cm2 was recorded for the uncoated sample which is much greater than the jcorr of the coated samples. This shows that the coating minimizes the exchange of current within the steel. The hardness value of the Zn-10SnO2-15Al2SiO5-coated steel was higher than other coated samples and 17.51% higher than the uncoated steel, and this indicates improvement in the mechanical property of the steel.

Keywords Characterization · Coating · Electroplating · Mild steel

1 Introduction
Enhancement of the service life of zinc coating by the addition of SnO2/Al2SiO5 nanoparticles into its bath preparation [1] promotes advantageous physical and mechanical characteristics for several industrial applications. The formation of thin-film barrier layers [2, 3], strong adhesion, high stability against mechanical abrasion and chemical attack, and improved microhardness properties are the unique attributes of nanoparticles inclusion in the reinforcement of mild steel [4].

Zinc coatings incorporated with nano had been enlisted as one of the main coating methods used for the protection of mild steel as a result of their cost-effectiveness and unmatchable improvement on the electrochemical and structural properties of mild steel [5]. Their application in manufacturing industries as a protective coating for large quantities of metal products and other fabricated ferrous metallic parts are enormous. Although, nanoparticle composite coatings have been discovered to improved physicochemical and structural properties of mild steel by providing a continuous barrier. However, any imperfection along its surface would inevitably serve as the starting and concentration point for deterioration, if the control is not accelerated [6–8].

During coating process, agitation of the coating bath suspends the particles in the bath and also aids the mass transportation of the particles from the anode to the cathode. The agitation must be moderate so as prevent the movement of the electrodes which could lead to the alteration of charge...
region and consequently altering the quality of particle deposits on the metal [9]. The particulate content in the coating bath and the properties incorporated in the composite deposits are functions of the shape, size, type of particle, and plating bath conditions such as pH, stirring rate, and temperature [10–12]. In the process of deposition, the zinc anode loses electron while the steel gain electrons.

Marine corrosion takes place with parts of piping and equipment that are used in saline water. Degradation of mild steel occurs as a result of constant or occasional exposure of components to seawater. Ships, pipelines, and maritime structures are well-known cases of systems that encounter marine corrosion. In view of this, 3.65% NaCl was simulated and this represents the marine or saline environment. This present research brings new insight into the physical and mechanical performance of mild steel coated with Zn-SnO2/Zn-SnO2-Al2SiO5 nanoparticles for various industrial applications.

### 2 Experimental procedures

#### 2.1 Material preparation

The base metal used in this research is rectangular A356 series mild steel plate whose percentage chemical composition is C, 0.15; Mn, 0.45; Si, 0.18; P, 0.01; Al, 0.005; S, 0.031; Ni, 0.008; and Fe, 99.166. Mild steel of dimension (50 mm × 30 mm × 2 mm) and zinc sheets of (90 mm × 50 mm × 10 mm) were prepared. The cathode was mild steel coupons and the anode was the commercially available pure zinc (99.99%). Mild steel was polished with different grades of emery papers. The mild steel sample was made active by dipping into a prepared 10% HCl solution for 5 s, and further rinsed in deionized water of room temperature.

#### 2.2 Bath formulation and deposition of Zn-SnO2/Zn-SnO2-Al2SiO5

The coating solution was prepared with analar grade of chemicals and deionized water at room temperature before coating. The bath formulation shown in Table 1 was prepared for the coating process and continuously stirred at 250 rpm and 45 °C constant heating although the deposition period, so as to obtain stabilized suspension that is devoid of particles’ agglomeration. Avoiding agglomeration of particles promotes the mobility electrophoresis of the coating solution [13].

In the deposition process, the mild steel being the cathode was placed equidistance from two zinc plates and connected to the negative terminal of the rectifier in the bath as shown in Fig. 1. The zinc anodes were connected to the positive terminal of the rectifier [14, 15]. The pH used was 4.5; other plating parameters such as voltage, current density, and time were kept at 2.0 V, 1.5 A/cm², and 10 min, respectively, as

![Fig. 1 Schematic diagram of a co-deposition system](image)

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Bath compositions of alloy co-deposition–based matrices</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Composition</strong></td>
<td><strong>Mass concentration</strong></td>
</tr>
<tr>
<td>ZnSO₄</td>
<td>70 g/L</td>
</tr>
<tr>
<td>SnO₂</td>
<td>10 g/L</td>
</tr>
<tr>
<td>Al₂SiO₅</td>
<td>5–15 g/L</td>
</tr>
<tr>
<td>Glycerin</td>
<td>5 g/L</td>
</tr>
<tr>
<td>Boric acid</td>
<td>5 g/L</td>
</tr>
<tr>
<td>Thiourea</td>
<td>5 g/L</td>
</tr>
<tr>
<td>Sodium sulfate</td>
<td>5 g/L</td>
</tr>
<tr>
<td>Potassium sulfate</td>
<td>5 g/L</td>
</tr>
<tr>
<td><strong>Operating conditions</strong></td>
<td></td>
</tr>
<tr>
<td>Cell voltage</td>
<td>2.0 V</td>
</tr>
<tr>
<td>pH</td>
<td>4.5</td>
</tr>
<tr>
<td>Time</td>
<td>10 (min)</td>
</tr>
<tr>
<td>Current intensity</td>
<td>1.5 (A/cm²)</td>
</tr>
</tbody>
</table>
presented in Table 1. The coatings of the samples were strategically done with reference to ASTM A53/A53M and A153.

2.3 Material characterization and structural test

The morphology and adhesion of Zn-SnO2/Zn-SnO2-Al2SiO5 on the surface mild were examined using a scanning electron microscope (SEM). The electrochemical behavior was investigated with the use of the standard three-electrode cell. Potentiodynamic measurements (−1.5 V/Ocp to 1.5 V/SSCE, 0.005 mV/s) were performed after 60 min of stabilization of open circuit potential in a 3.65% NaCl solution. Brinell technique was used to characterize the microhardness properties of the coated and uncoated samples. This was done in accordance with our previous work Ref. [16].

3 Results and discussion

3.1 Electrochemical test

Potentiodynamic polarization measurements were performed to evaluate the corrosion defense of the embedded nanoparticles. Figure 2 shows the plots of the potentiodynamic curves of Zn-SnO2/Zn-SnO2-Al2SiO5-coated and uncoated specimens. The values of corrosion current density of the coated samples were found to be smaller than those of the uncoated. This attests that the coating barred the active sites of the steel preventing transfer of current. The coatings were able to form inhibition barriers, therefore limiting the cathodic evolution and anodic metal dissolution reactions of the mild steel [17–20]. Zn-SnO2/Zn-SnO2-Al2SiO5 composite coatings are mixed inhibitors but less negative values of the Ecorr of the coated samples with respect to the control imply that the coatings performed predominantly as anodic inhibitors.

As indicated in Table 2, the corrosion rate of the uncoated steel was 2.59 mm/year; the Zn-10SnO2-coated steel has the highest corrosion rate among the coated samples with a value of 1.134 mm/year. Zn-10SnO2-15Al2SiO5-coated sample possesses a lower corrosion rate value of 0.0473 mm/year. The low corrosion rate could be attributable to the quality and tenacity of the passive film generated by Zn-10SnO2-15Al2SiO5 on the surface of the coated steel or elemental stability of the sample [21].

3.2 Microstructure analysis

The morphology of Zn-SnO2/Zn-SnO2-Al2SiO5-coated steel was exposed in the SEM micrographs shown in Fig. 3. Significantly, the crystallites of the deposits are homogenously distributed on the steel samples, signifying re-generated materials with better corrosion and mechanical properties [22]. The SEM micrographs present nanocomposite structure along the boundary as a result of the alliance of notable crystallite of SnO2-SnO2-Al2SiO5 nanoparticulates. More so, two expected phases can be seen in the SEM micrographs in Fig. 2, indicating the embodiment of the SnO2 and Al2SiO5 in the zinc interface, displaying immeasurable and embellished nodular structures on the coating network. This was found to grow with the addition in the mass concentration.

<table>
<thead>
<tr>
<th>Samples</th>
<th>jcorr (μA/cm²)</th>
<th>RP (Ω)</th>
<th>Ecorr (V)</th>
<th>Corrosion rate (mm/yr)</th>
<th>Percentage reduction of corrosion rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncoated</td>
<td>20.5</td>
<td>199.0</td>
<td>−1.2124</td>
<td>2.59</td>
<td>0</td>
</tr>
<tr>
<td>Zn-10SnO2</td>
<td>11.5</td>
<td>389.9</td>
<td>−1.0469</td>
<td>1.134</td>
<td>56.22</td>
</tr>
<tr>
<td>Zn-10SnO2-5Al2SiO3</td>
<td>9.15</td>
<td>297.0</td>
<td>−1.0980</td>
<td>0.965</td>
<td>62.74</td>
</tr>
<tr>
<td>Zn-10SnO2-10Al2SiO5</td>
<td>6.32</td>
<td>893.3</td>
<td>−1.0329</td>
<td>0.0734</td>
<td>97.17</td>
</tr>
<tr>
<td>Zn-10SnO2-15Al2SiO5</td>
<td>4.07</td>
<td>1175.8</td>
<td>−1.0058</td>
<td>0.0473</td>
<td>99.32</td>
</tr>
</tbody>
</table>
of Al$_2$SiO$_5$. It is worthy of note that the corresponding and synergistic effect of SnO$_2$ and Al$_2$SiO$_5$ nanoparticles strengthens the coating system and further provided refined and attractive morphology for the coated samples. This was indeed suspected considering the pathway of nucleation, which originated from the zinc metal as a load carrier; the diffusion of the particulates affects the nucleation domains and consequently improving the developed nanocomposites [23].

Moreover, it is vital to intimate that the scanty change in microstructure of Fig. 3c and d could be traceable to the increment in the mass concentration of Al$_2$SiO$_5$ nanoparticulates blended into the nanocomposite coatings resulting to improved precipitation and enhanced coating. One can, consequently, infer that the hardness of the composite coatings increased with the incorporation of Al$_2$SiO$_5$ particles in the coating. This is in accordance with the conclusion of other authors [24, 25].

### 3.3 Microhardness analysis

The microhardness results obtained for the Zn-SnO$_2$/Zn-SnO$_2$-Al$_2$SiO$_5$ deposit are presented in Fig. 4. Upon observation, Zn-10SnO$_2$-15Al$_2$SiO$_5$ gave the highest hardness reading. Using the Brinell hardness value, the substrate material hardness rose from 177 BHN to 208 BHN after composite deposition. This is in accordance with ASTM A-370 and A833. Generally, the hardness value for all the samples with differing additives shows an increase. This furthermore implies that the improvement in hardness could be attributed to the creation of an adhesive mechanism of the composite coating on the substrate sample. Also, microhardness of electrodeposited coatings is dependent on operating factors such as bath ingredients and other processing parameters [25, 26].
4 Conclusions

Incorporation of SnO2/Al2SiO5 into Zn composite coating improved the corrosion resistance, with mixed inhibitive characteristics. The Zn-10SnO2-15Al2SiO5-coated steel exhibits the lowest corrosion rate of 0.0473 mm/year, representing 99.32% reduction in corrosion rate compared to the uncoated sample. The SEM micrograph displays excellent morphology of SnO2-Al2SiO5-coated steel. The increase in microhardness from 177 BHN to 208 BHN attests to an improvement in the mechanical properties of the coated steel. The study has presented remarkable insight into the application of nanocomposite firm for corrosion protection and structural enhancing properties.

References


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