Effect of SiC concentration on electrochemical and mechanical behavior of Zn-SiC composite coating

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Abstract. Electrodeposition of zinc with SiC particles is a promising process that could effectively replace chromate process. Increasing of SiC concentration in the bath solution could increase the incorporation of SiC particles into zinc matrix and help in improvement of corrosion resistance and hardness of composite coating. However, it is difficult to obtain composite coating with uniform, dense and high SiC content. The aim of this study to investigate the effect of SiC concentration on electrochemical and mechanical behavior of Zn-SiC composite coating. Zn-SiC composite coatings were successfully deposited on mild steel plate using electrodeposition technique. Zinc sulfate bath containing 2 micron-sized of SiC particles were prepared to deposit the composite coating. The deposition was carried out under operating conditions of current density 40 mA/cm² and 600 rpm of agitation rate. Various concentrations of SiC (0, 5, 10, 15 and 20 g/l) were investigated. Electrochemical behavior of Zn-SiC coating was performed using linear polarization method. The hardness of the coating was carried out using Vickers hardness tester and the measurements were taken through cross section of the coating. Coating thickness and morphology of the coating were examined using SEM. The experimental results observed an improvement in corrosion resistance and hardness of the coating with increasing SiC content. The microhardness value of 166 (Hv) was obtained at optimum concentration of 20 g/l. The corrosion results showed that the corrosion rate of 6.05 x 10⁻¹ mm/yr and 3.0 x 10⁻¹ mm/yr were obtained for Zn (0 g/l of SiC) and Zn-SiC (20 g/l of SiC) coatings respectively. SEM images of the surface and cross section of the coating showed an embedding of SiC into zinc coating and its particles were distributed along cross section of the coating. Finally average thickness of the coating was recorded at 19 microns.

1. Introduction
The deterioration of metal structures due to corrosion is one of the most serious problem in the world. Corrosion causes durability reduction of steel structures which leads to a loss of hundreds of billions every year. Recently sacrificial metal coating especially zinc coating is shown the most effective method to protect steel against corrosion. Several methods have been developed to deposit zinc coatings, one of which is electrodeposition. The purpose of electrodeposition process is generally to enhance the
The surface preparation of steel specimen involved abrasion of the steel surface with various SiC papers from #200 to #2000 grits and polished to 0.05 microns using alumina powder and then ultrasoniced in acetone for 5 minutes and finally washed with distilled water. Zinc anode was immersed in HCl (10%) for 30s and washed with water for activation purpose. The anode and the cathode were immersed in the plating bath and connected to DC power supply. The electrodeposition process started when DC power supply was switched on. All experiments were performed under operating conditions of 600 rpm of stirring rate, current density of 40 mA/cm², deposition time of 25 min and various SiC concentrations (0, 5, 10, 15 and 20) were used. pH of solution was kept constant at value of 4.5 during the deposition process. After the deposition process completed, the coated samples were rinsed with distilled water and dried.
Table 1. Chemical composition of zinc sulfate bath

| Chemicals                        | Concentration (g/l) |
|---------------------------------|---------------------|
| Zinc sulfate (ZnSO₄)            | 200                 |
| Boric acid (H₃BO₃)              | 16                  |
| Sodium Dodecyl Sulfate (SDS)    | 0.4                 |
| Sodium chloride (NaCl)          | 40                  |

The microstructure and surface morphology were characterized using scanning electron microscopy SEM (Zeiss Supra Model 35VP) and the composition of the coating was identified by energy dispersive system (EDX). The microhardness of Zn-SiC coatings were evaluated using microhardness tester (Shimadzu Co.Ltd., Japan) where 10 gr load and 10 seconds duration time were used. Electrochemical behavior of composite coatings were investigated using linear polarization technique (Auto lab PGSTAT-30). The coating weight and coating thickness were measured and recorded.

3. Results and discussion

3.1. Coating weight measurements

The coating weight was estimated by measuring the sample weight before and after the coating and the difference in the coating weight per unit area was expressed as the coating weight. The coating weight of the Zn-SiC composite coating at various concentrations of SiC was estimated. It was observed that the concentration of 20 g/l of SiC exhibited higher coating weight (0.01685 gr/cm²) compared with other concentrations. This was due to higher incorporation of SiC particles in the coating.

3.2. Microhardness measurements of Zn-SiC composite coating

Microhardness values of the composite coating with various of SiC concentrations (0 to 20 g/l) were measured (figure 1). The results demonstrated that the microhardness raised with increasing in concentration of SiC in the plating bath. This attributed to the higher hardness of SiC particles. The hardness of Zn-SiC composite coatings were depended on the hardness of SiC particles and as SiC concentration increased, the higher hardness was achieved where it was recorded at 166 and 80 Hv for 20 and 0 g/l of SiC content respectively. Incorporation of SiC into zinc matrix leads to increase in microhardness of Zn-SiC composite coating by refining the coating structure. The coating has many SiC particles which can inhibit further propagation of dislocations and resulted in increase in hardness of Zn-SiC composite coating [14,15].

Figure 1. Microhardness of Zn and Zn-SiC composite coatings.
3.3. Morphology and composition of Zn-SiC composite coating

SEM micrographs of Zn-SiC composite coating obtained at various concentrations of SiC are shown in figure 2. It was observed that SiC concentration increased from 5 to 20 g/l in the bath, the incorporation rate of SiC was increased and the steel surface was fully covered with zinc matrix contained SiC particles. Zn-SiC composite coatings have microstructure consisted of large and small grains. These structures were due to the embedment of SiC particles in zinc matrix that perturbs crystalline growth of the metal deposit in some regions [16,17]. Majority of Zn-SiC composite coatings present hexagonal grains parallel to each other. The chemical composition of Zn-SiC composite coatings were obtained using EDX analysis as shown in figure 2(c) and (f). Zn-SiC composite coatings were mainly contained zinc and silicon. At lower concentration of SiC (5 g/l) indicted that zinc matrix contained less amount of SiC particles while at higher concentration of SiC (20 g/l) show higher incorporation of SiC into zinc matrix with less porosity. Incorporation of SiC into zinc matrix is clearly shown in figure 2(b) and (e).

![SEM micrographs of Zn-SiC composite coating](image1)

![SEM micrographs of Zn-SiC composite coating](image2)

Figure 2. SEM and EDX of Zn-SiC composite coatings respectively (a,b and c) for concentration of 5g/l and (d,e and f) for concentration of 20g/l of SiC.
3.4. Electrochemical studies

Corrosion tests were conducted using testing solution of 3.5% NaCl. Corrosion characteristics of Zn and Zn-SiC composite coating such as corrosion potential ($E_{corr}$), corrosion current density ($i_{corr}$) and corrosion rate were determined from polarization curve using Tefal extrapolation method (figure 3 and 4). Table 2 presents the values of EIS studies. As shown in figure 3 and 4, increasing in SiC concentration has positive effect on corrosion behavior of Zn-SiC composite coatings and Zn-SiC coatings were shifted towards the positive direction compared to zinc coating. Almost all polarization curves of Zn-SiC composite coatings show transition to passivation where SiC particles lead to positive shift in potential from -1160 mV to -1100 mV for zinc and Zn-SiC-CO4 respectively. This demonstrates that the presence of SiC in zinc matrix improved the corrosion behavior. This attributed to formation of protective layer of Zn-SiC where the composite coating surface exhibited dense coating and SiC particles filled the gaps and defects between the grains of zinc matrix.

Table 2. Corrosion behavior of Zn and Zn-SiC composite coatings.

| Coatings            | $i_{corr}$ (A/cm²) | $E_{corr}$(mV) | Corrosion Rate(mm/yr) |
|---------------------|--------------------|----------------|-----------------------|
| Zn-SiC-CO4 (20 g/l of SiC) | 2.09 x 10⁻⁵      | -1100         | 3.0 x 10⁻¹            |
| Zn-SiC-CO3 (15 g/l of SiC) | 2.31 x 10⁻⁵      | -1117         | 3.47 x 10⁻¹           |
| Zn-SiC-CO2 (10 g/l of SiC) | 4.79 x 10⁻⁵      | -1140         | 4.18 x 10⁻¹           |
| Zn-SiC-CO1 (5 g/l of SiC)  | 2.91 x 10⁻⁵      | -1147         | 4.36 x 10⁻¹           |
| Zn (0 g/l of SiC)       | 4.0 x 10⁻⁵       | -1160         | 6.05 x 10⁻¹           |

It has been reported that the presence of SiC particles in zinc matrix could lead to formation of corrosion microcells in which SiC particles act as cathode and zinc matrix acts as anode. Because the standard potential of SiC more positive than zinc so that the formation of these microcells facilities anodic polarization, as result of this the localized corrosion was inhibited and homogenous corrosion could occur only [18].

4. Conclusion

Zn-SiC composite coatings were successfully deposited on steel surface using zinc sulfate bath and under direct current condition. SEM images of Zn-SiC composite coating prove the incorporation of SiC into zinc matrix. The surface morphology of Zn-SiC composite coating was smooth and the gaps in
the surface of the coating were filled with SiC particles. These conditions resulted in improvement of corrosion behavior of Zn-SiC composite coating where SiC particles act as inert barriers to the initiation of corrosion defects and modify the microstructure of Zn-SiC composite coating. Zn-SiC-CO4 with concentration of (20g/l SiC) was recorded the lowest corrosion rate and was positively shifted in potential. Microhardness of Zn-SiC composite coatings were increased compared to pure zinc coating. This was due to incorporation of SiC particles in coating structure and inhibiting dislocation propagation. All SiC concentrations used in this study show an improvement in the electrochemical and mechanical properties of Zn-SiC composite coating with the best results obtained at 20g/l of SiC.

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