Development of compositionally modulated multilayer Zn–Ni deposits as replacement for cadmium

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Abstract

Compositionally modulated multilayer (CMM) Zn–Ni deposits were electrodeposited from single acidic bath (pH=4.7) by using a potentiostatic sequence. The Zn and Ni composition in the alloy was tailored as a function of distance from the steel substrate. X-ray diffraction studies of the deposit showed the presence of γ-phase with a composition of Ni5Zn21. The corrosion properties of modulated multilayer coatings were studied in 5% NaCl solution using electrochemical corrosion techniques. The polarization resistance of the deposits varied as a function of Ni content between 1700 and 3440 Ω. CMM Zn–Ni with 20 wt% Ni exposed in ASTM B117 salt spray test did not show any red rust formation after 400 h.

Keywords: Compositionally modulated multilayer; Zn–Ni alloy; Cadmium replacement; Corrosion rate; Microhardness

1. Introduction

Cadmium has been used for years as a corrosion resistant coating in aerospace, electrical, and fastener industries owing to its excellent corrosion resistance and engineering properties [1]. Currently, efforts are being made to find a suitable alternative because of toxicity of the metal and its salts, risk of failure due to hydrogen embrittlement and to avoid cyanide baths for plating cadmium [2–5]. Hydrogen embrittlement in steel occurs due to the absorbed atomic hydrogen which is discharged as an unavoidable electrode reaction during electrodeposition. Zinc–nickel alloy coatings are being extensively studied as a replacement for cadmium coating due to their good corrosion protection property [6–8], superior formability, and improved welding characteristics [9–11]. Zn–Ni alloys containing 15–20 wt% nickel have been shown to possess four times more corrosion resistance than cadmium–titanium deposit [12]. However, Zn–Ni alloys have more negative potential than cadmium due to the high zinc content in the deposit and hence dissolve rapidly in corrosive environments. Although Ni is nobler than Zn, the co-deposition of Zn–Ni is anomalous and a higher percent of Zn is present in the final deposit [13,14].

Typical nickel composition in the alloy is approximately 5–10%, and further increase in nickel content has been achieved by using a higher Ni amount in the plating bath [15–17]. An enhancement in the nickel composition would lead to more positive open-circuit potential, which in turn will reduce the driving force for the galvanic corrosion. The barrier properties associated with nickel-rich deposits are also superior compared to other coatings [18–20]. Zn–Ni alloys prepared by the pulse process [21] and a multilayer approach [22] were also adopted in order to obtain high corrosion resistant alloys. Several attempts have been made to decrease the anomaly and increase the nickel content either by introducing inert species in the bath or by developing a ternary alloy [23–27]. Co-deposition of phosphorous along with Zn–Ni improves the corrosion [25] and hydrogen permeation [26] characteristics of the electrodeposits. Zhou and Keeffe [32] studied the effect of tin addition on the anomalous deposition of Zn–Ni alloy. The nickel ratio increased from 6 to 8% with the addition of small amounts of tin. However, the observed small increase of Ni content in the alloy did not improve the Zn–Ni barrier properties. Other alloys studied as corrosion protection coatings include Zn–Mn [28–30] and Zn–Sn [31,32].
The objective of the present investigation is to synthesize compositionally modulated Zn–Ni multilayer deposits with varying nickel concentration (from 15 to 30 wt.%) on carbon steel substrate. The goal is to deposit a zinc rich deposit close to the steel substrate and nickel rich deposit on the surface. Also, the goal of the present study is to evaluate the physical properties of the prepared coatings such as adhesion and microhardness and compare their corrosion properties in 5% NaCl solution with commercial Zn–Ni (13–15% Ni) and cadmium coatings.

2. Experimental

2.1. Electrolyte preparation and deposition

The deposition was performed using chloride electrolyte (pH=4.7) consisting of nickel chloride (NiCl₂.6H₂O), zinc chloride (ZnCl₂.7H₂O), ammonium chloride and boric acid. Plating and subsequent corrosion studies were done on low-carbon cold-rolled steel plates (Q-Panels, USA) of 0.8 mm thick and 4×2.5 cm² in area. Initially, the steel samples were mechanically polished with successively finer grades of emery paper. Next, they were degreased with soap water and rinsed with de-ionized water followed by treatment in 10% (v/v) sulphuric acid solution for 1 min to remove any adherent oxide layer present on the surface. Finally, the samples were washed in de-ionized water. This procedure was repeated until a clean and smooth surface was obtained. The plating was carried out initially at different potentials followed by a potential sequence shown in Fig. 1.

2.2. Material characterization and mechanical properties evaluation

Energy Dispersive Analysis using X-rays (EDAX) was used to analyze the distribution of the elements in the final deposit. To ensure accuracy of the element distributions, EDAX was done at several points on the surface of the substrate. The surface morphology and the microstructure of the coating were analyzed using Scanning Electron Microscopy by means of a Hitachi S-2500 Delta Scanning Electron microscope. Backscattering scanning electron microscope (BSEM) and electron microprobe analysis (EMPA, Cameca SX50) were used to determine the distribution of the elements across the thickness of the deposits.

The mechanical characterization studies such as adhesion and micro-hardness were performed according to ASTM B 571-97 and ASTM B 578-87 respectively. A Vickers hardness indenter (Buehler Micromet 1 Microhardness Tester) was used to indent the prepared Zn–Ni alloys with a diamond tip. Commercial Zn and Zn–Ni deposits were also subjected to hardness measurements for comparison. The physical deformation that occurs during the indentation process at an applied load of 100 g for 10–15 s was observed under a microscope and the dimensions of the depression were marked. Vickers hardness number (VHN) was calculated based on the observations made on the indent using the formula

\[
VHN = \frac{2P}{d^2 \sin \left(\frac{\alpha}{2}\right)}
\]

where, \(d\) is the diagonal length left by the diamond shaped pyramid indenter. The angle between the phases of the pyramid is \(\alpha = 136^\circ\). \(P\) is the load used in kilograms and the units of \(d\) are in millimeter.

2.3. Electrochemical characterization and ASTM B 117 Salt Spray Test

A variety of electrochemical techniques such as linear and Tafel polarization studies were used to evaluate the barrier resistance properties of the coating. The electrochemical characterization was performed using an EG&G PAR model 273 A potentiostat/galvanostat interfaced with a computer and a three-electrode setup in 5% NaCl solution. The steel substrate with the coating was used as the working electrode and a platinum mesh was used as the counter electrode. A saturated calomel electrode (SCE) was used as the reference electrode. All potentials mentioned in this study are referenced to the SCE.
ASTM B 117 salt spray test was performed on CMM Zn–Ni deposits together with commercial Cd plated sample using Atotech environmental test chamber model P22E001 to evaluate the first white and red rust formation time. Appearance of white rust indicates the dissolution of zinc from the coating and formation of corrosion products of Zn on the surface. Red rust indicates the complete dissolution and subsequent corrosion of underlying steel substrate.

3. Results and discussion

3.1. Effect of applied potential

Initially, Zn–Ni deposition was performed on steel substrates at different potentials for 30 min to identify the Zn and Ni composition at individual potentials. Significant amount of the deposit was obtained when deposition was done at potentials more negative than −1.15 V vs. SCE. The current efficiency was greater than 92% at more cathodic potentials. Variation of the Zn and Ni composition as a function of applied potential is shown in Fig. 2. Increase in applied cathodic potential leads to an increase in the concentration of the zinc in the deposit due to the anomalous behavior of Zn–Ni deposition. A similar trend was observed by Roventi et al. [33] and Elkhatabi et al. [34], who observed non-anomalous Zn–Ni deposition at low

![Fig. 3. Effect of end potential on the composition of CMM Zn–Ni deposits.](image)

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![Fig. 4. Scanning electron micrographs of CMM Zn–Ni deposits. (A) Sample A, (B) sample B, (C) sample C and (D) sample D.](image)

Fig. 4. Scanning electron micrographs of CMM Zn–Ni deposits. (A) Sample A, (B) sample B, (C) sample C and (D) sample D.
potentials \([-0.7 \text{ to } -0.9 \text{ V vs. Ag/AgCl}]\). The nickel rich non anomalous deposits obtained at low potentials were non-uniform and exhibit poor adhesion. With a decrease of applied potential (more positive), both the deposition current efficiency and the deposition rate decreased. These deposits were not feasible for corrosion protection of steel. With this preliminary knowledge on the Zn–Ni deposition process, compositionally modulated multilayer deposits were prepared by varying the applied potential.

### 3.2. Effect of potential sequence

The objective of the present study is to engineer compositionally modulated Zn–Ni alloys with varying nickel as a function of coating thickness. If the nickel content increases as a function of distance from the substrate, we expect a resulting zinc rich sacrificial layer close to the steel substrate and a nickel rich barrier layer at the surface of the deposit. Compositionally modulated Zn–Ni alloys were obtained by varying the potential sequence illustrated in Fig. 1 and the composition obtained using these potential sequences are shown in Fig. 3. As shown in the figure, Zn–Ni deposits with varying nickel content (from 34 to 15 wt.%) can be prepared by changing the potential sequence of the deposition process. The starting potential denotes the first step of the potentiostatic process (which starts in all cases at \(-1.3 \text{ V vs. SCE}\)). The end potential is the final step of the sequence. In the case of sample A, the starting potential is \(-1.3 \text{ V vs. SCE}\) followed by less cathodic potentials (\(-1.25, -1.20, \ldots, -0.90 \text{ V vs. SCE}\)). The composition values mentioned in the figure is the average composition of the deposits measured on the surface of the deposit by EDAX. Of several samples obtained with the varying potential sequence, four samples prepared with different nickel concentration (approximately 30, 25, 20 and 15 wt.% for samples A, B, C & D respectively) were chosen for further studies. The end potentials used for the above samples are \(-0.9, -1.0, -1.15 \text{ and } -1.3 \text{ vs. SCE}\) for samples A, B, C and D respectively. Zn–Ni deposits having nickel concentration more than 30 wt.% are not considered for further studies since it is beyond the scope of the present study. The thickness of all the samples was fixed at 12 μm.

Fig. 4 (A–D) shows the scanning electron micrographs of CMM Zn–Ni deposits A–D. The morphology of the electrodeposits varied from a plate-like shape to a fine granular shape depending upon the change in composition and structure of the electrodeposits. No cracks are seen on the surface in the case of both low and high nickel containing alloys. It can be seen that the particles are spherical at low end potential (\(-0.90 \text{ and } 1.0 \text{ V vs. SCE}\)) indicating the presence of more nickel in the alloy. In the case of Zn–Ni alloys deposited using high end potential (\(-1.15 \text{ and } -1.3 \text{ V vs. SCE}\)) the morphology is pyramidal which indicates the presence of higher amount of zinc in the deposit.

### 3.3. Effect of pH

The effect of pH on the composition of Zn–Ni deposits when using the potential sequence was studied using plating bath with 3 different pH values. No difference in the composition of Zn and Ni was noticed with the change in the pH of the electrolyte. The Zn and Ni composition of the CMM Zn–Ni deposits at three different pH values was identical to the ones shown in Fig. 3.
(pH=4.7) at all applied end potential. Fig. 5 (A–C) shows scanning electron micrographs of Zn–Ni deposits prepared with an end potential of $-1.25$ V vs. SCE at different pH. Small dendrite like particles are seen throughout the surface in the case of deposits prepared at pH 2.7 and 3.7 whereas, the deposit prepared at pH 4.7 showed uniform pyramidal morphology. Experiments at pH 5.7 were not carried out due to the precipitation of metal salts as hydroxides in the electroplating bath.

3.4. X-ray diffraction studies

Fig. 6 shows the X-ray diffraction patterns of samples A–D prepared by using different potential sequences. Three strong peaks and few weak peaks are present in the case of samples A–C and one strong peak is noticed in the case of sample D. The strong peaks which correspond to γ phase Zn–Ni alloy show an increase in the intensity with the increase in the end potential. The peak intensity is minimum in the case of sample A (end potential $=-0.85$ V vs. SCE) and maximum in the case of sample D ($-1.3$ V vs. SCE). This peak which is assigned to the crystal plane (600) can be attributed to the formation of γ phase Ni$_5$Zn$_{21}$ [35–38]. The intermediate phase or the γ phase which has a Zn–Ni ratio of 4:1, exhibits a body-centered cubic structure. It has been reported that the structure change of the electrodeposits is closely related to the Ni content. Mixed phase of η and γ was found below 10 wt% of Ni while only the γ-phase was observed above 10 wt% of Ni [39]. In our study, all the samples contain more than 10 wt.% Ni in the deposit, hence, only γ phase is predominantly observed. The diffractograms show the presence of an intermediate γ-phase (Ni$_5$Zn$_{21}$) with the high intensity peak at $2\theta=62.5^\circ$ which corresponds to the (600) plane [40]. The intensity of the (600) peak decreases with the change in deposition sequence reveals that this plane is mainly situated near the surface and is preferentially masked by the other γ-phase planes (222) and (444) when the end potential is changed to more positive values. It can be safely concluded that, at higher overpotentials γ-phase corresponding to (600) planes are preferentially deposited while lower overpotential leads to the deposition of other crystal planes of γ-phases namely (222), (330) and (444).

3.5. Cross-sectional analysis

Cross sectional BSEM and EDAX analysis were employed to obtain the variation of deposit composition as a function of the distance from the substrate. Fig. 7A and B show the BSEM image and EMPA cross-section line scan of the samples A and D respectively. The compositional values measured as a function of distance from the substrate for Sample A is plotted in Fig. 8. The line scan and elemental distribution across the substrate is uniform for sample D. This behavior is expected since the applied potential is constant for preparing this sample ($-1.3$ V vs. SCE) and is the conventional Zn–Ni alloy with 15 wt.% Ni and 85 wt.% Zn. On the other hand, for sample A prepared by the potentiostatic sequence, the composition is found to vary as a function of distance from the substrate. The composition of the alloy is uniform and appears similar to the conventional Zn–Ni alloy with 15 wt.% Ni for a thickness of 6 μm from the substrate. The deposit in this region is obtained from deposition at high cathodic potential of $-1.3$ and $-1.25$ V vs. SCE. With further increase in distance from the substrate, the nickel composition increases due to a decrease of the cathodic applied potential. Nickel content as high as 34 wt% is obtained at the surface of the deposit when an end potential of $-0.85$ V vs. SCE was applied for the deposition.

Fig. 6. X-ray diffraction patterns of CMM Zn–Ni deposits.
3.6. Mechanical properties

Table 1 lists the composition of different CMM Zn–Ni deposits and their mechanical properties such as adhesion and microhardness. Commercial Zn–Ni deposit was also tested for comparison. The qualitative test for adhesion showed no peeling and/or flaking in the case of commercial Zn–Ni and compositionally modulated multilayer Zn–Ni alloys at 4× magnification when the plated specimens were bent 180°. In the case of samples A and B, the coating was separated after the test indicating its unsatisfactory adhesion with the steel substrate. This can be attributed to the stress imposed by higher amount of nickel since the deposits having up to 20% Ni are ductile and those having above this limit are somewhat brittle [17]. The table also shows the results obtained from Vicker’s Hardness Test. The hardness number is indicated as VHN$_{100gf}$. The hardness values for pure Zn and Zn–Ni (with 8–10% Ni) are VHN$_{100gf}$=95.53 and 130.52 respectively. The CMM Zn–Ni deposits showed hardness values of VHN$_{100gf}$=184.86, 170.44, 163.99, and 134.31 for alloys containing 30, 25, 20 and 15 wt.% Ni respectively. The hardness value decreased with the decrease in nickel content in the deposit.

3.7. Electrochemical characterization

Corrosion characteristics of compositionally modulated Zn–Ni deposits [A, B and C] were evaluated using Tafel

<table>
<thead>
<tr>
<th>Sample</th>
<th>Zn (wt.%)</th>
<th>Ni (wt.%)</th>
<th>Adhesion</th>
<th>Microhardness (VHN$_{100gf}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>70</td>
<td>30</td>
<td>Moderate</td>
<td>184.86</td>
</tr>
<tr>
<td>B</td>
<td>75</td>
<td>25</td>
<td>Moderate</td>
<td>170.44</td>
</tr>
<tr>
<td>C</td>
<td>80</td>
<td>20</td>
<td>Good</td>
<td>163.99</td>
</tr>
<tr>
<td>D</td>
<td>85</td>
<td>15</td>
<td>Good</td>
<td>134.31</td>
</tr>
</tbody>
</table>

Fig. 7. Back-scattered electron micrographs of CMM Zn–Ni deposits (A) sample A and (B) sample D.

Fig. 8. Back-scattered electron micrographs of CMM Zn–Ni deposits (A) sample A and (B) sample D.

Fig. 8. Composition through cross-section of CMM Zn–Ni deposits (sample A).
polarization techniques and Electrochemical Impedance Spectroscopy studies. Sample D represents conventional Zn–Ni alloy deposited at a constant potential (−1.3 V vs. SCE).

3.7.1. Linear and Tafel polarization studies

The Tafel polarization study was performed to evaluate the kinetic parameters of the corrosion processes. Tafel plots were obtained by varying the potential of Zn–Ni deposits by ±200 mV from the open circuit potential at a scan rate of 10 mV/s and the resulting Tafel plots are shown in Fig. 9. The electrochemical characteristics such as, polarization resistance ($R_p$), corrosion current ($I_{corr}$), corrosion rate (in mpy) and corrosion potential ($E_{corr}$) obtained are summarized in Table 2. The polarization resistance of the coatings increased with the increase in the nickel content in the CMM Zn–Ni deposits since nickel offers barrier protection to the coating. The CMM Zn–Ni with 30 wt.% nickel showed the highest $R_p$ value of 3440 Ω and the conventional Zn–Ni deposit with 15 wt.% Ni showed polarization resistance value of only 1700 Ω.

The corrosion current is much smaller ($I_{corr}=2.4 \times 10^{-6}$ mA/cm$^2$) for sample A with Zn/Ni alloy composition 70/30 with an $E_{corr}$ value of −0.783 V vs. SCE. Other CMM deposits with the nickel content of 25, 20 wt.% showed corrosion current value of $3.4 \times 10^{-6}$ and $9.39 \times 10^{-6}$ mA/cm$^2$ respectively. The Zn–Ni alloy deposited at −1.3 V vs. SCE (15% Ni) showed highest corrosion current of 0.00014 mA/cm$^2$ with a corrosion potential of −1.076 V vs. SCE. With increase in zinc content in the deposits, the corrosion potential of the system becomes more electronegative which increases the driving force for corrosion resulting in higher corrosion currents.

The corrosion rate calculated using the corrosion current for the prepared Zn–Ni deposits are 1.28, 1.85, 5.21 and 78.98 mpy for samples A, B, C and D respectively as indicated in Table 2. The corrosion rate and the corrosion rate are higher for the sample C (20% Ni) when compared to samples A and B. This is to be expected since the later samples have high nickel content. The corrosion potential and corrosion rate for pure nickel are −0.358 V vs. SCE and 0.858 mpy respectively [41,42]. Although high nickel containing Zn–Ni deposits show better corrosion characteristics in electrochemical measurements, it has a deleterious effect in real life applications.

3.7.2. Open circuit potential measurement

The variation of open circuit potential with time in 5% NaCl solution was measured to obtain and insight in to the corrosion protection behavior offered by the compositionally modulated alloys. The open circuit potential behavior of the conventional Zn–Ni and two selected compositionally modulated Zn–Ni multilayer (samples B and C) is shown in Fig. 10. It can be seen that, there is not much fluctuation in the initial OCP behavior with time indicating the high protective action by the coatings [44]. It has been reported in the literature that aluminum alloy with chromate conversion coating showed OCP fluctuation which has been attributed to the pit formation and repassivation [45]. In our study, no chromate conversion coatings were used hence the fluctuations can be attributed to the galvanic corrosion of Zn in the Zn–Ni bulk.

Sample D, owing to its high zinc content (85 wt.%) exhibits more electronegative potential of −1.05 V vs. SCE. The potential gradually tends to become more positive with the dissolution of zinc and reaches the potential close to that of steel after 30 days. The dissolution of sample B illustrates corrosion behavior of compositionally modulated Zn–Ni alloys. The initial OCP value of −0.74 V vs. SCE progressively changed to more negative potential (−0.77 V vs. SCE) due to the exposure of zinc rich phase to the test solution and remained at the same potential for the entire testing period. The important observation is that, sample D reached the potential close to that of steel indicating rapid dissolution of Zn from the deposit. On the other hand, sample B and C did not show any significant change in

<table>
<thead>
<tr>
<th>Sample</th>
<th>Polarization resistance ($R_p$)</th>
<th>$I_{corr}$ (A/cm$^2$)</th>
<th>$E_{corr}$ (V vs. SCE)</th>
<th>Corrosion rate (mpy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>3440</td>
<td>$2.4 \times 10^{-6}$</td>
<td>−0.783</td>
<td>1.28</td>
</tr>
<tr>
<td>B</td>
<td>2825</td>
<td>$3.4 \times 10^{-6}$</td>
<td>−0.857</td>
<td>1.85</td>
</tr>
<tr>
<td>C</td>
<td>2262</td>
<td>$9.39 \times 10^{-6}$</td>
<td>−0.908</td>
<td>5.21</td>
</tr>
<tr>
<td>D</td>
<td>1694</td>
<td>0.00014</td>
<td>−1.076</td>
<td>78.98</td>
</tr>
</tbody>
</table>

Fig. 9. Tafel polarization curves of different CMM Zn–Ni deposits.

Fig. 10. Open circuit vs. time plots for different CMM Zn–Ni deposits.
the potential values and remained constant for the entire study period of 35 days.

Both conventional Zn–Ni deposit with uniform 15 wt.% Ni and compositionally modulated Zn–Ni with high nickel concentration close to 30 wt.% did not offer corrosion protection for longer duration in the immersion test. This disagrees with the corrosion resistance and corrosion current values obtained through Linear and Tafel polarization plots obtained for samples A and B. Sample A showed high corrosion resistance in the Linear and Tafel polarization studies owing to the increased barrier resistance offered by high amounts of nickel present in the deposits. However, with duration, the nickel rich Zn–Ni alloy corrodes at a faster rate due to the formation of galvanic cells between nickel and zinc [15]. Therefore, compositionally modulated Zn–Ni alloys with nickel concentration in the range of 20 wt.% can provide corrosion protection for longer duration.

3.8. ASTM B 117 salt spray testing

Salt spray testing was performed in salt spray test chamber to evaluate the coating performance under accelerated corroding conditions. The temperature in the chamber was set at 35 °C with a tower temperature of 49 °C. The samples were exposed to a constant 5% salt fog in accordance with the ASTM B 117 specifications. The appearance of white rust, red rust and the failure of the samples were observed as a function of time. Five percent of red rust on the surface of the samples was defined as the basis for failure criterion. The deposit thickness in all the cases was ~12 μm. No post treatment or passivation was provided on the surface of the coatings. Compositionally modulated Zn–Ni multilayer samples A–D were tested under these conditions and the results are summarized in Table 3. Visual observations such as white/red rust spot formation were made after taking out the panels at regular intervals (usually every 24 h). Prior to visual observation, the test panels were washed with cold water and dried under flowing air. First white rust formation was noticed after 144 h for all the Zn–Ni deposits. The first red rust spots were noticed after 300 and 350 h for samples A and B respectively whereas sample D showed red rust after 396 h. Sample C with nickel content of 20 wt.% did not show any sign of red rust for over 396 h (Sample D) of testing and signs of red rust were noticed after 484 h. The red rust formation time for CMM Zn–Ni coatings are better than the values obtained in the literature for Cd and Zn–Ni coatings without any passivation [17]. The commercial Cd coating (12 μm) without any passivation tested in our laboratory showed red rust after 144 h testing in salt chamber. The high stability of the CMM Zn–Ni can be explained as follows. It has been reported in the literature [43] that the enthalpy of γ phase Zn–Ni deposits is lower and hence has the highest thermodynamic stability when compared to other phases such as α and η phases. Also, the ability of γ phase towards passivation is very high. These qualities make the CMM Zn–Ni deposits to have better corrosion protection property since all the prepared deposits showed the presence of only γ phase. The ASTM B 117 results confirm the stability of compositionally modulated Zn–Ni multilayer deposit with 20% Ni and can be considered as an alternate to the existing Cd and conventional Zn–Ni alloy with 8–15 wt.% Ni.

4. Conclusion

Compositionally modulated Zn–Ni alloy were deposited from acidic bath on carbon steel substrates. The nickel content was varied as a function of thickness by applying a varying potential sequence. With the use of a decreasing potential sequence, a uniform deposit with nickel content as high as 34 wt% was obtained at room temperature. The CMM Zn–Ni with 20% Ni showed good adhesion and hardness to withstand the corroding environment. Scanning electron microscopy studies revealed that the prepared CMM Zn–Ni coatings with high nickel showed spherical particles and that of high zinc showed pyramidal structure when examined under the microscope. Electrochemical characterization such as Linear and Tafel polarization studies showed increase in corrosion resistance with an increase in nickel content. The CMM Zn–Ni with 20% Ni showed red rust after 484 h where as the commercial Cd showed red rust after 144 h of testing in salt spray chamber. Open circuit potential measurement and ASTM B 117 studies suggests that the compositionally modulated Zn–Ni multilayer with 20 wt.% Ni can be considered as an alternate to the conventional Zn–Ni with 8–15 wt.% Ni and commercial cadmium coatings.

Acknowledgments

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