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Electrodeposition of Zinc-Nickel Alloy Coatings: Effect of Deposition Parameters on its Surface Morphology

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Abstract

Zinc-Nickel alloys are widely utilized as sacrificial coatings for the protection of steel against corrosion. In this study, Zinc-Nickel electrodeposits has been produced from a chloride bath using direct current. Deposit thickness and current efficiency were determined by weight measurement method. Influence of current density on the deposition process was also investigated. Scanning Electron Microscope and Field Emission Gun Scanning Electron Microscopes were utilised to study the morphological transformations of the deposits. Changes in morphology due to temperature and nickel content of the deposit were also investigated. The elemental composition of the coatings was determined using Energy dispersive spectroscopy (EDX). Temperature of the bath and nickel content in the deposit had marked influence on the morphology of the deposits. It was observed that the bath exhibited anomalous deposition behaviour.

Keywords: Zn-Ni alloy, Morphology transformation, Current density, Electrodeposition, Parameter effect

1. Introduction

Most marine and offshore structures that are produced from steel can be prevented from degrading by creating a barrier between the structural and corrosive environments by applying metal electroplated coatings. Zinc and its alloys have been utilised for many decades as protective and decorative coatings. They are preferred over a number of metal substrates, the most common which is steel. Zn coatings act as a barrier on the steel surface, thus protecting steel parts against corrosion and also galvanically protecting their substrates (Anwar et al., 2019; Tafreshi et al., 2016; Del Angel et al., 2015; Clifford Biddulph, 2012; Panagopoulos et al., 2011). The use of Zn coatings has attracted a lot of attention because of its non-toxic nature, which has replaced cadmium coatings which are carcinogenic and toxic nature (Anwar et al., 2019; Benachour et al., 2022; Farooq et al., 2022). Despite their advantages, Zn coatings corroded rapidly due to their higher electrode potential than steel. By alloying Zn with Ni, Fe, Co, or Sn, the dissolution rate and corrosion potential difference between Zn and steel can be reduced while the coating's sacrificial characteristics are maintained (Tafreshi et al., 2016; Abou-Krishna, 2011; Dubent et al., 2010).



Several procedures for applying zinc coatings have been devised, depending on the substrate, coating requirements, and cost. Electrodeposited alloy films can provide desirable surface features when compared with single-metal films, but alloy deposits can be difficult to apply because of the need to control uniformity of composition, thickness, and microstructure (Lotfi et al., 2018). It is well known that zinc alloys such as Zn-Ni, Zn-Co, and Zn-Fe can provide protection for steel against corrosion (Eliaz et al., 2010; Tuaweri, 2013). However, much attention has been given to the Zn-Ni alloy coating compared to other Zn-based alloy coatings because of its high corrosion resistance, excellent ductility flexibility, and relatively lower hydrogen embrittlement. It has been stated in most reports that the maximum protective ability of Zn-Ni is reached with a nickel content between 10 and 15% (Farooq et al., 2022; Chouia et al., 2021). Studies have proven that higher amount of Ni content improves the barrier characteristics of the Zn-Ni coating, while a low Ni concentration could induce a deleterious effect on the dissolution rate (Farooq et al., 2022; Eliaz et al., 2010; Conde et al., 2011). Particularly, Zn-Ni alloy coatings are considered to be a less harmful substitute for cadmium (Anwar et al., 2019). The electrodeposition of the Zn-Ni alloy provides significantly better corrosion resistance to coated steel structures in an aggressive environment. Fe is cathodically protected by Zn-Ni alloy coatings containing up to 12% Ni (Benachour et al., 2022; Bielawski, 2010). The deposition parameters, alloy chemical composition, and coating structure all have a significant role in how well Zn-Ni alloy coatings resist corrosion. The quality of the coating is significantly influenced by the deposition parameters such as the electrolyte composition, current density, temperature, and pH (Bielawski, 2010; Rashmi et al., 2020)

As opined by (Tuaweri, 2013), zinc-nickel alloys can be obtained using plating baths of different compositions and operating conditions, e.g., chloride, sulphate, ammonia, sulphate-sulfamate, sulphate-chloride, pyrophosphate, and cyanide. Usually, Zn-Ni deposits obtained from cyanide solutions have a lower nickel content than their counterparts from cyanide-free systems, and the undesirable characteristics of cyanide may therefore be eliminated when considering coating for maximum corrosion resistance. Most studies regarding the deposition of zinc and nickel have been made with acid baths containing simple salts of the metals. However, many commercial baths contain ammonium chloride, which causes effluent treatment problems and is also undesirable because of the negative environmental impact of ammonia (Tafreshi et al., 2016; Bhat et al., 2021). Since the range of nickel concentrations for maximum corrosion resistance is relatively narrow, it is crucial that small changes in operating conditions do not lead to substantial changes in nickel concentration from the optimum. In other words, any plating parameter through a mechanism might make it easier for the pH of



the zinc-nickel electrolyte to rise, which would encourage zinc deposition (Bhat et al., 2021).

In contrast to the HSM theory, Selverston et al (2017) proposed in their experiment that the pH value of zinc-nickel alloy electrolytes rises as a result of a reduction in zinc concentration in coatings.

Different methods are employed in producing coatings, but because of low cost usage in production, the ability to work at low temperatures with limited induced energy, and the ease of treatment for large and complex geometry, electrodeposition remains a prominent technique to produce highly improved nanoparticulate coatings (Fouladvani et al., 2023; Jabbar et al., 2017; Fayomi et al., 2017). Limitations have resulted from the electrodeposition of metals and alloys in aqueous electrolytes due to the narrow electrochemical window, hydrogen evolution, and inferior film produced from the route. In order to overcome these challenges, the use of ionic liquids has attracted significant attention as an alternative to electrodeposition because of their large potential window, acceptable ionic conductivity, high concentration of ionic species, high thermal stability, negligible vapour pressure, and high deposition speed (Fashu et al., 2015; Whitehead et al., 2010; Haerens et al., 2009). Alloy deposition, where it is valuable to reduce the difference in deposition potentials between two metals, the complexing capacity of ionic liquids with strongly coordinating anions is likeable. The electrodeposition of Zn-Ni alloy is often an anomalous co-deposition in which the less noble metal zinc deposits preferentially and its proportion in the deposit is greater than that in the electrolyte. Many attempts have been made to explain the anomalous co-deposition of alloys, but there is still no universally accepted theory. An outcome positing an anomalous deposition to a limited rise in the pH of the cathode has been revealed by a few studies Bhat et al., 2021; Lin et al., 2012; Walsh et al., 2020). Jabbar et al. (2017) evaluated the deposition temperature effect on the morphology of nickel graphene and revealed that temperature has a great impact on the electrodeposition characteristics. Their results showed that at 45 °C, Ni-graphene composite coatings exhibited refined grain size, coarse surface morphology, high microhardness, and excellent corrosion resistance. Addition of graphene to coatings results in enhanced microhardness and tribological properties, as reported by Algul et al. (2015). An investigation by Bajat et al. (2009) which examined the influence of deposition current density, temperature, and composition of the deposition solution on the morphology of Zn-Co alloy coatings concluded that the ratio of Co to Zn ions in the plating bath strongly affects the phase structure and corrosion stability of Zn-Co alloy. The plating baths with the lowest and highest ratios of cobalt and zinc ions exhibited the lowest corrosion rate. Byk et al. (2008) examined the effects of electrodeposition parameters on the microstructure of Zn-Ni films and found that electrodeposition conditions had a great influence

on the coating Ni content and corrosion resistance. Gharahcheshmeh & Sohi, (2009) explored the corrosion performance of Zn and Zn-Co coatings acquired from an alkaline bath through direct current application. The study revealed that the corrosion resistance of these deposits is significantly affected by the composition and structure of the coatings. Among these, Zn-Co coatings containing 0.89 wt.% Co demonstrated superior corrosion resistance attributed to their single-phase structure and finer morphology. Different bath compositions containing cyanide, sulphate, chloride, and pyrophosphate have been used for Zn-Ni alloy cobalt deposition, and it was found that different phases are formed during Zn-Ni co-deposition, which highly depend on the nickel contents in the coating. The ability to control the effective deposition of Zn-Ni alloy is largely a function of several parameters, such as current density, pH, organic additives, buffer capacity, and concentration of solution components. Skilful manipulation of each of these variables could lead to changes in the kinetics of electrodeposition, composition, and morphology of the coatings, as well as in their physico-mechanical characteristics (Tuaweri, 2013; Rashmi et al., 2020; Walsh et al., 2020). This study, therefore, seeks to investigate the influence of some of these variables on a specific bath composition to establish conditions that could determine the range of nickel percentage composition and morphology for improved corrosion resistance. The ultimate aim of studying the electrodeposition behaviour of the zinc-nickel system was to produce coatings with the desired concentration of nickel being 10 to 15 wt% for optimum corrosion resistance, morphology, and microstructure and hence phase distribution of the electrodeposit. The need therefore, to optimise the concentrations of the different metal ions in the plating solution to obtain the said range and other characteristics as mentioned above was crucial. However, in this work, only the effect of $\text{NiCl}_2 \cdot 6\text{H}_2\text{O}$ in 5 g/l increments was considered. An acid chloride bath was used to investigate the effect of nickel ion concentration in the bath and its concentration in the electrodeposit.

2. Materials and Method

2.1 Raw materials

Rectangular mild steel panels measuring 60mm x 20mm x 1mm and with a chemical composition as specified in Table 1 were used as the substrates. The mild steel panels functioned as the cathode, while a 99.9% pure zinc sheet measuring 30mm x 20mm x 1mm was employed as the anode. Additionally, nickel foil anode with a thickness of 0.6mm was utilized in the Zn-Ni electroplating process. Prior to the electroplating process, the surfaces of the mild steel panels underwent polishing using various grades of emery paper, ranging from 600 to 2000 grits. This was carried out to achieve a mirror-like surface free from any scale

defects. Subsequently, the panels were thoroughly cleaned with distilled water and methanol. The specific details of the experimental process was as described in (Tuaweri, 2013; Qiao et al., 2013).

Table 1: Elemental composition of mild steel

Element	C	Si	Mn	Cr	P	Al	S	Fe
Wt%	0.19	0.22	0.43	0.007	0.002	0.005	0.015	Bal

2.2 Preparation of bath (electrolyte solution)

Electrolyte solutions were precisely prepared using deionized water and laboratory-grade reagents, including zinc chloride, nickel chloride, and ammonium chloride. The bath formulations comprised 62.5 g/l of $ZnCl_2$, 60.7 g/l of $NiCl_2 \cdot 6H_2O$, and 200 g/l of NH_4Cl , with a pH level of 3.5. These formulations were crucial in assessing several key characteristics, such as throwing power and current efficiency, for each electrolyte. This evaluation aimed to determine the most suitable electrolyte for the intended purpose.

2.3 Calculation of cathode current efficiency

Pre-weighed samples were rinsed with deionised water after plating and dried in a hot stream of air. The dried samples were weighed again to obtain the weight gain. The cathode current efficiency was determined using the following expression:

$$CCE = \frac{\Delta W (wt\%_{Ni} / M_{Ni} + wt\%_{Zn} / M_{Zn}) \times 2F}{jAt} \times 100\% \quad (1)$$

Where:

CCE = cathode current efficiency, (%)

ΔW = change in weight after plating, (g)

$wt\%_{Ni}$, $wt\%_{Zn}$ weight percentages of nickel and zinc in the deposit

$wt\%_{Ni} + wt\%_{Zn} = 100\%$

M_{Ni} , M_{Zn} atomic weight of nickel and zinc (g/mol)

F = Faraday constant (96500 C/mol)

j = applied current density (A/dm²)

A = effective cathode surface area (dm²)

t = plating duration (second)

2.4 Electrodeposition and characterization process

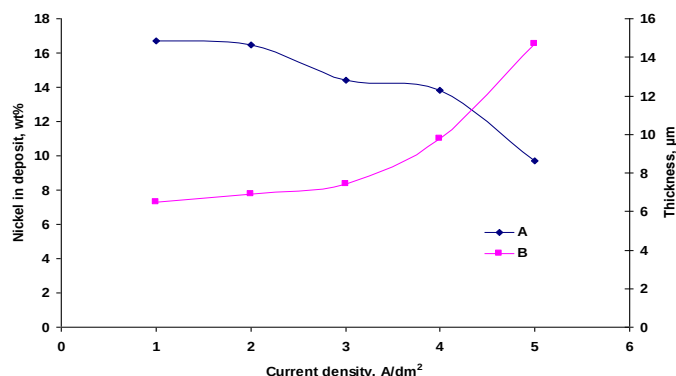
Electroplated coatings were applied to mild steel panels. In order to improve deposition efficiency, the panels were first washed in an alkaline bath containing 25.0 g/l NaOH, 25.0 g/l Na_2CO_3 , and 50.0 g/l Na_3PO_4 . They were then etched in 50 vol.% (S.G 1.18) hydrochloric acid for roughly 20 seconds before being rinsed in flowing tap water and deionised water. They were immediately placed into the electroplating bath in order to prevent reoxidation of the surface. All of the electrodeposition tests were carried out with DC currents galvanostatically. Zinc foil made up the anode material in every instance. The compositions and morphologies of coatings were examined using scanning electron microscopes (SEM) and SEMs equipped with energy dispersive analysis (EDX).

3. Results and Discussion

The investigation involved the selection of a chloride bath. This bath was extensively employed to study the effects of different parameters, such as current density, temperature, agitation, pH, and metal ion concentration, on the morphological characteristics of the electrodeposits.

3.1 Effect of current density

Figure 1 shows the relationship between current density, deposit thickness and weight percentage of nickel in the deposit. The depoiste thickness emanated from from a sulphate bath containing 264.5 g/l $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$, 350 g/l $\text{NiSO}_4 \cdot 6\text{H}_2\text{O}$ and pH 3.5-4, $T = 25^\circ\text{C}$. It was revealed that the film appearance and deposit degradation rate are significantly influenced by current density. From the analysis, it was an evident that the nickel content of the deposit decreases with increasing current density as higher percentages of nickel were observed at lower current densities. The observation that nickel content decreases with increase in current density is in close agreement with the works of other investigators (Farooq et al., 2022; Bhat et al., 2021). A reduction in nickel content with increasing current density reflects the faster kinetics of zinc deposition at greater electrode polarizations. This is an indication that at lower values of current density there is transition from anomalous to normal codeposition. When the current density is increased, the transition from normal to anomalous deposition occurs with the amount of the noble metal in the deposit falling below the concentration of the metal in the bath. This transition is said to result from the formation of a critical concentration of zinc hydroxide at the cathode surface (Niu et al., 2015). At higher current densities, there is yet another transition, where the normal takes over from the anomalous type.



Figurer 1: The composition of nickel deposition and deposit thickness at different current density.

3.2 Bath temperature and Concentration effect

Figure 2 shows the influence of temperature on the weight percentage of nickel in the electrodeposit. These investigations were carried out using a chloride-based acid solution containing 62.5 g/l ZnCl_2 , 60.7 g/l $\text{NiCl}_2 \cdot 6\text{H}_2\text{O}$, 200 g/l and pH 3.5. For the given deposition conditions, it can be seen that as the temperature increased from 25 to 40 °C, the nickel content of the deposit increased from 8.4 to 13.4 wt%. This indicates that temperature increase favours nickel deposition. Such behaviour was attributed to the decrease in cathode polarisation and enhanced temperature-dependent kinetics parameters and specifically related to nickel deposition, such behaviour is primarily the result of the intrinsically slow nickel kinetics (Eliaz et al., 2010). An acceptable nickel content for corrosion resistance (10-15 wt.%) as reported by Chouia et al. (2021) was obtained in a temperature range of 25 to 40 °C. The results presented here are in close agreement with earlier investigations (Farooq et al., 2022) on a chloride bath. All the data presented in Fig 2 were produced at a current density of 3 A/dm², which falls within the optimum range of current densities of 2 to 4 A/dm² to produce deposits containing 12 to 13 wt.% nickel for a nickel bath composition with 5 to 10 g/l nickel (Farooq et al., 2022). Figure 3 shows that current efficiency was generally stable at around 70% over a wide range of deposition time (current density 0.3 A/dm², pH 3.8, T 32°C). This is an indication that deposition time does not have any significant influence on the deposition behaviour of zinc-

nickel for the conditions of deposition investigated here and might not be an appropriate parameter to be considered while studying the properties of a zinc-nickel electrolytic bath.

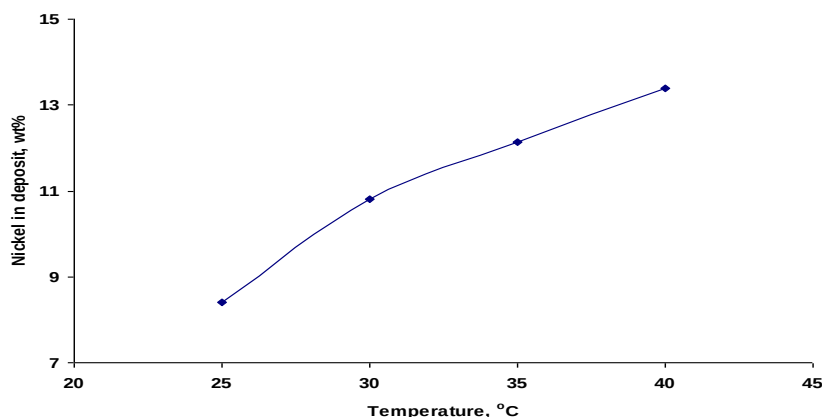


Figure 2: Variation of nickel content with deposition temperature

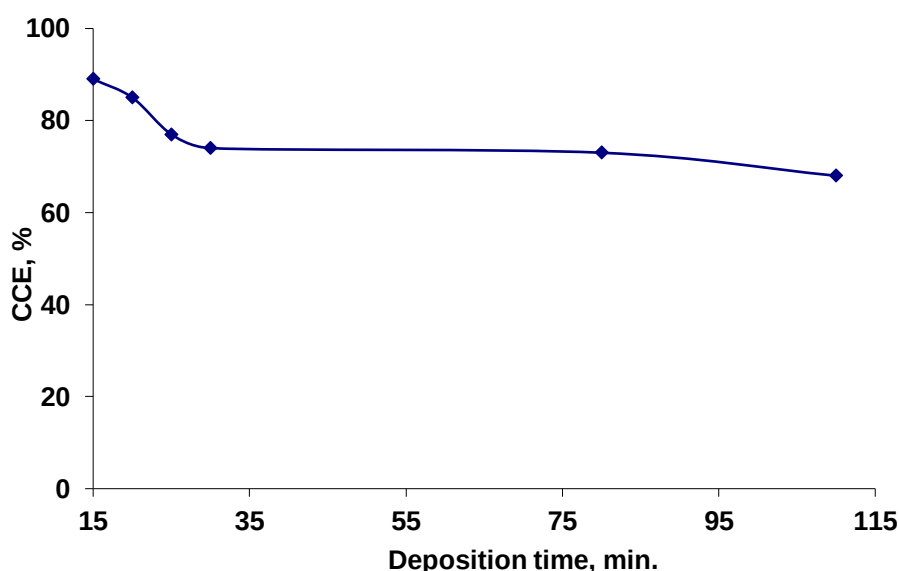


Figure 3: Deposition time on cathode current time efficiency of Zn-Ni electrodeposition

$\text{NiCl}_2 \cdot 6\text{H}_2\text{O}$ concentration in the range of 65.7 to 80.7 g/l was considered to study the effect of nickel ion concentration in the bath on nickel content in the deposit as shown in Figure 4. It is obvious from Figure 4 that changes in the nickel content of the deposit took a minimal increasing trend from about 10.4 wt% to about 13.3 wt% as the bath concentration of $\text{NiCl}_2 \cdot 6\text{H}_2\text{O}$ was increased from 60.7g/l to 75.7g/l consequently maintaining an acceptable range of 10.4 to 13.3 wt% nickel in the deposit for optimum corrosion resistance. However, beyond 75.7g/l increase in the nickel content of the deposit shows a sharp gradient. This is an

indication that for the bath in question, up to a bath concentration of 75.7g/l $\text{NiCl}_2 \cdot 6\text{H}_2\text{O}$, the deposition showed an anomalous behaviour. Beyond this concentration, normal deposition begins to take place where the more noble nickel is deposited in preference to the less noble zinc. The overall trend is consistent with previous works (Conde et al., 2011) in that increasing the Ni^{2+} ion in the bath results in an increase in the nickel content of the deposit and supports the theory that the reduction of nickel ions is controlled by diffusion (Conde et al., 2011).

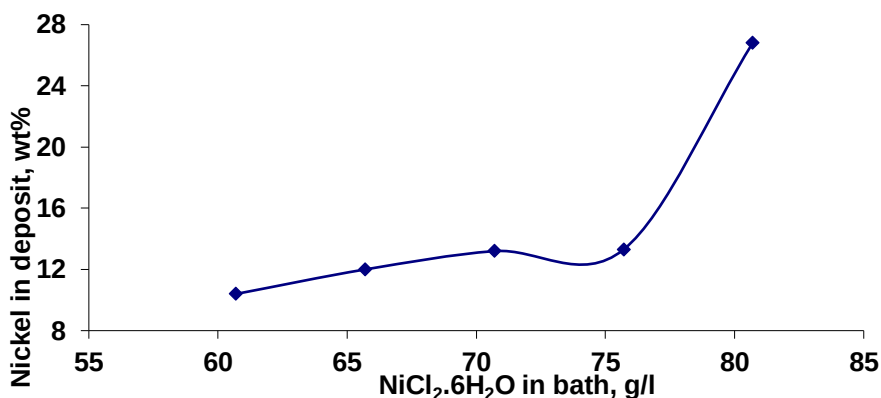


Figure 4: Effect of $\text{NiCl}_2 \cdot 6\text{H}_2\text{O}$ concentration in the bath on percentage of nickel in the electrodeposit.

3.3 Morphology of Deposits

The morphology of Zn-Ni alloy electrodeposits was investigated. It was evident that variables such as current density, temperature and metal ion concentration of the bath had a marked effect on the morphology of the electrodeposits. Changes in morphology of zinc-nickel electrodeposits with nickel content in the deposit have been reported (Del Angel et al., 2015). Since each of these parameters either increases or decreases the nickel content of the electrodeposit, morphological changes, which are largely a function of the elemental composition of the electrodeposits, are inevitable.

3.4 Uneven current distribution

It is perceived that uneven current distribution at the cathode produces dissimilar surface morphologies. This observation was made for coatings from the bath containing 62.5 g/l ZnCl_2 , 60.7 g/l $\text{NiCl}_2 \cdot 6\text{H}_2\text{O}$, 200 g/l NH_4Cl produced at a Current density of 3 A/dm², pH of 4.5, and $T = 30^\circ\text{C}$. In an attempt to verify this, investigation on the percentage of nickel on both the edges and centres of a number of samples were carried out and the results are presented in Table 2. It is evident that in almost all the investigations, the percentage of nickel at the centres was higher than at the edges where the current is thought to be higher. These observations seem

to compliment previous observations in Figure 1 where the percentage of nickel in the deposit decreases with higher current densities. The influence of this uneven current distribution and hence the percentage of the codepositing elements on the surface of the cathode with more nickel at the centre than at the edges of the cathode is further illustrated in Figure 5 (a and c) with their corresponding 3D surface images Figure 5 (b and c). As can be seen in Figure 5a, the morphology has hexagonal-based pyramidal crystals with each hexagonal crystal separated from its adjacent neighbour by intergranular cracks. Such distinct pyramidal crystals are not prominent at the centre of the deposit (as shown in Figure 5c), as they tend to form clusters of irregularly shaped crystals with obvious intergranular cracked boundaries possibly due to stress in the process of nucleation and crystal growth typical of zinc-nickel electrodeposits. The 3D surface image was performed to ascertain the topographical characteristics of Zn-Ni coating according to their uneven distribution. The colour intensity on the 3D surface plot gives a graphic vision and description of the observed surface morphology of the Zn-Ni coating alloy.

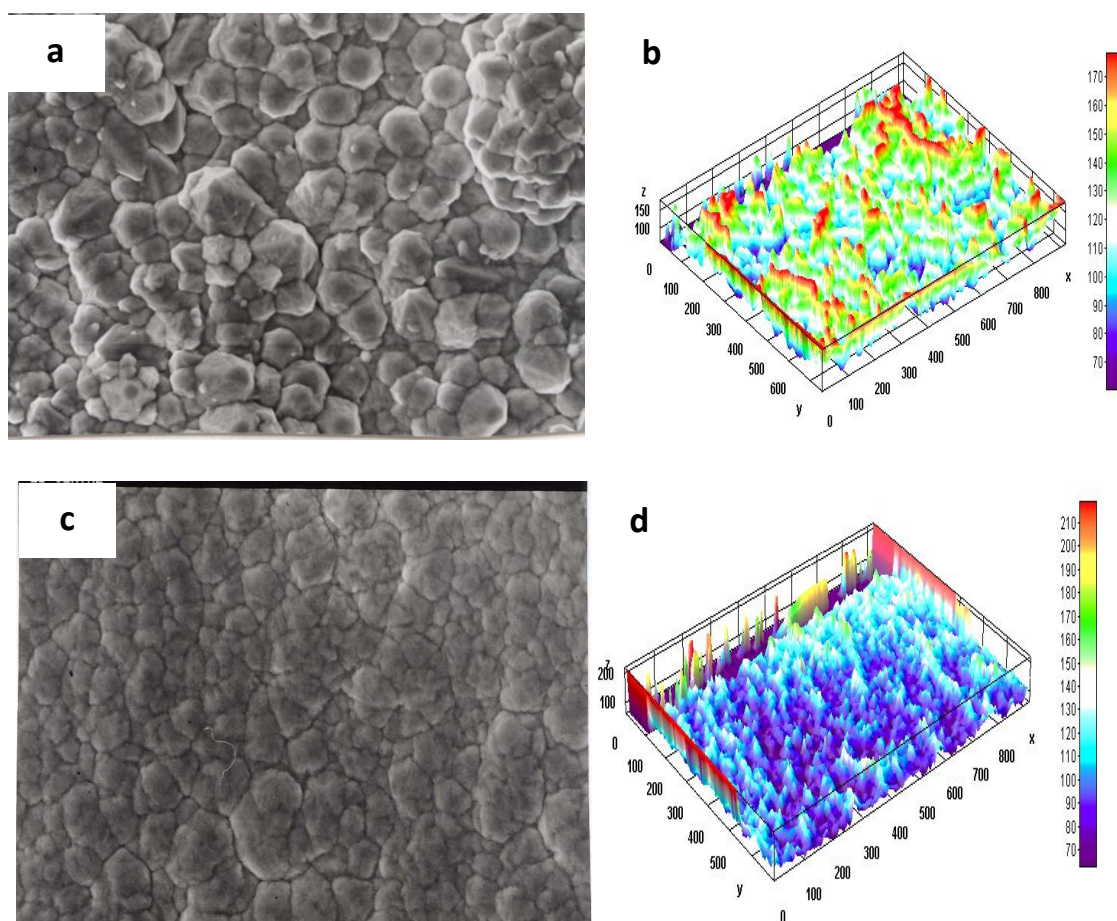


Figure 5: SEM morphology and 3D interactive surface images of zinc-nickel electrodeposit with 10.6 wt% of nickel in the deposit (a) and (b) shows the edge while (c) and (d) shows the centre of sample from a bath.

Table 2: Results of uneven distribution of current on the surface composition of the cathode produced from a bath containing 62.5 g/l ZnCl_2 , 60.7 g/l $\text{NiCl}_2 \cdot 6\text{H}_2\text{O}$, 200 g/l NH_4Cl , pH 3.5 and $T = 30^\circ\text{C}$.

Sample	Ni wt%	Ni wt%	Ni wt%
Designation	(Edge of deposit)	(Centre of deposit)	(Edge + Centre)/2
A	9.6	10.8	10.2
B	10.1	10.8	10.4
C	10.6	10.6	10.6
D	11.7	12.3	12.0
E	12.2	13.0	12.6
F	12.6	13.8	13.2
G	12.4	14.1	13.2

3.4 Influence of temperature and nickel content on zinc-nickel morphology

As earlier mentioned, the morphological changes observed in zinc-nickel electrodeposits are largely a function of changes in the nickel content of the deposit associated with changes in the individual parameters. In Figure 2, it was found that increase in temperature was met with a corresponding increase in the nickel content of the deposit. These results are further complimented in Figure 6 (a-c), which shows SEM micrographs of zinc-nickel electrodeposits produced from an acid chloride bath at different temperatures with different contents of nickel in the deposit. At 25°C as can be seen in Figure 6a the alloy exhibits regularly shaped nodular grains with gaps between individual grains. This is an indication that such deposits could be porous and hence poorly corrosion resistant. Interestingly, the percentage of nickel in this deposit is 7.5 wt%, which is less than the widely reported range of 10 to 15 wt% nickel for optimum corrosion resistance.

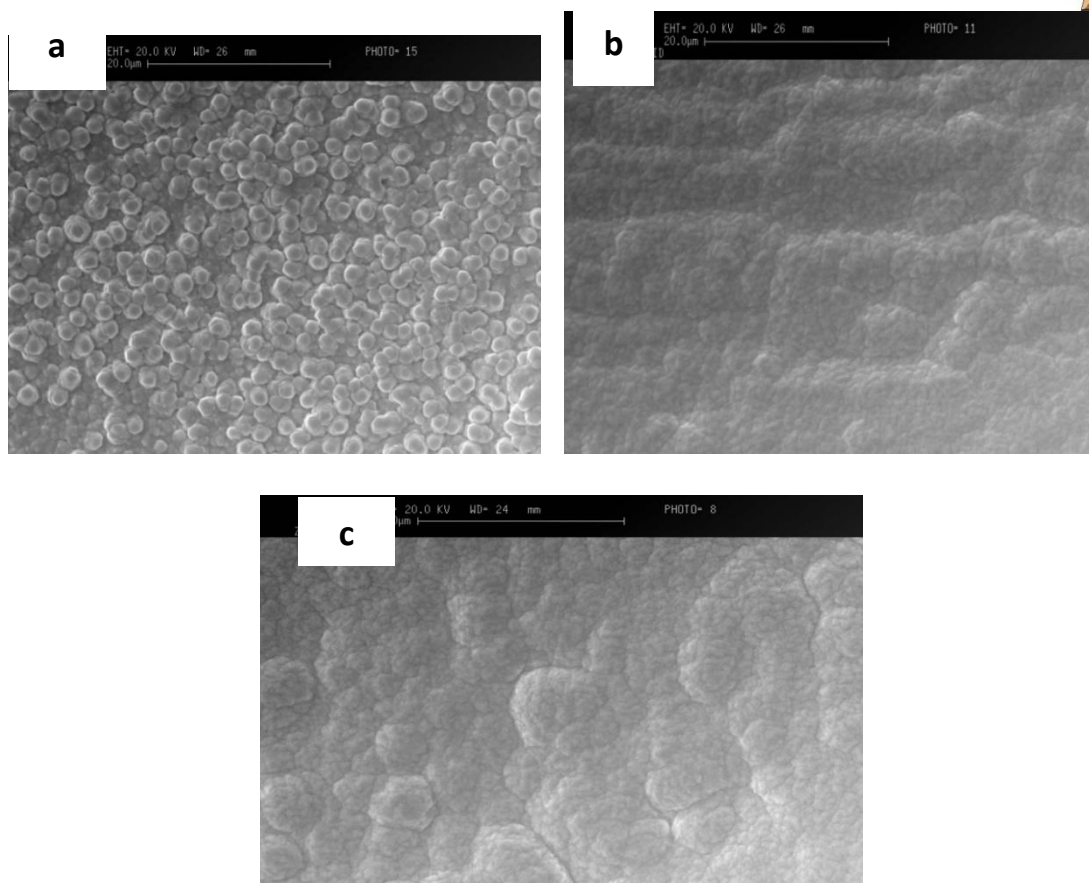


Figure 6: SEM micrographs of zinc-nickel electrodeposits produced from a bath containing 62.5 g/l ZnCl_2 , 60.7g/l $\text{NiCl}_2 \cdot 6\text{H}_2\text{O}$, 200 g/l NH_4Cl , pH 3.5 at different temperatures. (a) $T = 25^\circ\text{C}$, Ni 7.5 wt%, (b) $T = 30^\circ\text{C}$, Ni 11.7 wt%, (c) $T = 40^\circ\text{C}$, Ni 13.4 wt%.

Apart from being porous and inhomogeneous, zinc-nickel electrodeposits with lower percentages of nickel than the optimum range of 10 to 15 wt% nickel, are capable of developing dendritic growths as can be seen in Fig 7. Similar morphologies have previously been reported (Rashmi et al., 2020). As the temperature was increased from 25 to 30 °C, the nickel content of the deposit simultaneously increased to 11.7 wt% with obvious morphological transformations from the predominantly regular grain shaped morphology observed in Fig 6a to a homogeneously compact morphology as can be seen Fig 6b. Such homogeneously compact and crack-free morphologies probably account for the excellent corrosion resistance of zinc-nickel electrodeposits as it is less likely for corrosive species to migrate and penetrate these electrodeposits easily than those with some form of porosity.

It has been suggested that the lower Zn-Ni alloy corrosion rates, when compared to Zn-Co and Zn-Fe, are due to the predominant presence in this layer of crystallographic planes with a higher packing density (Whitehead et al., 2010). Further increase in temperature up to 40 °C was

accompanied with a corresponding increase in the percentage of nickel in the deposit up to 13.4 wt%. However, as can be seen in Fig 6c, initiation of microcracks or fissures in the coatings accompany the morphological changes probably as a result of increase in nickel content of the coatings at higher temperatures. This is an indication that at higher contents of nickel in the deposit, the deposits could become stressed and brittle. Other investigators (Jabbar et al., 2017) have made similar observations on changes in nickel content of the deposit with changes in temperature. According to Bajat et al. (Bajat et al., 2009) for deposits produced at 25 °C, a rough surface morphology was obtained and the structure contained a fine-grain matrix of γ -phase and coarse η -phase crystals. However, they noted that deposits produced at 40 °C were much smoother and the deposit consisted entirely of γ -phase with nodular fine-grain structure morphology with grain size in the range of 0.5-2 μm . The slight difference in morphological changes observed in these works is probably due to difference in individual bath formulations. It has also been shown previously that nickel content in the deposit is the major parameter controlling the morphology in pulse-plated Zn-Ni alloys. Generally, the usual pyramidal morphology of the pure Zn film is changed to cauliflower by alloying it with Ni. Cluster size is increased and microcracks appeared on the surface of the alloy coatings by increasing their Ni content. Hydrogen entrapment and residual stress rise with increment of the coatings Ni content, which causes formation of microcracks on the surface of Zn-17 wt%Ni (Algul et al., 2015; Qiao et al., 2013).

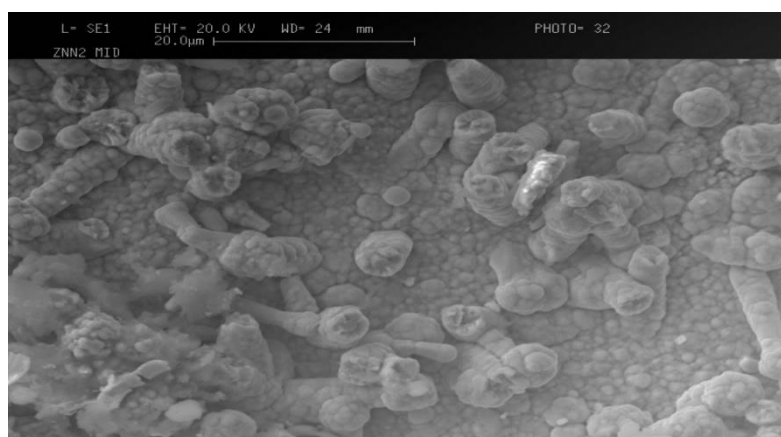


Figure 7: SEM micrographs of zinc-nickel electrodeposits with 9.5 wt% Ni.

4. Conclusions

As the current density increased, the Ni content in the coatings exhibited an inversely proportional relationship with the coating thickness. Zn-Ni electrodeposition was shown to exhibit anomalous behaviour in most investigations, with Zn, the less noble element, being

deposited preferentially. The Ni content in the electrodeposits continuously declined with increasing current density, even when various sets of data were acquired at different metal ion concentrations and current densities. The rate of nickel deposition was enhanced with higher temperatures and an increased Ni ion concentration in the bath. To achieve the best corrosion performance, a Ni content of 10-15 wt% in the coatings was found to be optimal when using a chloride bath formulation containing 62.5 g/l ZnCl₂, 60.7 g/l NiCl₂·6H₂O, and 200 g/l NH₄Cl. The morphological changes in Zn-Ni electrodeposits were linked to the Ni content of the deposit, and these changes appeared to vary with different deposition parameters. The 3D surface images provided insights into the surface chemistry and topography of the Zn-Ni alloys, offering explanations for the improved corrosion resistance of the coatings. The intensity of colour variations due to uneven current distribution during electrodeposition was assessed. Differences in composition were observed on the surfaces of individual Zn-Ni samples, particularly between the central and edge areas of the samples. These variations are attributed to the uneven current distribution on the sample during the electrodeposition.

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