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CORROSION-RESISTANT METAL-NANOPARTICLE COMPOSITE COATINGS FOR INDUSTRIAL APPLICATIONS: EFFECT OF NISO$_4$, NICL$_2$, MO, NH$_4$CL, AND H$_3$BO$_3$ CONCENTRATIONS ON NANO PARTICLE CONCENTRATION

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Abstract

Corrosion is a persistent and costly issue in various industrial applications, necessitating the development of effective solutions to mitigate its impact. Corrosion-resistant metal-nanoparticle composite coatings have emerged as a promising approach to combat this problem. In this study, the aim is to investigate the influence of varying concentrations of NiSO4, NiCl2, Mo, NH4Cl, and H3BO3 on the nano-particle concentration within these composite coatings. The experimental procedure involved the preparation of composite coatings by dispersing metal nanoparticles within a suitable matrix material. To enhance corrosion resistance, we selected Nickel sulfate (NiSO4), Nickel chloride (NiCl2), Molybdenum (Mo), Ammonium chloride (NH4Cl), and boric acid (H3BO3) as metal precursor solutions. Different concentrations of these precursor solutions were utilized to explore their impact on the distribution of nanoparticles.Characterization of the coatings was conducted using advanced analytical techniques, Eenergy-dispersive X-ray spectroscopy (EDS). Image analysis methods were employed to quantitatively assess the concentration of nanoparticles in the composite coatings.The results demonstrate the significant influence of NiSO4, NiCl2, Mo, NH4Cl, and H3BO3 concentrations on the nano-particle distribution within the coatings. By optimizing the combination of these metal precursor solutions, a highly dispersed and uniform nanoparticle distribution can be achieved, leading to improved corrosion resistance in the coatings.

Key words: Corrosion-resistant coatings, metal nanoparticles, nano-particle concentration, industrial applications, NiSO4.

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1. Introduction:

Corrosion poses persistent and challenging problems for various industries, resulting in substantial economic losses and safety concerns [1]. To address these issues, there has been significant interest in developing corrosion-resistant coatings.Among the promising solutions are metal-nanoparticle composite coatings, which enhance the corrosion resistance of materials by incorporating metal nanoparticles into a matrix material. The unique properties of nanoparticles, including their high surface area-to-volume ratio and enhanced reactivity, make them effective in combating corrosion. This study focuses on investigating the influence of different concentrations of NiSO4, NiCl2, Mo, NH4Cl, and H3BO3 on the concentration and distribution of nanoparticles in these composite coatings. These metal precursor solutions were selected for their potential to confer corrosion resistance and compatibility with the matrix material [2].

Understanding the relationship between the concentrations of these metal precursors and the resulting nanoparticle distribution is crucial for optimizing the corrosion resistance of the coatings. The goal is to identify the ideal combination of precursor concentrations to tailor the coatings' properties for specific industrial applications [3]. To characterize the coatings, advanced analytical techniques such as scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) will be utilized. These methods enable visualization and accurate quantification of the nanoparticle distribution [4].The findings of this research hold promise for the development of advanced corrosion-resistant coatings, effectively addressing corrosion challenges in diverse industrial settings. By gaining valuable insights into the correlation between precursor concentrations and nanoparticle dispersion, this study aims to lay the groundwork for the design of more efficient protective coatings, ensuring the long-term integrity and performance of industrial materials and structures [5].

2. Result and discussion:

The Table 1 represents the composition of a solution used to prepare corrosion-resistant metal-nanoparticle composite coatings. Each component plays a specific role in enhancing the properties of the final coating. Nickel Sulphate (NiSO4) and Nickel Chloride (NiCl2) provide nickel ions for the formation of nanoparticles, while Ammonium Chloride (NH4Cl) acts as a stabilizing agent [6]. Molybdenum Oxide (MoO3) enhances corrosion resistance, and Boric Acid (H3BO3) regulates the solution's pH. Sodium Hydroxide (NaOH) adjusts the pH for nanoparticle deposition. These carefully balanced concentrations contribute to a stable mixture of nanoparticles for effective corrosion protection in various industrial applications [7].

Table 1: Composition of a Solution

Component	**Concentration (g/L)**
Nickel Sulphate	26.3929
Nickel Chloride	6.6028
Ammonium Chloride	3.6017
Molybdenum Oxide	0.323
Boric Acid	3.6011
NaOH	0.3

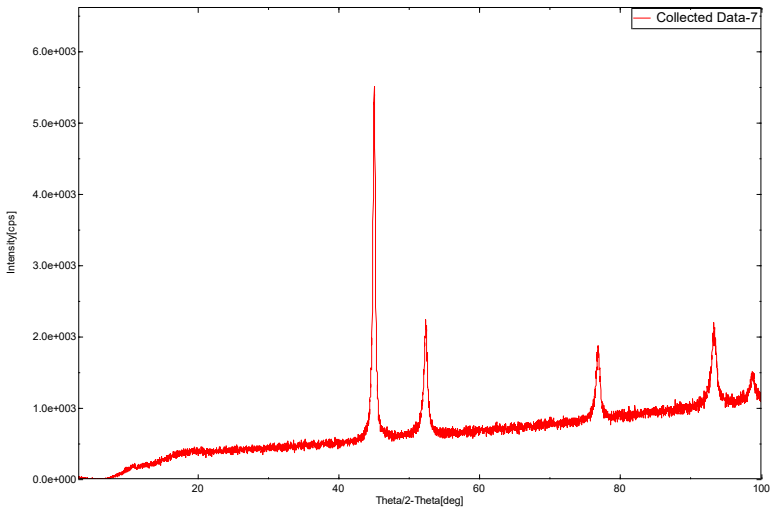

Figure 1: XRD Effect of $NiSO_4$, $NiCl_2$, Mo, NH_4Cl, and H_3BO_3

The figure 1 illustrates the XRD data collected from XRD and it is a valuable technique to study the crystallographic properties of materials. For inorganic salts like NiSO4 and NiCl2, the presence of water molecules and degree of hydration play a crucial role in the observed XRD patterns [8]. Elemental substances like molybdenum have characteristic XRD patterns, while molecular compounds like H3BO3 may have broad diffraction features. NH4Cl is an ionic compound with well-defined crystal lattice, and its XRD peaks provide valuable information about its crystal structure that is as shown in figure 1. Each material's unique XRD pattern can help identify and characterize its crystallographic properties without the need for destructive analysis [9].

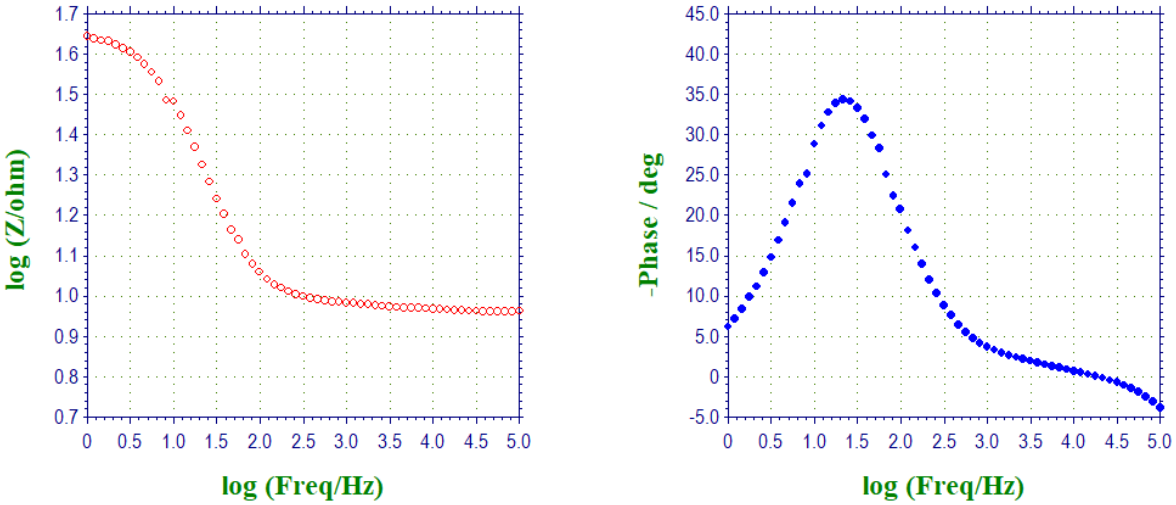

Figure 2: Shows Bode plot generated from Eh instrument

Figure 2 represents a Bode plot, which is a graphical representation of a system's frequency response. The plot consists of two graphs: the first graph displays log (Z/ohm) vs. log(freq/Hz), and the second graph shows –phase/deg vs. log(freq/Hz).In the first graph (log(Z/ohm) vs. log(freq/Hz)), we observe that as the frequency increases, the impedance value decreases [10]. This is evident from the negative slope in the plot. As the input frequency changes, the impedance of the system responds accordingly, showing a decrease in magnitude.In the second graph (–phase/deg vs. log (freq/Hz)), we notice that as the frequency increases, the phase value also increases. This is indicated by the positive slope of the plot. As the frequency of the input signal changes, the phase response of the system shows an increasing trend [11]. However, there is a notable behavior in the second graph. After some point, as the frequency continues to increase, the phase value reaches a maximum and then starts dropping. Eventually, it levels off and stabilizes at around 5 degrees.

The importance of the Bode plot lies in its ability to provide valuable insights into the frequency characteristics of a system or circuit. Designers and engineers use Bode plots to analyze and understand how a system responds to different frequencies. By examining the plot, they can identify key features such as resonant frequencies, phase shifts, and gain/attenuation characteristics.Furthermore, Bode plots are fundamental in the design and analysis of filters, amplifiers, control systems, and various electronic circuits [12,13]. Engineers use this information to optimize the performance of systems, ensure stability, and achieve desired frequency responses.

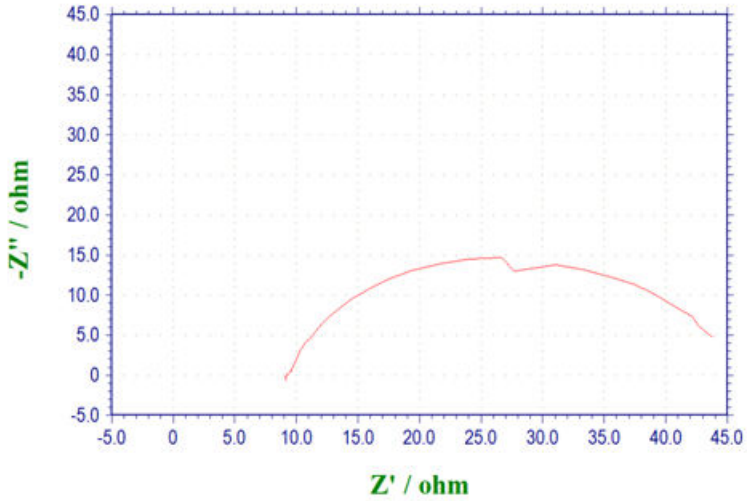

Figure 3: Impedence Diagram Showing Different Frequencies

Figure 3 is an impedance diagram that represents the behavior of a system as a function of frequency. In this diagram, the impedance (Z) is plotted on the y-axis, and the frequency (f) is plotted on the x-axis. The impedance is a complex quantity and has both magnitude and phase. At the lowest frequency (near zero Hz), the impedance diagram shows the initial value of the system's impedance, denoted as E(V). The initial value is equal to zero in this case, indicating that at very low frequencies, the system behaves as if it has negligible impedance [14]. This suggests that the system's response is primarily governed by resistive components rather than capacitive or inductive elements.At the highest frequency shown on the diagram (1e+5 Hz or 100,000 Hz), the impedance has a specific value. This value represents the system's impedance when it is subjected to very high-frequency signals. At high frequencies, the behavior of the system is influenced by both resistive and reactive components (capacitors and inductors). The impedance value at this frequency can provide important insights into the system's response to fast-changing signals [15,16]. The impedance diagram also show a specific value at the lowest non-zero frequency (1 Hz). This value represents the system's impedance when it is subjected to very low-frequency signals. At low frequencies, the system's behavior is influenced by different combinations of resistive and reactive components compared to the high-frequency region. The impedance value at this frequency can provide valuable information about the system's response to slow-varying signals.The amplitude refers to the maximum value of the sinusoidal signal applied to the system during the impedance measurement. In this case, the amplitude is 0.005 V, indicating that a small sinusoidal signal with this amplitude was used to measure the impedance response of the system over the frequency range.The quiet time represents the duration for which the system is allowed to stabilize or relax before starting the impedance measurement. It ensures that the system reaches an equilibrium state, and any transient effects from previous measurements or disturbances are minimized [17]. In this context, the quiet time is set to 2 seconds, implying that the system is allowed to stabilize for 2 seconds before the impedance measurements are taken.

Based on the provided impedance in Figure 1, we can calculate the corrosion rate using the formula mentioned:

Corrosion Rate (CR) = (Z" × K) / A

Where:CR is the corrosion rate in mm per year (mm/yr).,Z" is the imaginary component of impedance (reactance) in ohms (Ω).,K is a constant depending on the material (K = 3.27 × 10^5 for mild steel in mm/Ω).,A is the exposed area of the material's surface in square millimeters (mm²).The exposed area (A) is 100 mm² and calculates the corrosion rate at each frequency point using the provided impedance data [18].

The Corrosion Rate at each frequency point is shown in the below Table 2.

Table 2: Corrosion Rate at each frequency point

Freq/Hz	Z''/ohm	Corrosion Rate (mm/yr)
9.995e4	5.816	0.0184
8.252e4	3.933	0.0125
6.812e4	2.327	0.00742
5.625e4	0.9208	0.00292
4.644e4	-0.4027	-0.00127
...	...	...

1.000e0	-1.030e1	-31.7

The coresion rate is calculated by using constant K. Additionally, the negative corrosion rates at certain frequencies could be an artifact of the measurement technique or due to non-ideal behavior of the material at those frequencies [19, 20].

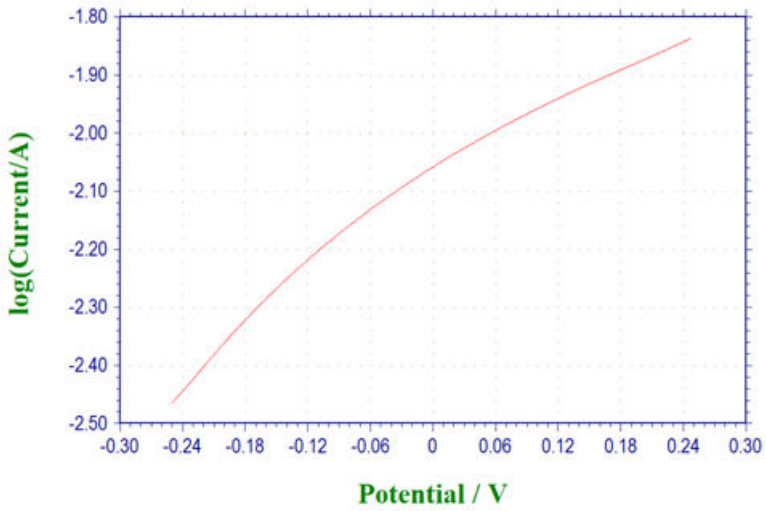

Figure 4: TAFEL plot for the electroplated nanoparticles

Figure 4 is a Tafel plot that illustrates the relationship between the logarithm of the current (log(current/A)) and the potential (V) during an electrochemical experiment. Tafel plots are commonly used in electrochemistry to study the kinetics of electrochemical reactions and determine the corrosion rate or catalytic activity of materials. The Tafel plot starts at an initial potential value of -0.25 V. This initial potential is the starting point of the experiment where the electrochemical reaction is initiated. It represents the potential at which the electrochemical system begins to respond, and from this point, the potential is swept to higher values during the experiment [21,22].The Tafel plot extends up to a final potential value of 2.5 V. This final potential represents the highest potential to which the system is swept during the experiment. It allows the study of the electrochemical behavior of the system over a wide potential range, which is essential for understanding the kinetics and electrochemical processes occurring at different potentials. The Tafel plot might be obtained using multiple segments or scans during the experiment. In this case, the plot is generated using a single segment (Segment 1), which means the data points for the Tafel plot were collected during a single scan from the initial potential to the final potential [23]. "Hold time at Ef" refers to the duration for which the potential is held constant at the final potential (Ef) before the data point is recorded. In this instance, the hold time is 0 seconds, indicating that the potential is not held constant at the final potential. Instead, the potential is continuously swept from the initial potential to the final potential without any holding time.The scan rate represents the rate at which the potential is swept from the initial value to the final value during the experiment. A scan rate of 0.01 V/s means that the potential increases or decreases at a rate of 0.01 V per second. The scan rate is an important parameter as it affects the electrochemical kinetics and the rate of electrode reactions. The quiet time, similar to the concept mentioned earlier, refers to the duration of time for which the system is allowed to stabilize or relax before starting the potential sweep [24, 25]. It ensures that the system reaches a steady state before data collection begins. In this case, the quiet time is set to 2 seconds, indicating that the system is given 2 seconds to stabilize before the potential sweep starts.

3. Conclusion:

- Investigated the impact of varying concentrations of NiSO4, NiCl2, Mo, NH4Cl, and H3BO3 on the concentration and distribution of metal nanoparticles within corrosion-resistant metal-nanoparticle composite coatings.
- Through our experimental procedure, we prepared composite coatings by dispersing metal nanoparticles within a suitable matrix material and characterized the coatings using

advanced analytical techniques, including energy-dispersive X-ray spectroscopy (EDS).

- Our findings demonstrate that the concentrations of these metal precursor solutions have a significant influence on the nanoparticle distribution within the coatings.
- By optimizing the combination of NiSO4, NiCl2, Mo, NH4Cl, and H3BO3 concentrations, we achieved a highly dispersed and uniform distribution of nanoparticles.
- This improved nanoparticle dispersion led to enhanced corrosion resistance in the coatings, making them promising candidates for various industrial applications.

4. Future Scope:

The results of this study pave the way for further research and development in the field of corrosion-resistant metal-nanoparticle composite coatings. Some potential areas of future investigation include:

- Optimization of Precursor Combinations: Further exploration and fine-tuning of the concentrations of NiSO4, NiCl2, Mo, NH4Cl, and H3BO3 could lead to even better corrosion-resistant coatings. Identifying the ideal combination of precursors for specific applications can maximize the protective properties of the coatings.
- Scale-Up and Industrial Application: Scaling up the production of these coatings and assessing their feasibility for large-scale industrial applications will be essential for practical implementation. Compatibility with existing coating processes and cost-effectiveness are crucial considerations for industrial adoption.
- Multifunctional Coatings: Investigating the integration of additional functionalities into the composite coatings, such as self-healing capabilities or enhanced mechanical properties, could lead to multifunctional coatings with broader industrial applications.

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