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Zn-Ni Plating Process for Corrosion Protection of Aircraft Grade High Strength Steel-development and Airworthiness Certification

Meenu Srivastava[1*], N. T. Manikandanath[1], Sai Venkata Pramod Kumar[1], M. Ganesh[1], B. Shri Prakash[1], Ashish R Narkale[2], R. K. Rayudu[2], T. Ram Prabhu[3], C. M. Bhuvaneswari[3], Shirish S Kale[3] and J. N. Balaraju[1]

[1] Division of Surface Engineering, CSIR-National Aerospace Laboratories, HAL Airport Road, Bengaluru - 560017, Karnataka, India

[2]Aeronautical Development Agency (ADA), Suranjan Das Rd, New Tippasandra, Bengaluru - 560075, Karnataka, India

[3]RCMA (F and F), Division of HAL Helicopter, RCMA (H/c) Building, CEMILAC, Bengaluru - 560017, India

Abstract

The aim of the present study is to develop Zn-Ni plating process on high strength steel using production level plating facility. The corrosion resistance of the Zn-Ni plating has been further enhanced by providing a trivalent chrome conversion coating. The complete coating system has been evaluated as per the AMS 2417 and found satisfactory. The process has been accorded approval by the certifying agency for use on aircraft components.

Keywords: Plating; Zn-Ni; Corrosion resistance; Hydrogen de-embrittlement; AMS 2417

1. Introduction

Aerospace structural components namely landing gear, bushes and fasteners are made of high strength steels due to their good mechanical properties, such as yield and ultimate tensile strengths. During use, they are exposed to corrosive environments and cyclic loading. Hence, sacrificial protective coatings are required to enhance the life of these components. Cadmium (Cd) was found to provide excellent corrosion protection from saltwater containing NaCl and other kinds of salts, also the diffusion rates of hydrogen in Cd are low resulting in reduced embrittlement. Cd is also relatively cheap and also has low coefficient of friction which is required in bushes and fasteners[1]. However, the significant problem with cadmium plating is the use of cyanide based chemicals during the plating process. Additionally, the cadmium plating is followed by a hexavalent chrome passivation treatment to enhance the corrosion protection. The chromate layer acts as a barrier, preventing corrosive substances from reaching the cadmium and the underlying substrate, thus improving overall corrosion resistance. Although hexavalent chromium imparts excellent corrosion protection, it is toxic and carcinogenic in nature. There are ongoing efforts to develop alternative passivation treatments and sacrificial corrosion protection coatings.

Zn-Ni electroplating with trivalent chrome passivation treatment is a viable and an environmentally safer alternative to cadmium plating for corrosion protection and galvanic interaction in various applications[2]. It offers comparable corrosion resistance to cadmium, especially in marine environments, and is a sacrificial coating that corrodes before the base material. It can be used in applications where cadmium is traditionally used, such as on steels, cast iron and other metals[3]. The main motivation for this shift is due to environmental

*Email: meenusri@nal.res.in

concerns and safety issues associated with cadmium and hexavalent chrome. Further, Zn-Ni has a lower tendency to cause hydrogen embrittlement compared to cadmium when plated from close to neutral or basic electrolytes, a concern in high strength steel applications[4]. Additionally, it is a cost-effective process especially with the use of existing electroplating facilities.

Most of the available literature is focussed on understanding the effect of process variables on the corrosion protection of mild steels[5]. Scarce reports are available on the troubleshooting experienced particularly during the Zn-Ni coating on high strength steel substrates used in aerospace applications and on the structural property evaluation. The present study is aimed to develop Zn-Ni plating from an acid based electrolyte on Nickel-Chrome-Molysteel (BS 5S 99E), followed by trivalent chrome passivation. Some of the challenges encountered during the coating process and the remedial measures adopted shall also be discussed. The Zn-Ni plated high strength steel was evaluated in accordance with AMS 2417 J standard for its performance. Subsequent to the plating and successful evaluation, the Zn-Ni plating process was certified by RCMA (F and F), CEMILAC, India for use in aircraft grade high strength steel components.

2. Experimental Details

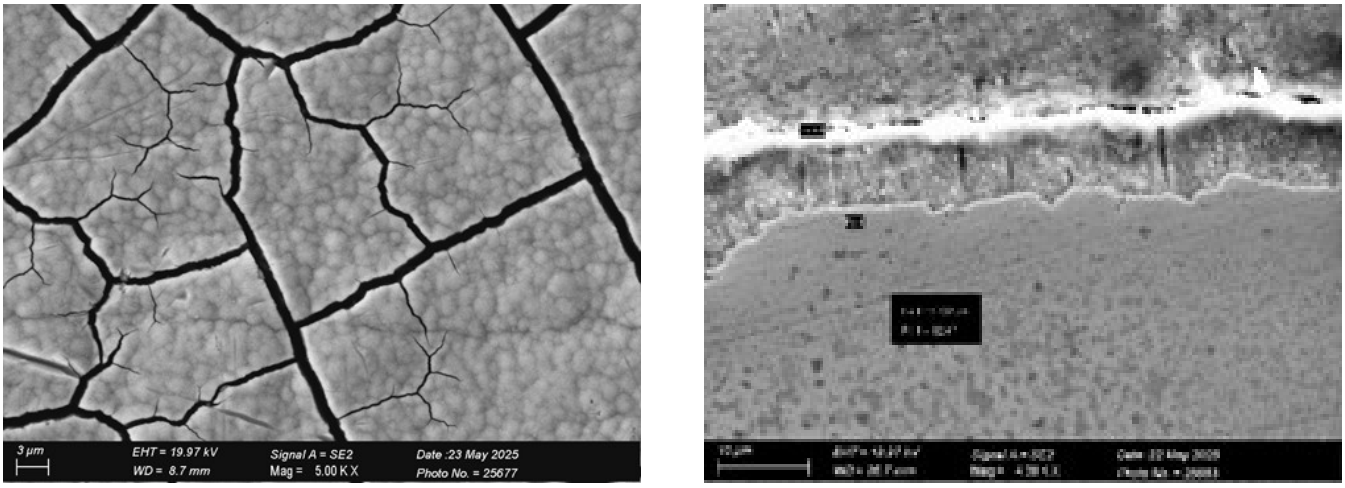
The Zn-Ni coating with Ni content in the range of 10 to 16 wt% and thickness in the range of 5-15 µm was electroplated from an electrolyte containing $ZnCl_2$ - 35-45g/L, $NiCl_2.6H_2O$-95-115g/L, KCl- 200-250g/L and proprietary additives. The electrolyte was prepared from distilled water and analytical grade chemicals. The pH of the coating electrolyte was maintained in the range of 5-6 with the help of HCl and KOH. The temperature during the coating process was maintained in the range of 30-35° C. Dual anodes *i.e* both Zinc and Nickel slabs were used as anodes and Nickel-Chrome-Moly steel was used as cathode and a current density in the range of 2.3-2.7A/dm^2 was applied for all the experiments. The steel specimens were initially vapour degreased followed by electrolytic cleaning in alkali solution. The specimens were neutralized in HCl followed by Nickel strike in Wood's nickel strike electrolyte. The specimens were then coated with Zn-Ni so as to achieve the desired thickness. The Zn-Ni coated steel was passivated by dipping for 30-50 sec at 30-50° C in a solution containing Cr^{3+}. The passivated Zn-Ni coated steel specimens were then subjected to hydrogen embrittlement relief baking as per AMS2759/9.

The Zn-Ni coating was characterized for the surface morphology and thickness using Carl Zeiss Supra Field Emission Scanning Electron Microscope (FESEM) and composition with the Energy Dispersive X-Ray (EDX) analysis attached to the FESEM. The adhesion of the coating with the steel substrate was tested using Elcometer cross-hatch tester as per ASTM D3359 standard. The corrosion behaviour of the coating was evaluated in continuous salt fog chamber (Ascott make) as per ASTM B117 standard. In addition to the corrosion resistance, it is essential that the structural properties of the NCM steel are not affected by the coating. Hence, the coated steel was evaluated for its structural properties namely tensile and fatigue strength. The room temperature tensile testing of the coated NCM steel specimens was performed in accordance with ASTM E8/E8M standard. The rotating beam high cycle fatigue testing was performed under room temperature condition at 600 MPa load as per BS 3518 Part 2 standard. The hydrogen de-embrittlement test was performed for 200 hours as per ASTM F519 Type 1a.1. The lubricity of the coatings was evaluated using linear reciprocating wear test as per ASTM G133 using 6mm Alumina ball as the counter material and applying a load of 1N, stroke length - 10mm, frequency - 2 Hz for a duration of 20 minutes.

3. Results and Discussion

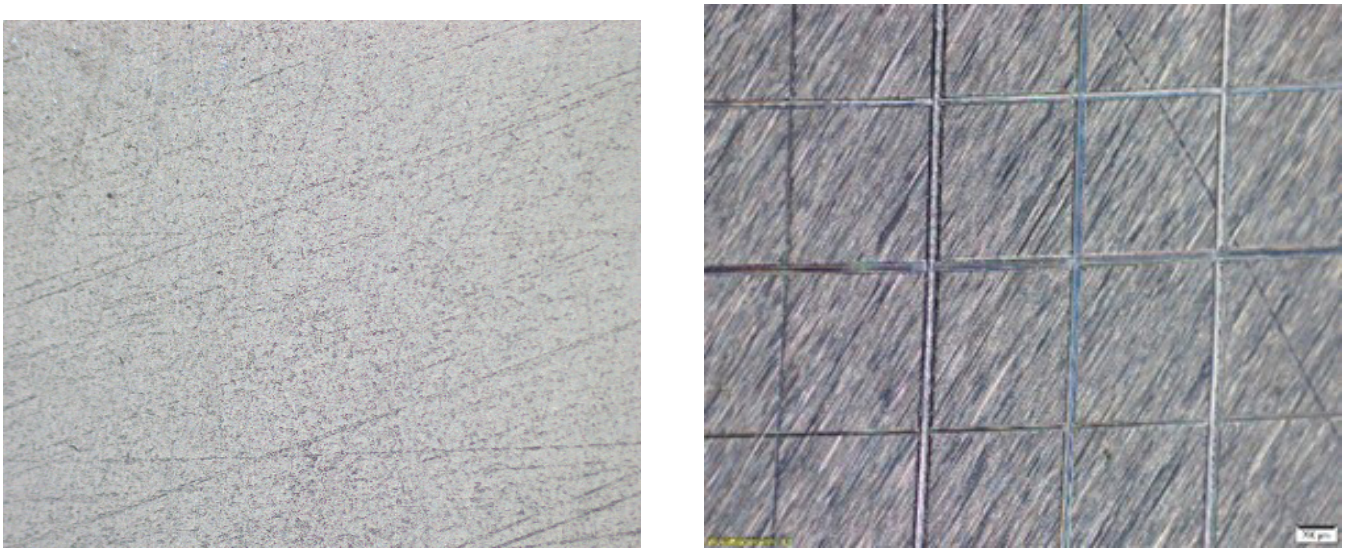
3.1. Surface Microstructure

The surface morphology of zinc-nickel alloy coating with nickel content in the range of 10-16 wt% and thickness in the range of 5 to 15 µm is displayed in Fig. 1a and b respectively. It can be seen that the crystallites are fine and uniform with micro-cracks uniformly distributed throughout (Fig. 1a). The micro-cracked nature of zinc-nickel alloy coating expels the trapped hydrogen during baking after plating indicating it will be an ideal candidate to replace cadmium on high-strength steel. The microstructure of electrodeposited zinc-nickel alloy coating depends on the current density, temperature, value of pH and nickel content[6,7]. In general, with current density greater than 1 A/dm^2 and increase in temperature, the rate of ionic diffusion and migration in plating solution increases resulting in more compact coatings. The value of pH also has great effects, when the value of pH is below 3, Zn anode dissolves quickly and when the value is above 6, the precipitation of hydroxide is observed in the coating.



(a) **(b)**

Figure 1. **(a)** FESEM micrographs depicting the surface morphology **(b)** Cross-section image depicting the thickness of Zn-Ni coating.



(a) **(b)**

Figure 2. **(a)** As-coated Zn-Ni plated specimen **(b)** Cross-hatch image after the adhesion test.

4. Adhesion and Micro-hardness

The adhesion of the Zn-Ni coating with the NCM steel substrate was evaluated using a cross-hatch test followed by tape test. No delamination of the coating was observed indicating good adhesion of the coating. The image of the cross-hatched coating is displayed in Fig. 2. The microhardness testing revealed an average micro-hardness of 407±30 VHN_{25gf} for the passivated Zn-Ni coating.

5. Corrosion Resistance

The corrosion behaviour of passivated Zn-Ni coating was studied by means of accelerated corrosion test in salt fog chamber as per ASTM B117 standard. The corrosion products formed on the surface were visually examined after 96 hours and 500 hours of exposure to neutral salt spray as per AMS 2417 J standard. Photographs of trivalent chrome passivated Zn-Ni coated NCM steel samples before and after the salt fog test are shown in

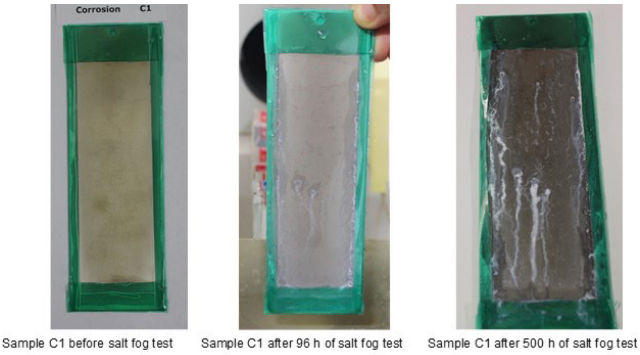


Figure 3. Images of passivated Zn-Ni plated NCM steel specimens subjected to salt fog environment.

Fig. 3. The first marks of white rust on the Zn-Ni coating surface was observed after 96 hours of exposure and no corrosion of NCM steel substrate (red rust) was observed even after 500 hours of exposure. The mechanism involved during corrosion is that during the exposure of Zn-Ni coating to chloride environment in salt fog chamber there is a spontaneous formation of zinc oxide or hydroxide which eventually reacts with chloride ions to form zinc-hydroxy-chloride $Zn_5(OH)_8Cl_2$ with varying water molecules[8]. The salt fog test was continued up to 1000 hours of exposure and no evidence of steel corrosion product was seen.

The coated NCM steel samples were also subjected to outdoor exposure studies at Mandapam, Rameshwaram, India. The samples were kept at a distance of nearly half a kilometre from the sea shore. The comparative image of the baked trivalent chrome passivated coated samples in as-deposited condition and after nearly 3600 hours of exposure is shown in Fig. 4. It can be seen from the figure 4 that even after 3600 hours of exposure no presence of steel corrosion product (red rust) is observed on the surface of the samples. Thus, it is evident that trivalent chrome passivated Zn-Ni coating is a promising coating for the corrosion protection of high strength steel.

6. Structural Properties

The tensile properties of the trivalent chrome passivated Zn-Ni coated NCM steel were evaluated in accordance with ASTM E8/E8M standard and the properties obtained are tabulated in Table 1.

It is seen from Table 1 that the tensile properties namely the tensile strength, 0.2% yield strength and % elongation of the Zn-Ni coated steel is comparable

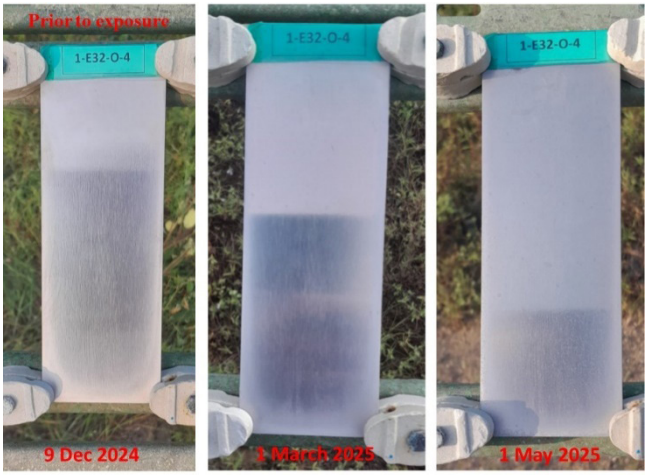


Figure 4. Images of passivated Zn-Ni plated NCM steel specimens after different durations of outdoor exposure studies.

Table 1. Comparative tensile properties of uncoated and Zn-Ni coated steel

Material	UTS, MPa	0.2% YS, MPa	% Elongation, 5D
Uncoated NCM steel	1230-1420	1080 Min.	10-15
Zn-Ni coated NCM steel	1255 1243 1233	1172 1165 1143	11.85 13.56 14.34

to that of the uncoated steel indicating that the process optimised for the Zn-Ni coating and passivation does not alter the strength of the NCM steel. The coated steel was also subjected to rotating beam fatigue testing at 600 MPa, Kt=1.0 and R=-1. The number of cycles to failure was recorded as $1.30x10^5$, $1.51x10^5$ and $1.47x10^5$ for three coated samples and the results are comparable to that of cadmium plated samples of the same substrate.

7. Hydrogen De-embrittlement

The electroplating process can lead to hydrogen embrittlement in steel, especially high-strength steels. This is because hydrogen is a by-product of the electroplating process and can diffuse into the steel, causing it to become more brittle and prone to cracking. Therefore, evaluating and mitigating hydrogen embrittlement is crucial in electroplating process involving steel, particularly for applications where structural integrity is a paramount. Towards this the trivalent chrome passivated Ni-Cr-

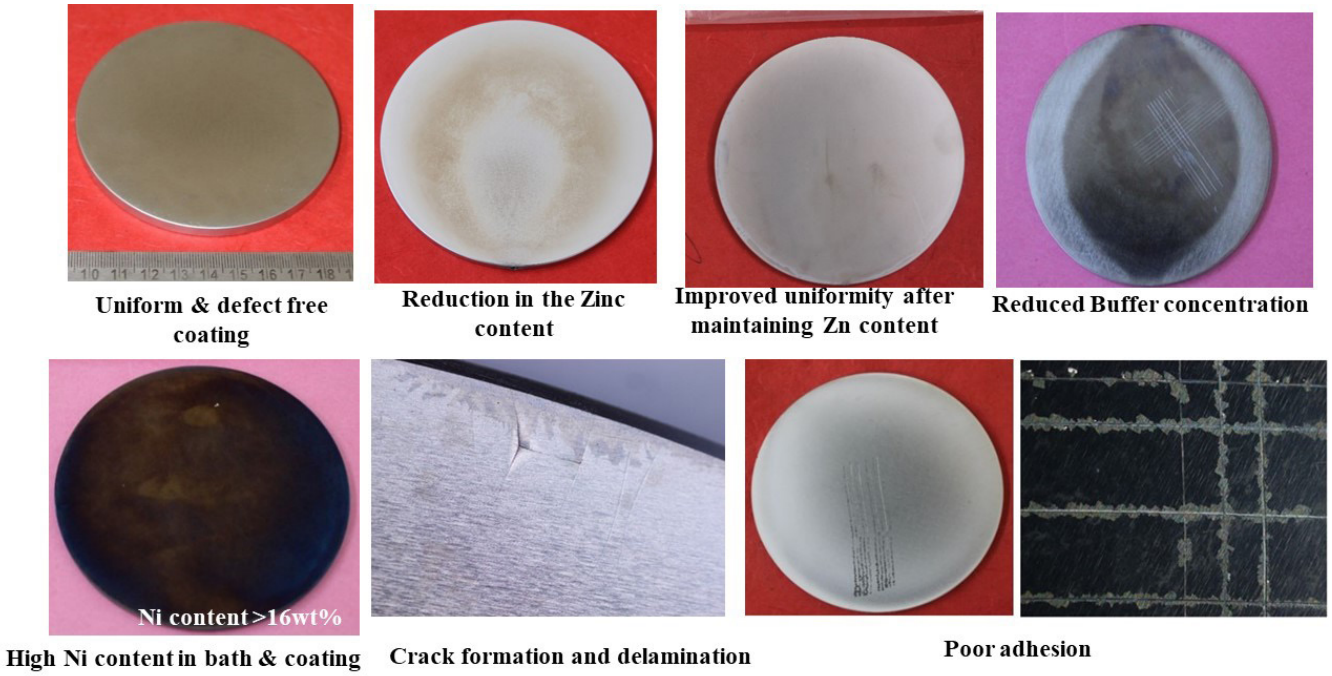


Figure 5. challenges faced during Zn-Ni plating.

Most steel samples were baked in accordance with AMS 2759/9 standard. The samples were evaluated for the de-embrittlement as per ASTM F519 for 200 hours and no failure of the coated samples was observed.

8. Lubricity

The lubricity of the Zn-Ni coated NCM steel samples was measured and expressed in terms of Coefficient of Friction (CoF) and an average value of 0.12±0.02 was obtained as against 0.20±0.02 for cadmium coating.

9. Trouble Shooting

Some of the issues experienced during the Zn-Ni coating process using a chloride bath is shown in Fig. 5. Invariably due to deviation in the zinc and nickel concentration it results in a non-uniform appearance particularly an increase in nickel content *i.e.* >18wt% in the coating results in a bluish appearance. Reduced buffer content in the coating also results in a non-uniform appearance. Improper pre-treatment results in poor adhesion, crack formation and improper additive concentration results in delamination of the coating.

The challenges explained in Fig. 5 were overcome and plating trials were performed on aircraft components namely bushes, sleeves as shown in Fig. 6.



Figure 6. Passivated Zn-Ni plated aircraft components.

10. Conclusions

The consolidated evaluation test matrix for the trivalent chrome passivated Zn-Ni coated Ni-Cr-Mo steel is given in Table 2 and is below and is found to be in compliance with AMS 2417J standard. This resulted in the certification of the Zn-Ni plating process by the aircraft certifying agency of India, RCMA (F and F), CEMILAC for use on aircraft grade high strength Ni-Cr-Mo steel.

11. Acknowledgement

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Table 2. Consolidated evaluation test matrix for the trivalent chrome passivated Zn-Ni coated Ni-Cr-Mo steel

Sl. No	Tests	Standard	Test Result	Remarks
1.	Chemical composition using EDX	AMS 2417J	Ni content shall be 10-16 wt% Bal. Zn	Complied
2.	Microstructure using metallographic examination	-	Micro-cracked structure	Complied
3.	Plating thickness using metallographic examination	AMS 2417J	5-15 microns	Complied
4	Adhesion test cross-hatch test	ASTM D3359 – X	No blisters, delamination, peeling of the coating observed	Complied
5.	Lubricity test (CoF)	ASTM G133	CoF :0.10 ± 0.03	Complied Comparable with Cd plated NCM steel
6.	Salt (fog) spray corrosion resistance	ASTM B117 & AMS 2417J	No white rust for 96 h and no red rust formation for 500 h	Complied
7.	Tensile test	ASTM E8/8M	UTS: 1333 MPa Proof Strength: 1244 MPa Elongation: 15.02 %	Base material properties unaffected
8.	Fatigue test	Stress: 600 MPa, Kt= 1.0, R= -1, 1 Lakh cycles BS 3518-2	No fracture, coating delamination after one lakh cycles	Complied
9.	Hydrogen de-embrittlement test	ASTM F519, Type1a.1	Shall pass 200 hours minimum	Complied

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12. References

1. Sadananda K, Yang JH, Iyyer N, Phan N, Rahman A. Sacrificial Zn-Ni coatings by electroplating and hydrogen embrittlement of high-strength steels. Corros. Rev. 2021; 39(6), 487-517. https://doi.org/10.1515/corrrev-2021-0038
2. Lotfi N, Aliofkhazraei M, Rahmani H, Darband GH. Zinc-Nickel alloy electrodeposition: Characterization, properties, multilayers and composites. Prot Met Phys. Chem. Surf. 2018; 54, 1102-1140. https://doi.org/10.1134/s2070205118060187
3. Julian Kubisztal, Jolanta Niedbała, Antoni Budniok, Eugeniusz Lagiewka. Corrosion resistance of Zn-Ni coatings exposured to neutral salt spray. AMST. 2010; 34(2), 59-70.
4. Conde A, Arenas MA, Damborenea JJ. Electrodeposition of Zn-Ni coatings as Cd replacement for corrosion protection of high strength steel. Corros. Sci. 2011; 53(4), 1489-1497. https://doi.org/10.1016/j.corsci.2011.01.021
5. Qiao X, Li H, Zhao W, Li D. Effects of deposition temperature on electrodeposition of zinc-nickel alloy coatings. Electrochim. Acta. 2013; 89, 771-777. https://doi.org/10.1016/j.electacta.2012.11.006
6. Byk TV, Gaevskaya TV, Tsybulskaya LS. Effect of electrodeposition conditions on the composition, microstructure, and corrosion resistance of Zn-Ni alloy coatings. Surf. Coat. Tech. 2008; 202(24), 5817-5823. https://doi.org/10.1016/j.surfcoat.2008.05.058
7. Basavanna S, Naik YA. Electrochemical studies of Zn-Ni alloy coatings from acid chloride bath; J. Appl. Electrochem. 2009; 39, 1975-1982. https://doi.org/10.1007/s10800-009-9907-1
8. AlFalah MGK, Abbar AH, Kandemirli F. Improving the corrosion behaviour of Zn-Ni alloy coatings on 316SS from chloride-sulfate bath by addition of triethanolamine or sucrose; J. Electrochem. Sci. Eng. 2025; 15(3). https://doi.org/10.5599/jese.2607