

Studying the Magnetic Properties and Corrosion Resistance of Coated NdFeB Magnets [†]

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Abstract: Commercial NdFeB magnets are often coated with different thin layers to increase corrosion resistance. Fast and reliable test methods are being developed, especially for the automotive industry. Since corrosion test methods can inadequately describe the operating conditions of the e-motor, magnets are usually only tested in the demagnetized state. Corrosion tests close to sintered NdFeB magnet e-motor application conditions have been applied. Corrosion tests for sintered NdFeB magnets are usually demagnetized and performed in aqueous solutions or vapor environments instead of organic substances such as oil. In this study, sintered NdFeB magnets were immersed in a pre-saturated water-based salt solution and placed in gearbox oil. The test conditions have been specially selected to test the suitability of the magnets for e-motor applications (e.g., in hybrid vehicles). The microstructural effect of magnetic properties and corrosion resistance on the NdFeB magnets have been systematically studied. The aim of the study is the realization of the coating on the sintered NdFeB magnet, which provides high corrosion resistance and significantly reduces the thickness of the coating and ensures maximum efficiency in the use of magnets. The results of these studies are thought to play an important role in determining and optimizing the usage strategy of coated NdFeB magnets.

Keywords: coating; NdFeB; magnetic properties; corrosion



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1. Introduction

NdFeB (Neodymium-Iron-Boron) magnets are renowned for their exceptional magnetic properties, including high-energy products and significant coercivity. These characteristics make them indispensable in a wide range of applications, from advanced electronics to automotive systems. NdFeB magnets are extensively utilized in various applications, such as motors and electronic devices [1]. Due to their advancing applications and significant advancement potential, NdFeB magnets have emerged as permanent magnetic materials. Sintered NdFeB permanent magnets are known for their excellent magnetic characteristics. However, the magnetic properties of NdFeB magnets are affected by different factors like the Nd-rich phase and grain size. The intrinsic coercivity of the NdFeB magnet is low and restricts the use of sintered NdFeB magnets [2]. Nd is highly reactive and tends to oxidize into Nd₂O₃, which impacts the magnetic performance of the material. The magnetic field influenced the corrosion behavior by oxygen concentrations on the surface, leading to the aggregation of Nd³⁺ ions and removed Nd₂Fe₁₄B particles. It could be attributed that corrosion associated with Nd is connected to hydrogen evolution. [3]. NdFeB magnets are vulnerable to corrosion because of the Nd-rich intermetallic phases. In a permanent magnet, the matrix of the Nd₂Fe₁₄B tetragonal ferromagnetic compound contains a dispersed

Nd-rich intermetallic phase. The Nd-rich phase exhibits the most active electrochemical potential, and it dissolves over other phases due to galvanic corrosion. Nd-rich phases are located at the grain boundaries of the Nd₂Fe₁₄B matrix, and corrosion leads to degradation of the NdFeB [4]. The main limitations of NdFeB magnets are their low-temperature coefficients of remanence, coercivity, and low corrosion resistance. The lack of corrosion resistance is related to the Nd content in the alloy and the neodymium-rich phases on the grain boundary. Different methods (alloy composition and coating) are used to enhance the corrosion resistance of the NdFeB magnets. It was specified that alloy elements can improve corrosion resistance, but they can diminish their magnetic properties [5]. Meanwhile, the surface coating prevents the degradation of magnetic properties and offers improved corrosion resistance [6]. Also, it could be explained that coating the surface of NdFeB magnets with Ni, Cu, Cr, and Zn enhances their corrosion resistance. Deposition techniques have been frequently employed for coating metallic surfaces. Nevertheless, chemical deposition results in a relatively loose layer and less precise control over its thickness. Also, it is mentioned that metals with electrode potentials more negative than that of the NdFeB substrate cannot be chemically deposited. Therefore, obtaining a uniform metallic coating on magnetic materials is a significant goal [7]. The choice of coating material is crucial in the electrodeposition process for NdFeB magnets. Commonly used coating materials include Ni, Cr, Zn, and Cu. The research indicates that NdFeB magnet materials with nickel and Ni-Cu-Ni coatings have been selected [8]. There is ongoing research to improve the coating process of the materials, as we lack a comprehensive understanding of the corrosion mechanisms of NdFeB magnetic material in the literature. Several research groups have investigated the electrochemical corrosion behavior of NdFeB magnets [9]. It has been suggested that NdFeB magnetic materials are influenced by the presence of a more Nd-rich phase to the Nd₂Fe₁₄B grain boundaries leading to the separation of the grains, and that hydrogen enlargement during corrosion causes hydride formation, which leads to the disengagement of grains [10]. This article investigates NdFeB magnets, focusing on the role of electrodeposition in enhancing corrosion resistance, and the influence of coatings on magnetic performance. Research on the relationship between microstructure and corrosion mechanisms has been quite limited. This paper presents the use of pulse current (PC) electro-deposition to create Ni-Cu deposits on NdFeB alloy. The study includes an analysis of how pulse current affects the microstructure of the Ni-Cu deposits and investigates the mechanisms contributing to their enhanced corrosion resistance.

2. Materials and Methods

An electrodeposition device was used for magnetic force agitation during the electrodeposition process. A mixing magnet, which continuously moves throughout the electrodeposition process, was installed beneath the electroplating bath. Sintered NdFeB alloy (30 mm × 20 mm × 5 mm) was utilized. The NdFeB alloy underwent a surface treatment where it was initially polished with silicon carbide sandpaper ranging from 400 to 1200. Then, the magnets were pretreated, including ultrasonic cleaning, deionized water, and alcohol. In order to relatively uniformly distribute transfer on the coating surface during the electrodeposition process, sintered NdFeB alloy was well-set in the coating bath. Then, the pulsed power supply was used to electrodeposit nickel onto the magnet surface. Ni was deposited on the NdFeB substrate used as the working electrode. The platinum electrode served as the counter-electrode, while a saturated calomel electrode (SCE) was used as the reference electrode. The current density was 1 A·cm⁻², with a duty cycle of 50%. The pulse current consisted of positive currents, reverse currents, and periods of no current, with the electro-deposition process involving the periodic repetition of this pulse current. Table 1 shows the deposition parameters and the composition of the coating bath.

Scios 2 DualBeam (Thermo Scientific, Waltham, MA, USA) focused ion beam. Scanning electron microscopy (FIB-SEM) was used to observe the morphology and cross-section of the coated layer. The mapping analysis of the NdFeB alloy and coating surface used to measure elemental distribution was carried out using energy dispersive X-ray spectrometer (EDS) analysis. The crystal structure and phase composition of the demagnetized NdFeB magnet were analyzed using a Miniflex 600 (Rigaku, Tokyo, Japan) X-ray diffractometer (XRD) with Cu-K α radiation. The 2θ range was between 20° and 100° , with a step size of 0.5° s. A Vibrating Sample Magnetometer (Cryogenic, London, UK) (VSM) was used to measure the magnetic properties of the magnets. Tafel curves were obtained using an electrochemical workstation by CS350M (Corrtest Instruments, Wuhan, China) with a 3.5 wt.% NaCl solution used as the corrosion medium with a scanning range of 0.5 V to -2.0 V and a scanning rate of 1 mV/s through negative to positive potential direction.

Table 1. The electrodeposition parameters of the Ni-Cu coating process.

	Composition	Concentration	Operating Parameters	
Ni plating	NiSO ₄ ·6H ₂ O	200 g/L	Temperature	50 °C
	NiCl ₂ ·6H ₂ O	60 g/L	pH	4.5
	H ₃ BO ₃	40 g/L	Duty cycle	50%
	C ₆ H ₅ NaO ₂ S	0.1 g/L	Time	30 min
	C ₁₂ H ₂₅ SO ₄ Na	0.1 g/L	Current density	1.0 A/dm ²
Cu plating	Cu ₂ P ₂ O ₇	50 g/L	Temperature	80 °C
	K ₄ P ₂ O ₇	350 g/L	pH	10
	NH ₃ ·H ₂ O	0.3 mL/L	Time	30 min

3. Results and Discussion

Figure 1 shows a cross-sectional SEM image of Ni-Cu-coated NdFeB alloy, where a complete coating is evident, with a layer thickness of approximately 5 μ m. The Ni-Cu plating layer thoroughly covers the sintered NdFeB alloy, demonstrating that the plating effectively protects it. The Ni-Cu plating layer is generally uniform and dense, ensuring a solid foundation for the subsequent layers. The Ni-Cu coating appears uniform, free of cracks, and shows no signs of peeling. EDS mapping analysis indicates that the surface of the NdFeB alloy consists of a Ni-Cu region. The Ni-Cu coating film was dense and well-adhered to the substrate. It can be concluded that copper did not significantly dissolve the Nd-rich phase, which is beneficial for preserving the magnetic properties [8]. Also, it could be said that the Ni-Cu-coated magnet demonstrated adequate adhesive coverage and strong adhesion [11].

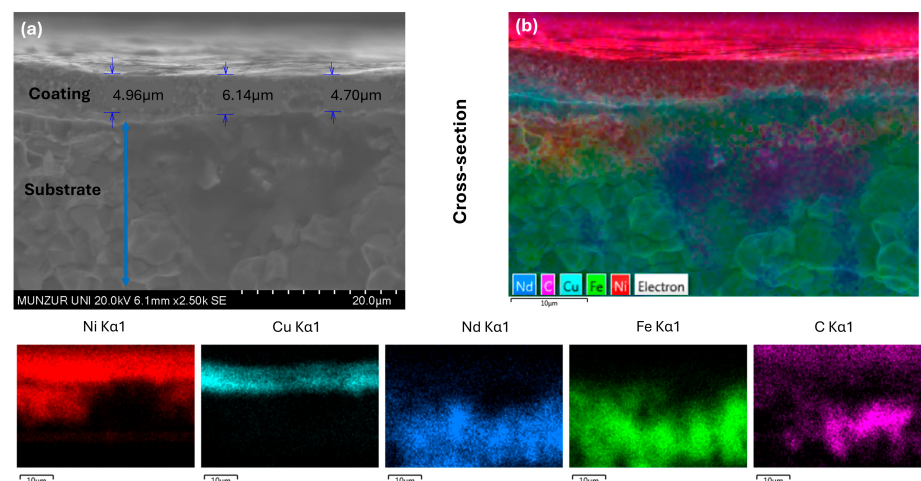


Figure 1. The cross-section image (a) and elemental mapping (Ni, Cu, Nd, Fe, and C) (b) of Ni-Cu coating on the sintered NdFeB alloy.

The XRD results show sharp diffraction peaks for Ni, corresponding to the crystal planes (111), (200), (220), and (311) of Ni and Cu, respectively (Figure 2). The figure reveals that the most intense peak occurs at an angle of 2θ equal to 42° . These findings suggest that flexible friction can alter the crystal growth structure of the deposit, enhancing the growth potential of the (111) crystal plane. The Ni coating deposited under flexible friction exhibits a preferred orientation along the (111) plane. As it is known, the (111) crystal plane features a high atomic density and low surface energy within the face-centered cubic structure, making it beneficial for enhancing coating performance [12]. It could be specified that the current density results in a notable increase in the preferred orientation of the (111) crystal plane. With more surface area available on the workpiece for Ni ions to deposit simultaneously, the current density is reduced, leading to improved surface quality.

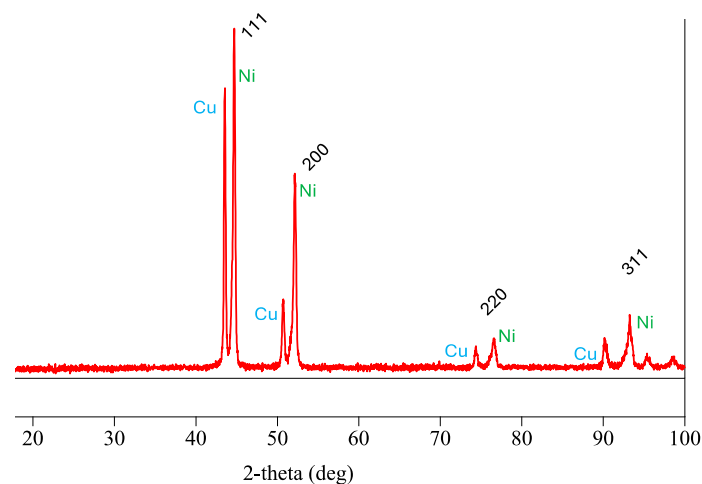


Figure 2. XRD pattern of the Ni-Cu-coated NdFeB alloy.

Figure 3 presents the demagnetization curve $B(H)$ and the corresponding $J(H)$ curve of the NdFeB magnet, comparing its state before and after the coating process. The magnetic powder exhibits a significant increase after the coating process. Clearly, the H value shows a substantial difference, while the B value remains relatively consistent. The remanence (J_r) decreases over time, reaching its value (0.93) in the sample that was coated with Ni-Cu. The lower coercivity of the surface layer, compared to the bulk, influences the overall magnetic properties of the magnets, especially when a Ni coating is applied. It could be said that when the surfaces of NdFeB-based particles are exposed to oxygen, the volumetric fraction of the magnetic phase and magnetization polarization decreases, which in turn causes a reduction in J_r . Moreover, it may help explain the reduction in the remanence related to the volumetric fraction of J_r [13]. Both H_c and M_r/M_s values rise with Ni-Cu coating. It could be mentioned that the increased saturation magnetization and remanence are related to the presence of fine particles and a high particle density [14]. However, the growth in particle and crystallite size negatively impacts H_{c1} . The Ni-Cu coating enhances the magnetic properties of the magnet powders. Table 2 summarizes the magnetic properties of magnets made from both coated and uncoated samples. Although the magnetic properties of both types decreased due to the oxidation of NdFeB, the coated samples demonstrated superior properties compared to the uncoated ones. This indicates that the Ni coating effectively prevents Nd from reacting with O_2 .

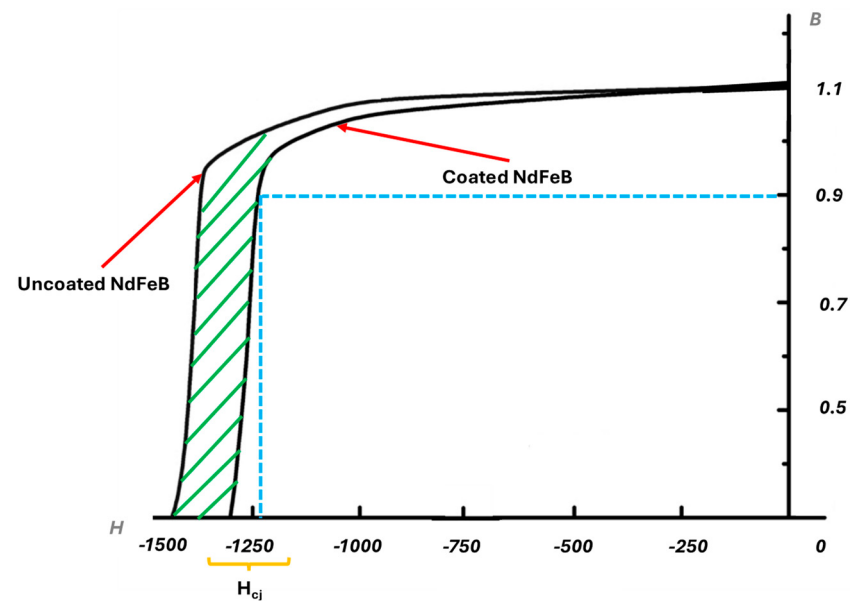


Figure 3. The M-H curve of the NdFeB magnet with and without Ni-Cu coating.

Table 2. Magnetic properties of Ni-Cu coated NdFeB magnet.

	$(BH)_{\max}/\text{kJm}^{-3}$	B_r/mT	H_{cj}/kAm
Coated	48.7	5.362	−1312
Uncoated	46.4	5.298	−1457

The diagram of the Tafel extrapolation method for the Ni-Cu-coated NdFeB alloy is presented in Figure 4. The corrosion potential ranged from 0.5 to -2 V, influenced by the polarity of the magnet's surface in contact with the environment. It is known that elevated corrosion potential values indicate that the coatings offer strong protection against corrosion [15]. The coating deposited from a solution demonstrated corrosion resistance, showing E_{corr} of -478 V and a current density of $1.34 \times 10^{-6} \text{ A cm}^{-2}$. It could be said that the Ni-Cu-coated surface improved the density of the NdFeB alloy and slowed the penetration of the electrolyte, which in turn reduced the corrosion current density at the cathodic sites. The values for the slope of the anode polarization zone (β_a), the slope of the cathode polarization zone (β_c), corrosion potential (E_{corr}), and the current density (I_{corr}) of the Ni deposits produced by various technologies were calculated and are presented in Table 3. It should be mentioned that Ni-Cu coating exhibited the lowest corrosion tendency and rate, significantly improving its corrosion resistance in 3.5 wt.% NaCl.

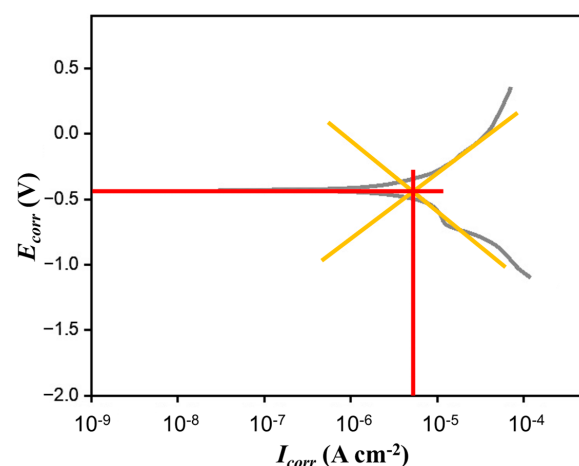


Figure 4. Diagram of Tafel extrapolation of Ni-Cu-coated NdFeB alloy.

Table 3. Tafel parameters of Ni-Cu-coated NdFeB magnet in 3.5 wt.% NaCl solution.

E_{corr} (Potential vs. SCE V)	I_{corr} (A cm ⁻²)	β_a	β_c
−478	1.34×10^{-6}	0.0964	0.5173

4. Conclusions

The electrodeposition process was effectively used to apply the Ni-Cu layer on sintered NdFeB alloy. Ni-Cu-coated NdFeB alloy exhibited a preferred orientation along the closely packed (111) crystal planes, leading to a reduction in extra phases. Ni-Cu-coated NdFeB magnet exhibited superior magnetic properties compared to the uncoated ones. The magnetization of the NdFeB alloy had no effect on its polarization. The H_{cj} is linked to the formation of a more uniform alloy, and the B_r and $(BH)_{max}$ are primary. The EIS measurements validated the protective barrier capabilities of the Ni-Cu coating on the NdFeB alloy. The Ni-Cu coating is sufficiently compact to effectively protect the sintered NdFeB alloy from oxygen, significantly enhancing its corrosion resistance. Ni-Cu-coated NdFeB alloy demonstrated the lowest corrosion resistance due to a lower number of defects and a higher level of smoothness.

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References

- Zheng, J.; Jiang, M.; Qiao, L.; Sheng, J.; Li, J.; Jiang, L. Surface modification of spherical NdFeB magnetic powders by a fluid-bed nickel electrodeposition. *Mater. Lett.* **2008**, *62*, 4407–4409. [\[CrossRef\]](#)
- Bae, K.-H.; Lee, S.-R.; Kim, H.-J.; Lee, M.-W.; Jang, T.-S. Effect of WS₂/Al co-doping on microstructural and magnetic properties of Nd-Fe-B sintered magnets. *J. Alloys Compd.* **2016**, *673*, 321–326. [\[CrossRef\]](#)
- Sueptitz, R.; Uhlemann, M.; Gebert, A.; Schultz, L. Corrosion, passivation and breakdown of passivity of neodymium. *Corros. Sci.* **2010**, *52*, 886–891. [\[CrossRef\]](#)
- Chitrada, K.; Raja, K.S.; Pesic, B.; Charit, I. Corrosion Behavior of Surface Modified NdFeB Permanent Magnet in Dilute Chloride Environments. *Electrochim. Acta* **2014**, *123*, 23–32. [\[CrossRef\]](#)
- Zheng, J.; Lin, M.; Xia, Q. A preparation method and effects of Al-Cr coating on NdFeB sintered magnets. *J. Magn. Magn. Mat.* **2012**, *324*, 3966–3969. [\[CrossRef\]](#)
- Wei, Y.-K.; Li, Y.-J.; Zhang, Y.; Luo, X.-T.; Li, C.-J. Corrosion resistant nickel coating with strong adhesion on AZ31B magnesium alloy prepared by an in-situ shot-peening-assisted cold spray. *Corros. Sci.* **2018**, *138*, 105–115. [\[CrossRef\]](#)
- Sheng, J.; Jiang, L.; Zheng, J. NdFeB magnetic powders surface modification by a fluid-bed electrodeposition. *J. Mater. Sci.* **2006**, *41*, 5735–5738. [\[CrossRef\]](#)
- Wang, F.; Chen, X.P.; Qiu, P.; Wang, X.D.; Lu, W. Corrosion Resistance of Electroplating of Cu-Ni/P Coatings on NdFeB Magnet Materials. *Int. J. Electrochem. Sci.* **2020**, *15*, 10476–10487. [\[CrossRef\]](#)
- Yan, J.; Wu, Q.; Hu, X.; Jia, J.; Zhao, Y.; Zou, M.; Ge, H. The effect of Dy-Cu co-deposition and grain boundary diffusion on the microstructure and magnetic properties of sintered NdFeB magnets. *J. Magn. Magn. Mat.* **2024**, *600*, 172129. [\[CrossRef\]](#)
- Sueptitz, R.; Tschulik, K.; Uhlemann, M.; Katter, M.; Schultz, L.; Gebert, A. Effect of magnetization state on the corrosion behaviour of NdFeB permanent magnets. *Corros. Sci.* **2011**, *53*, 2843–2852. [\[CrossRef\]](#)
- Cao, R.; Zhu, L.; Liu, H.; Yang, X.; Nan, H.; Li, W. Improvement of corrosion resistance and magnetic properties for sintered NdFeB by alumina sol-containing conversion film. *RSC Adv.* **2016**, *6*, 92510–92519. [\[CrossRef\]](#)
- Wang, X.; Shen, L.; Qiu, M.; Wang, K.; Tian, Z. Effect of Friction on Preparation of NdFeB Nickel Coating by Jet Electrodeposition. *Int. J. Electrochem. Sci.* **2018**, *13*, 7706–7717. [\[CrossRef\]](#)
- Périgo, E.A.; de Campos, M.F.; Faria, R.N.; Landgraf, F.J.G. The effects of the pressing step on the microstructure and aging of NdFeB bonded magnets. *J. Powder Technol.* **2012**, *224*, 291–296. [\[CrossRef\]](#)

14. Li, C.; Zhang, H.; Guo, D.; Ren, X.; Ma, Y. An Investigation of the Magnetic Properties and Structures of Sr-Ferrite/NdFeB Hybrid Magnets with Cold Pressing and SPS Methods. *J. Electron. Mater.* **2024**, *53*, 1763–1772. [[CrossRef](#)]
15. Lu, Y.; Luo, S.; Ren, Z.; Zou, Y.; Zhong, S.; Wu, Y.; Liu, C.; Yang, M. Corrosion mechanism of Ni deposits on magnets by pulse current electro-deposition. *Surf. Coat. Technol.* **2021**, *409*, 126833. [[CrossRef](#)]

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