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Short Communication

Corrosion Behavior of the Nickel Electrode in LiCl-KCl-MgCl₂ Molten Salt in Ni-Mg Alloy formation process

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Applications of the molten salt electrodeposition method have attracted researcher's attention in the preparation of magnesium-based alloys in the past decades. Sometimes, hot corrosion occurs on the surface of a metal electrode in molten salt. Here, the corrosion of a Ni electrode and its effect on the electrochemical formation processes of Mg-Ni alloys were studied in LiCl-KCl-MgCl₂ molten salt under an Ar atmosphere. Immersion experiments and some electrochemical experiments, such as cyclic voltammetry (CV), open-circuit chronopotentiometry (OCP), and potentiostatic electrolysis, were carried out to investigate the performance of a Ni metal electrode in LiCl-KCl-MgCl₂ molten salt. Hot corrosion of the Ni electrode became serious with the addition of MgCl₂, and MgO was deposited on the surface of the Ni sheet. The CV and OCP experiments showed that the water introduced from outside had serious effects on the electrochemical reaction processes in this experiment. Corrosion of the Ni substrate was dynamically and thermodynamically inhibited in the electrochemical formation processes of Mg-Ni alloys. However, there was a small amount of MgO in the Mg-Ni alloys, and corrosion of the Ni sheet showed obvious effects on the morphology of Mg-Ni alloys

Keywords: Molten salt; Corrosion behavior; Nickel; Electrodeposition; Mg-Ni alloys

1. INTRODUCTION

Ni-based alloys and low-carbon steel are potential functional materials in molten salt systems because of their excellent corrosion resistance [1-4]. A variety of studies regarding the corrosion behaviors of Ni-based alloys and low-carbon steel have been reported, such as effects of atmospheric environments (air, Ar, Ar+O₂, Ar+H₂O, etc.), effects of alloy composition, effects of surface treatment of metal, and effects of molten salt composition [5-8]. It had been observed that the corrosion rate of alloys decreases in an atmosphere of an inert gas [1, 9]. The immersion experiment is a traditional research method for characterizing the corrosion rate and morphology changes of a metal electrode in a molten salt. Shankar found that there is a weight loss for 316L stainless steel when it is immersed in

LiCl-KCl molten salt in an Ar atmosphere [10]. Horvath used OCP and CV techniques to investigate the corrosion behavior of Ni in LiCl-KCl molten salt under an Ar/H₂O atmosphere. Electrochemistry has the advantages of fast response and high sensitivity [11]. Ding investigated the corrosion processes of Ni alloys in MgCl₂-KCl-NaCl molten salt under an atmosphere of an inert gas [12] and found that MgO formed on the surface of Ni alloys during the corrosion process. Shankar found that NiO formed on the surface of the Ni substrate in the LiCl-KCl molten salt whether or not the reaction system was protected with an inert gas [1, 5], and they found that a certain amount of Cr enhanced the corrosion resistance of Ni alloys. Wang studied the corrosion of Ni-based alloys in NaCl-MgCl₂ melt and suggested that the corrosion mechanism is a combined effect of the alloy dissolution as the anode, preferential oxidization, and chlorination [13, 14]. Liu investigated the corrosion behavior of Ni alloys in the NaCl-CaCl₂-MgCl₂ system under an atmosphere of air [15]. The Ni-rich alloy has good corrosion resistance to aggressive chloride melts, and Ni has also been used as an alloying element in the electrochemical formation of Mg, Al, Pr, Dy, and Nd in molten salt systems [16-21]. Generally, corrosion of metallic Ni shows different behaviors with changes in the molten salt and the gas in the atmosphere. The corrosion mechanism was not clear. In this work, the corrosion behavior of a Ni sheet and its effects on the electrochemical formation processes of Mg-Ni alloys were investigated using immersion experiments and the electrochemical method in LiCl-KCl-MgCl₂ molten salt under an inert atmosphere.

2. EXPERIMENTAL

2.1. Experimental chemicals and melt preparation

All reagents used in this experiment were analytical grade (Aladdin Reagent Company) and were dried in a vacuum dryer under 473 K for 24 h. Eutectic molten salts based on LiCl and KCl (mole ratio, 58.5:41.5) were mixed in a glove box that was filled with Ar gas. Different amounts of MgCl₂ were added to the mixture in a reaction container, which was a high-purity alumina crucible that was placed under an argon atmosphere. The crucible furnace was pre-heated to 473 K under an Ar atmosphere. The crucible furnace was heated to 773 K at a rate of 3 K/min when the LiCl-KCl-MgCl₂ mixture was placed in the chamber.

2.2. Immersion tests

Ni sheets (0.2 mm thick) were fully immersed in LiCl-KCl-MgCl₂ molten salt under an Ar atmosphere, and the corrosion behavior was investigated. The MgCl₂ concentration of the molten salt was controlled to be 1.0%, 5 %, 10 %, 15 %, or 30 % (wt. %). Immersion times were varied from 5 to 10 h.

2.3. Electrochemical tests

A three-electrode system was used for the electrochemical studies. Ni wires (Ø 0.5 mm) or Ni plates ($10 \times 5 \times 0.2$ mm) were used as the working electrode, which were carefully polished and cleaned

before use. A graphite rod (\emptyset 6.0 mm) and a Pt wire (\emptyset 0.5 mm) were used as the auxiliary electrode and reference electrode, respectively. CV, OCP, and potentiostatic electrolysis experiments were performed on an Im6 electrochemical workstation (Zahner Co., Ltd.). A detailed description of the testing system can be found in a previously published report [22]. The Mg-Ni alloy samples were prepared by potentiostatic electrolysis at 823 K in the LiCl-KCl-MgCl₂ molten salt. The electrolysis was changed from -1.8 V to -2.43 V. After electrolysis, the samples were washed with ethylene glycol (99.7%) to remove agglutinated salts and allowed to air dry before analysis.

2.4. Characteristics

Crystalline phases of the immersed samples, pre-electrolyzed samples, and potentiostatic electrolyzed samples were characterized using a DX-2700 X-ray diffractometer (XRD) with monochromatized Cu K radiation (k = 0.154145 nm). The morphologies of the surfaces and cross-sections of samples were examined using field-emission scanning electron microscopy (FE-SEM, JSM-7001F).

3. RESULTS AND DISCUSSION

3.1. Immersion experiments

To investigate the effects of corrosion of the Ni substrate on the electrochemical formation processes of Mg-Ni alloys, the corrosion behavior of the Ni sheet was first investigated in LiCl-KCl-MgCl₂ (1.0 wt.%) molten salt without a bias potential. Immersion time was controlled to be 5, 10, or 15 h. XRD spectra of the samples are shown in Fig. 1. There is a weak peak that corresponds to MgO in all of the Ni sheet samples after immersion in LiCl-KCl-MgCl₂ (1.0 wt.%) molten salt. There should be some water at the surface of the Ni substrate and in the LiCl-KCl-MgCl₂ (1.0 wt.%) molten salt because of the strong hygroscopicity of MgCl₂. The emergence of MgO should be attributed to the hydrolysis of MgCl₂, as described in Equation 1 and Equation 2 [12]. MgOHCl and HCl were also produced in the hydrolysis of MgCl₂. The amount of MgCl₂ is just 1.0 wt.%, and this is too low to attract much water. At the same time, the immersion experiment was carried out under an Ar atmosphere. The water content of the LiCl-KCl-MgCl₂ (1.0 wt.%) molten salt was very low, and thus, hydrolysis of MgCl₂ should be controlled by water content instead of by the immersion time. As a result, there were almost no changes in the peak intensity of MgO when the immersion time was longer. On the other hand, the Ni sheet showed a little weight loss, and the molten salt turned blue because of the dissolution of Ni (as described in Equation (3)). The formation of a small amount of MgO at the surface of the Ni sheet did not inhibit corrosion of the Ni sheet in the LiCl-KCl-MgCl₂ (1.0 wt.%) molten salt.

$$MgCl_2 + H_2O \rightarrow MgO + 2HCl$$
(1)

$$MgCl_2 \bullet H_2O \to MgOHCl + HCl$$
 (2)

$$Ni + 2HCl \rightarrow NiCl_2 + H_2$$
 (3)



Figure 1. XRD pattern of the Ni substrate after immersion in LiCl-KCl-MgCl₂ (1 wt. %) for different lengths of time.

The effects of the MgCl₂ concentration on the corrosion behavior of the Ni sheet were also investigated. The MgCl₂ concentration was controlled to be 1 %, 5 %, 10 %, 15 %, or 30 % (wt. %), and the immersion time was 10 h. The changes in MgO content at the surface of the Ni sheets is reflected by changes in the intensity of the diffraction peak of MgO. The intensity of the MgO diffraction peak increased with the addition of MgCl₂ until the MgCl₂ concentration was 10% (wt.%). Then, the intensity of the MgO diffraction peak decreased sharply with the further addition of MgCl₂. The quantity of MgO deposited on the surface of the Ni sheet should follow the same trend as that of the intensity of the MgO diffraction peak. The water content in the molten salt increases with the addition of MgCl₂, and this caused more serious hydrolysis reactions. As a result, an increasing amount of MgO was deposited on the surface of the Ni sheet with an increase in the MgCl₂ concentration. Also, the surface of the Ni substrate became because of corrosion caused by HCl, which was produced in the hydrolysis process of MgCl₂, and this was advantageous for the deposition of MgO. However, the deposited MgO layer was too thick to be firmly combined with the Ni substrate when the MgCl₂ concentration was higher than 10% (wt. %). The MgO layer would crack and peel off from the Ni substrate as a result of thermal stress and growth stress [13, 14].

Meanwhile, the deposition of MgO became difficult because of the rapid dissolution of the Ni substrate. As seen from Fig. 2, there was almost no diffraction peak corresponding to MgO when the MgCl₂ concentration was 30% (wt. %). All of the Ni sheet showed weight loss after it was immersed in the LiCl-KCl-MgCl₂ molten salt. Corrosion of the Ni sheet became serious with an increase in the MgCl₂ concentration in the molten salt. The Ni sheet completely dissolved in the molten salt when the MgCl₂ concentration was 30% (wt. %). Hydrolysis of MgCl₂ generates a higher HCl content in the molten salt, and this causes an increase in the corrosion rate. At the same time, the color of the molten salt turned blue and continued to deepen with an increase in the MgCl₂ concentration, which indicates that an increasing amount of Ni metal dissolved into the molten salt.



Figure 2. XRD pattern of the Ni substrate after immersion for 10 h in LiCl-KCl molten salt containing different amounts of MgCl₂.



Figure 3. Surface and cross-sectional morphologies of the Ni substrate after immersion for 10 h in LiCl-KCl molten salt containing different amounts of MgCl₂: (a) surface morphology, 1% (wt.%); (b) cross-sectional morphology, 1% (wt.%); (c) surface morphology, 5% (wt.%); (d) cross-sectional morphology, 5% (wt.%); (e) surface morphology, 10% (wt.%); (f) cross-sectional morphology, 10% (wt.%).

Fig. 3 shows images of the surface and cross sections of the Ni sheet after 10 h of immersion in LiCl-KCl molten salt with different amounts of MgCl₂. The amount of MgO particles continued to increase when the MgCl₂ concentration increased from 1% to 10% (wt.%). However, the MgO particles did not form a continuous film at the surface of the Ni substrate. The Ni substrate was bare even when the MgCl₂ concentration was 10% (wt.%). Thus, it can be inferred that the Ni substrate was not protected against the erosion of molten salt. The corrosion layer became thicker (increasing from 5.6 µm to 17.8 µm) with an increase in the MgCl₂ concentration from 1% to 10% (wt.%).

According to previous studies, NiCl₂ can be hydrolyzed to NiO as a result of H₂O in the molten salt [1, 9]. Horvath also investigated the corrosion of Ni in LiCl-KCl molten salt when H₂O was introduced, and it was found that the formed NiO might dissolve in molten salt [11]. The hydrolysis reaction of NiCl₂ is described in Equation 4. However, in this experiment, there is no NiO at the surface of the Ni sheet. Wang found that there was no NiO at the surface of the Ni alloys in NaCl-MgCl₂ molten salt, and they attributed this to the low oxygen partial pressure at the oxide/metal interface [13]. In this experiment, the formation of MgO blocked the oxidization of Ni because of the lower Gibbs free energy for the formation of magnesium oxide compared with that of NiO. The Gibbs free energies for the formation of MgO and NiO are shown in Tab.1.

$$NiCl_2 + H_2O \rightarrow NiO + 2HCl$$
(4)

ΔG ⁰ (KJ/mol)/T(K)	723 K	773 K	823 K	873 K
MgO	-523.6	-518.3	-513.0	-507.7
NiO	-172.9	-168.5	-164.0	-159.6

Table 1. Gibbs free energies for the formation of MgO (Equation (1)) and NiO (Equation (4))

3.2. Electrochemical experiments

Fig. 4 shows the CV curve of the Ni wire electrode in LiCl-KCl-MgCl₂ (1 wt.%) molten salt at 823K without pre-electrolysis. The initial scanning potential was set at -1.0 V to avoid the anodic dissolution of Ni metal in the molten salt. The first current peak (M) in the cathodic sweep corresponds to the reduction of Ni²⁺ ions that formed in the corrosion process of the Ni electrode. The second cathodic current peak (O) corresponds to the reduction of MgOH⁺ ions, as described in Equation (6). MgOH⁺ ions were generated in the hydrolysis processes of MgCl₂ (Equation (2)), and thus it can be inferred that the electrochemical reduction process and MgO might be generated at the surface of the Ni electrode due to the hydrolysis of MgCl₂. A cathodic limiting current (A) appeared with further scanning toward negative potential. The cathodic current A corresponds to the reduction of Mg²⁺ at the Ni wire electrode. Two small anodic current peaks appear in the anodic scan. The anodic current peak (O') might correspond to the oxidation of O²⁻ ions. O²⁻ ions can be formed in two ways: one is the reaction between H₂O and Cl⁻, as described in Equation (8), and the second is the reduction of MgO, as described in Equation (9).

The reduction of MgO was confirmed by Tan and Korenko even though MgO is an insulating material [23-25]. Korenko investigated the electro-reduction of MgO in CaF₂-NaF and MgF₂-CaF₂ molten salt [24, 25]. Tan prepared Mg-Ni alloys in CaCl₂-NaCl using a mixture of MgO and NiO as the cathode [23]. Generally, it is supposed that O^{2-} ions are generated from the reactions described in Equation (8) and Equation (9). More experiments are needed to confirm a definite source of O^{2-} .



Figure 4. Cyclic voltammogram of the Ni wire electrode in LiCl-KCl-MgCl₂ (1 wt. %) melt at a scan rate of 0.03 V s⁻¹ without pre-electrolysis.

$Ni^{2+} + 2e \rightarrow Ni$	(5)
$MgOH^{+} + e \rightarrow MgO + 1/2 H_{2}$	(6)
$Mg^{2+} + 2e \rightarrow Mg$	(7)
$H_2O + 2Cl^- \rightarrow O^{2-} + 2HCl$	(8)
$2O^{2-} \rightarrow O_2 + 4e$	(9)
$MgO + e \rightarrow Mg + O^{2-}$	(10)

Fig. 5 shows a series of CV curves which were recorded at different values of cathodic inversion potential in LiCl-KCl-MgCl₂ (1.0 wt.%) molten salt after pre-electrolysis for 10 h under -1.8 V (*vs.* Pt). The cathodic inversion potentials were controlled at: -2.33 V, -2.45 V, and -2.60 V (*vs.* Pt). There were no obvious cathodic current peaks until -2.25 V, and this indicates that the MgOH⁺ and Ni²⁺ were eliminated in the pre-electrolysis process. There were two alloy phases of MgNi₂ and Mg₂Ni at 773 K, according to the Mg-Ni binary phase diagram. The first pair of redox peaks (A/A') were obtained at a cathodic inversion potential of -2.33 V and correspond to the formation and anodic dissolution of MgNi₂ alloy. The second pair of redox peaks (B/B') appeared when the cathodic inversion potential was varied from -2.33 V to -2.45 V. B/B' corresponds to the formation and dissolution of Mg₂Ni. The last cathodic current peak corresponds to the electrodeposition of pure phase Mg. This result is obviously different from the CV curves shown in Fig. 4. There was only one cathodic limiting current (A) when the potential was more negative than -2.0 V (*vs.* Pt), and this corresponds to the formation of the MgO passivation layer at the surface of the Ni electrode.



Figure 5. CV curves of the Ni wire electrode in LiCl-KCl-MgCl₂ (1 wt. %) melt at a scan rate of 0.03 V s⁻¹ with different inversion potentials after pre-electrolysis at -1.8V (*vs.* Pt) for 6 h.



Figure 6. (a) Cross-sectional morphology and (b) XRD pattern of the sample obtained via potentiostatic electrolysis on a Ni plate at -1.8 V (*vs.* Pt) for 10 h in LiCl-KCl-MgCl₂ (1 wt.%) melt at 823 K.

Fig. 6 shows the XRD results of the Ni sheet samples after 10 h of immersion in LiCl-KCl-MgCl₂ (1.0 wt.%) molten salt under different values of pre-electrolysis potential. The pre-electrolysis potential was controlled to be -1.7 V, -1.8 V, or -1.9 V (*vs.* Pt). There is a small amount of MgO in all of the samples. The intensity of the MgO diffraction peak showed almost no changes, and this indicates that the MgO that formed at the Ni substrate was not related to the bias potential. The MgO content is generated according to Equation (1) and Equation (2), which are limited by the amount of water in the molten salt. Fig. 6 (b) shows SEM images of the surfaces of the samples that were obtained under a bias potential of -1.8 V (*vs.* Pt). The products at the surface of the Ni sheet were branch-shaped. The branch-shaped products are Ni metal that was the re-electrodeposition of dissolved Ni. No obvious weight loss was observed for the Ni sheet after the immersion experiment that was conducted under a bias potential of -1.8 V (*vs.* Pt).

Fig. 7 shows the photos of the Ni sheets and the molten salt after the immersion experiment with a bias potential or not. The sample became rough after it was immersed in molten salt without a bias

potential. The color of the molten salt turned blue because of dissolved Ni²⁺ ions (shown in Fig. 7 (a)). Meanwhile, a black film developed at the surface of the Ni substrate after 10 h of immersion in the molten salt under a bias potential of -1.8 V (*vs.* Pt), and this corresponds to re-electrodeposited Ni. There was almost no change in the color of the molten salt after the immersion of the Ni sheet under a bias potential of -1.8 V (*vs.* Pt). This phenomenon provides visual evidence that corrosion of the Ni sheet was significantly weaker under a negative bias potential.

$$Ni^{2+} + 2e \rightarrow Ni$$
 (11)



Figure 7. Photos of the Ni sheets and molten salt after the immersion experiment under different conditions: (a) before pre-electrolysis and (b) after pre-electrolysis without a bias potential and (c) after pre-electrolysis at -1.8V (*vs.* Pt) for 4 h.



Figure 8. Open-circuit potential transient curves of a Ni sheet electrode after application of an electrodeposition potential of -2.50 V for 60 s in LiCl-KCl-MgCl₂ melt (a) without pre-electrolysis and (b) for 180 s in LiCl-KCl-MgCl₂ melt after pre-electrolysis at -1.8V (*vs.* Pt) for 4 h.

For reversible and quasi-reversible processes, the electro-deposition process of metal has a corresponding anodic dissolution. Open circuit chronopotentiometry (OCP) provides information regarding anodic dissolution processes, and this can be helpful for exploring the mechanism of electrodeposited processes from molten salts. Fig. 8 (a) and (b) shows the OCP curves of the samples that were obtained with and without pre-electrolysis under -1.8 V (vs. Pt), respectively. There are four

similar potential platforms in Fig. 8 (a) and (b); these are denoted as (I), (II), (III), and (V). These plateaus characterize the dissolution processes of Mg, Mg₂Ni, MgNi₂, and Ni, respectively. The potential plateau (IV) in Fig. 8 (a) does not appear in Fig. 8 (b). This potential plateau is attributed to the oxidization of O^{2-} , and it is in accordance with the potential of the anodic current peak O' seen in Fig. 4. Thus, it can be inferred that the MgOH⁺ ions were completely eliminated in the pre-electrolysis processes.

Potentiostatic electrolysis was carried out in LiCl-KCl-MgCl₂ (1.0 wt.%) molten salt to further explore the effects of corrosion behavior on the formation of Mg-Ni alloys. The potentials for potentiostatic electrolysis were chosen on the basis of the CV and OCP results. One sample was obtained via 5 h of potentiostatic electrolysis under a potential of -2.33 V (*vs.* Pt). Another sample was obtained via 2 h of potentiostatic electrolysis under a potential of -2.43 V (*vs.* Pt). These samples were characterized using XRD and SEM after the samples were carefully cleaned. Fig. 9 shows the XRD results and an SEM image of the sample that was electrodeposited under a potential of -2.33 V (*vs.* Pt), MgNi₂ formed at the surface of the Ni sheet under a potential of -2.33 V (*vs.* Pt), and this confirms that the reduction current peak A corresponded to the formation of MgNi₂. The thickness of the MgNi₂ layer was about 16.0 μ m. The MgNi₂ film was porous and coarse, and this might be related to the dissolution and electrodeposited under a potential of -2.43 V (*vs.* Pt). The Sample electrodeposited under a potential of -2.43 V (*vs.* Pt). The Mg2Ni alloy appeared at this potential. This result demonstrates that the redox process of B/B' in Fig. 4 corresponds to the deposition and dissolution of Ni dissolution as a result of the rapid formation of Mg (as described in Equation 12).



Figure 9. (a) XRD pattern and (b) SEM images of samples obtained via potentiostatic electrolysis on a Ni plate at -2.33 V (*vs.* Pt) for 5 h from LiCl-KCl-MgCl₂ (1 wt.%) melt at 823 K.

Each of the two samples (one obtained at -2.33 V and one obtained at -2.43 V (*vs.* Pt)) showed an increase in weight. The molten salt remained colorless and translucent. The same phenomenon was observed when the concentration of MgCl₂ was increased. These results show that corrosion of the Ni sheet was dynamically inhibited by the cathodic bias potential. Garciadiaz showed that the corrosion of Ni was a fast dynamic process in MgCl₂-KCl molten salt [26]. The corrosion rate decreased with the addition of metallic Mg in the molten salt. Metallic Mg has a lower electrochemical reduction potential than Ni, and this can thermodynamically inhibit corrosion of the Ni substrate. The reaction might follow Equation 12. Generally, corrosion of the Ni substrate was dynamically and thermodynamically inhibited in the electrochemical formation processes of Mg-Ni alloys.

$$Mg + Ni^{2+} \rightarrow Ni + Mg^{2+}$$
(12)



Figure 10. (a) XRD pattern and (b) SEM images of samples obtained via potentiostatic electrolysis on a Ni plate at 2.43 V from LiCl-KCl-MgCl₂ (1 wt.%) melt at 823 K.

In addition to the Mg-Ni alloys, there was also a small amount of MgO phase in the electrolysis samples (Fig. 9 (a) and Fig. 10 (a)). Ding also observed that MgO formed at the surface of Ni alloys in MgCl₂-KCl-NaCl molten salt under an inert atmosphere [17]. A similar phenomenon has been observed when various methods (such as vacuum drying and pre-electrolysis) have been used to eliminate water and to avoid the formation of MgO. The products were cooled with N₂ gas and washed with glycol to avoid the oxidation of Mg-Ni alloys. However, MgO cannot be eliminated in Mg-Ni alloys. The formation of MgO has been attributed to trace amounts of water that are carried by the Ni working electrode. The corrosion resistance and mechanical strength of Mg-Ni alloys can be improved with the presence of a small amount of MgO. Generally, there are many chemical and electrochemical reactions in the electrodeposition process of Mg-Ni alloys in LiCl-KCl-MgCl₂ melt.

4. CONCLUSIONS

The corrosion behavior of a Ni sheet was carefully investigated in LiCl-KCl-MgCl₂ molten salt under an insert atmosphere. With extended immersion time, there were no changes in the amount of MgO when the concentration of MgCl₂ was 1.0 wt.%. MgO continuously increases and even peels off of the Ni substrate with a further increase in the MgCl₂ concentration. Meanwhile, the corrosion rate of the Ni substrate became more and more serious. The water brought by the addition of MgCl₂ is supposed to be the key factor for the formation of MgO and corrosion of the Ni substrate. Introducing MgCl₂ inhibited the formation of NiO because the Gibbs free energy of MgO is lower than that of NiO. The electrochemical deposition processes of Mg at the Ni substrate were investigated using CV, OCP, and potentiostatic electrolysis experiments. Two different Mg-Ni alloys (MgNi₂ and Mg₂Ni) were formed, and the dissolution and re-electrodeposition of Ni affected the morphology of the Mg-Ni alloys. Corrosion of the Ni substrate can be dynamically and thermodynamically inhibited in the electrochemical formation processes of Mg-Ni alloys. Controlling the water and oxygen are key factors for the electrochemical deposition of Mg-Ni alloys.

DATA AVAILABILITY STATEMENT

All data generated or analyzed during this study are included in this article.

COMPETING INTERESTS

The authors declare that they have no competing interests.

AUTHOR'S CONTRIBUTIONS

Jiaqi Sun and Yaru Peng carried out the experiment; Zeng Chen analyzed the data and finished figures in the manuscript. All authors read and approved the final manuscript.

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