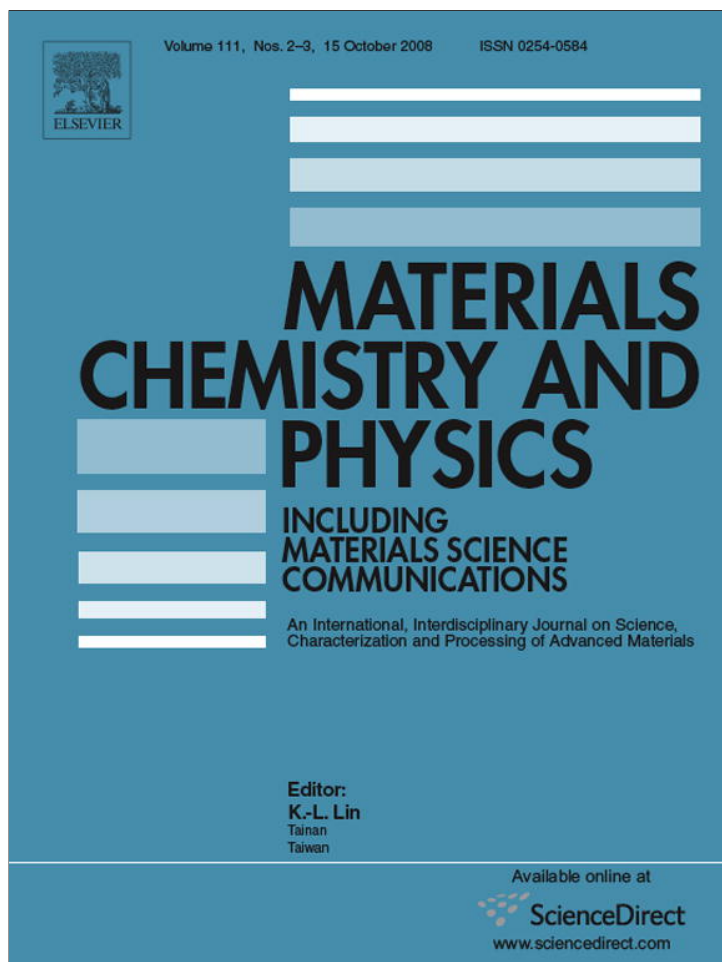




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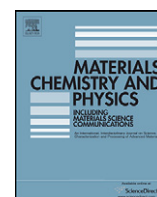
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Neodymium conversion layers formed on zinc powder for improving electrochemical properties of zinc electrodes

Liqun Zhu, Hui Zhang*, Weiping Li, Huicong Liu

School of Materials Science and Engineering, Beihang University, Beijing 100083, China

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ABSTRACT

Zinc powder, as active material of secondary alkaline zinc electrode, can greatly limit the performance of zinc electrode due to corrosion and dendritic growth of zinc resulting in great capacity-loss and short cycle life of the electrode. This work is devoted to modification study of zinc powder with neodymium conversion films coated directly onto it using ultrasonic immersion method for properties improvement of zinc electrodes. Scanning electron microscopy and other characterization techniques are applied to prove that neodymium conversion layers are distributing on the surface of modified zinc powder. The electrochemical performance of zinc electrodes made of such modified zinc powder is investigated through potentiodynamic polarization, potentiostatic polarization and cyclic voltammetry. The neodymium conversion films are found to have a significant effect on inhibition corrosion capability of zinc electrode in a beneficial way. It is also confirmed that the neodymium conversion coatings can obviously suppress dendritic growth of zinc electrode, which is attributed to the amelioration of deposition state of zinc. Moreover, the results of cyclic voltammetry reveal that surface modification of zinc powder enhances the cycle performance of the electrode mainly because the neodymium conversion films decrease the amounts of ZnO or Zn(OH)_2 dissolved in the electrolyte.

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1. Introduction

Zinc has been an attractive anode material for secondary alkaline batteries [1,2] that are widely applied in military, aeronautic, commercial and other fields because it has many advantages in low cost, electrochemical reversibility, high-specific energy, and low equilibrium potential [3–5]. However, zinc is typically corroded in alkaline solution because of more negative redox potential than hydrogen, which produces self-discharge reactions [6–8] and wastes the capacity of zinc electrodes in alkaline batteries, as



In addition, dendritic deposits of zinc [9–11] curtail cycle life of zinc electrodes owing to high solubility of zinc oxidation products in the electrolyte during the charging. These facts are receiving tremendous interests in new ways to modify zinc electrodes [12–14] and

in extensive development of electrode additives [15–18] for settling the issues of zinc electrodes.

It is well known that rare earth films prepared by simple immersion process can lead to increased corrosion protection of many metals [19,20]. Following the achievements of rare earth films, there have been attempts to modify zinc electrodes with rare earth films for enhancing the electrochemical properties of zinc electrodes [21]. Also rare earth element additives have been reported to be well used for other cell system, such as lithium-ion batteries [22]. Based on the above researches and less attention on modification of zinc powder with rare earth compounds, we have modified zinc powder in the $\text{Nd(NO}_3)_3$ solutions and investigated the effect of neodymium conversion films on electrochemical properties of zinc electrodes in the present work. In particular, the unique sonochemical modification method, which is ultrasonic immersion [23–25], is employed because ultrasound intensifies extremely intermolecular collision in the liquid–solid ($\text{Nd(NO}_3)_3$ –Zn) system and enhances considerably mass transfer in the electrochemical process. These facts are favorable to rapid formation and uniform distribution of neodymium conversion layers on zinc powder. The main aim of this study is to examine the influence of the neodymium conversion films coated in direct contact with the zinc powder by ultrasonic immersion on the electrochemical performance of zinc electrodes.

* Corresponding authors at: School of Materials Science and Engineering, Beihang University, 37# Xueyuan Road, Haidian District, Beijing, China. Tel.: +86 1082317113; fax: +86 1082317133.

E-mail address: hui1218@mse.buaa.edu.cn (H. Zhang).

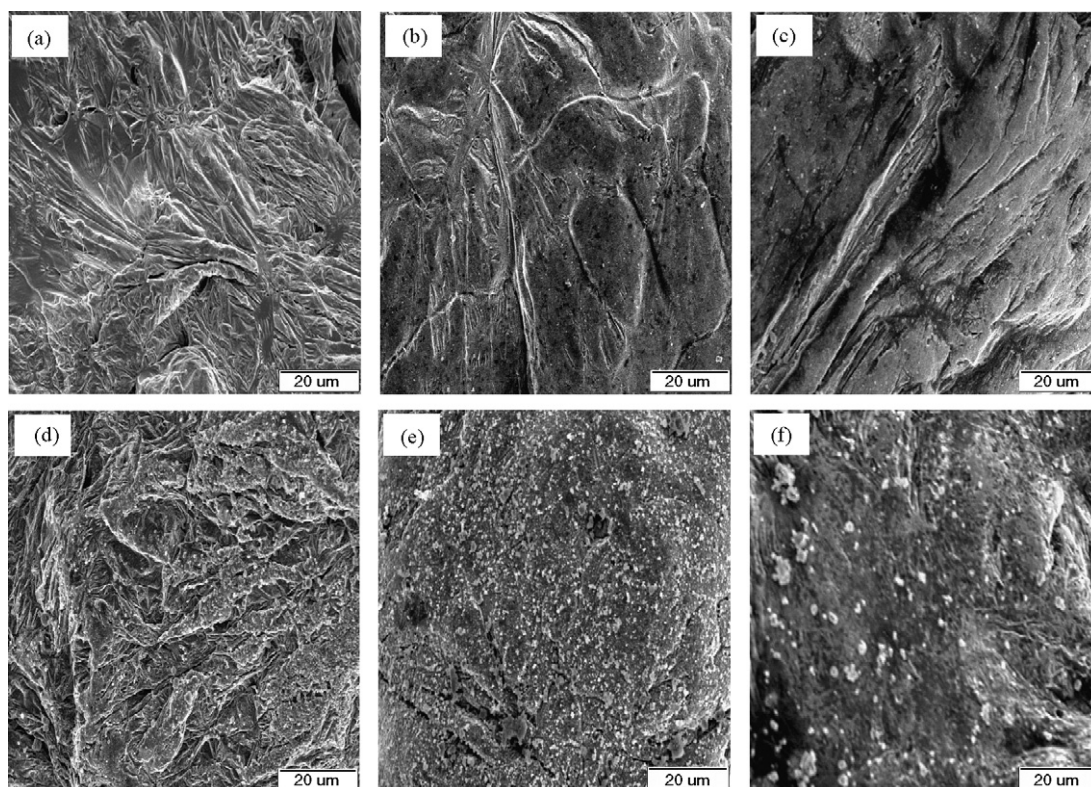


Fig. 1. SEM images of zinc powder modified by ultrasonic immersion in different concentrations of $\text{Nd}(\text{NO}_3)_3$ solutions. (a) Bare zinc powder; (b) in 0.003 mol L^{-1} $\text{Nd}(\text{NO}_3)_3$ solution; (c) in 0.015 mol L^{-1} $\text{Nd}(\text{NO}_3)_3$ solution; (d) in 0.030 mol L^{-1} $\text{Nd}(\text{NO}_3)_3$ solution; (e) in 0.045 mol L^{-1} $\text{Nd}(\text{NO}_3)_3$ solution; and (f) in 0.060 mol L^{-1} $\text{Nd}(\text{NO}_3)_3$ solution.

2. Experimental

Bare zinc powder was immersed in $\text{Nd}(\text{NO}_3)_3$ solution and stirred for 5 min at room temperature. Then an ultrasound with a constant ultrasonic frequency of 40 kHz and a constant ultrasonic power of 660 W was utilized to modify the zinc powder in $\text{Nd}(\text{NO}_3)_3$ solution for 10 min. The preparation of neodymium conversion films on modified zinc powder was completed by the following procedures which consisted of filtering out the zinc powder, rinsing repeatedly with distilled water and drying at vacuum state of 100°C . Simultaneously, the modification experiments were conducted, respectively, using the same ultrasonic immersion process by adjusting the concentration of $\text{Nd}(\text{NO}_3)_3$ solution (20 mL) with 0.003, 0.015, 0.030, 0.045 and 0.060 mol L^{-1} .

Afterwards, the morphology of bare or modified zinc powder was observed by scanning electron microscopy (SEM) with JSM-5800. The point composition of white deposits on modified zinc powder was obtained using elemental standard for Nd, O, Zn through energy dispersion spectrometry (EDS) with GENESIS 60S. The surface composition of modified zinc powder was further analyzed by Auger electron spectroscopy (AES) on a PHI 700 instrument. The AES spectra were acquired at a primary electron beam energy of 5 keV and a primary electron beam current of 10 nA. The characterization analysis of modified zinc powder was also carried out with a JEM-2100F transmission electron microscope (TEM) operating at an acceleration voltage of 200 kV. The specimen for TEM and HRTEM observations were prepared by sonicating dry modified zinc powder in ethanol and depositing one drop of the suspension onto a copper grid. The X-ray photoelectron spectroscopy (XPS, Axis Ultra analyzer) measurements were performed using Al K α radiation (1486.71 eV) generated by a X-ray tube working at 15 kV and 225 W. The Shirley method was used to subtract background and so-prepared experimental spectra were numerically fitted using the 80% Gaussian and 20% Lorentzian model.

The bare or modified zinc powder was mixed by a few drops of ethanol, electrolyte and PTFE, and they were agitated into a paste mixture. Nickel foam was used as the current collector, incorporated with the paste and thus pressed to shape a pasted zinc electrode which had an apparent area of 1 cm^2 . Then, polarization experiments were performed using a CHI 660A type of electrochemical system on a three-electrode cell which included a Hg/HgO electrode as the reference electrode, a nickel sheet as the counter electrode and a pasted zinc electrode as the working electrode. Potentiodynamic polarization recorded over the range of -1700 to -1000 mV in 6 M KOH saturated with ZnO at a constant scan rate of 0.5 mV s^{-1} . While potentiostatic polarization was carried out at the overpotential of -150 mV in 6 M KOH saturated with ZnO for 2000 s. On the side, zinc electrodes were polarized from -600 to -1800 mV versus Hg/HgO electrode using cyclic voltammetry

technique at a constant scan rate of 10 mV s^{-1} after the electrodes were kept in the electrolyte of 6 M KOH saturated with ZnO for about 10 min to reach a steady state. All the electrochemical measurements were repeated three times for the reproducible data.

3. Result and discussion

3.1. Characteristic analysis of modified zinc powder

The surface micrographs of bare zinc powder and the zinc powder modified in different concentrations of $\text{Nd}(\text{NO}_3)_3$ solutions are illustrated in Fig. 1. Based on the clean and rough surface of bare zinc powder, it is obviously noted that the modification of ultrasonic immersion results in the formation of white deposits on zinc powder. Besides, it is clearly seen from the SEM images that the white deposits are multiplied as the concentration of $\text{Nd}(\text{NO}_3)_3$ solution increases to 0.045 mol L^{-1} . Especially, the appearance of the zinc powder modified in 0.045 mol L^{-1} $\text{Nd}(\text{NO}_3)_3$ solution is provided with a large quantity and uniform distribution of white deposits. However, accumulation phenomenon of white deposits emerges on the zinc powder modified in 0.060 mol L^{-1} $\text{Nd}(\text{NO}_3)_3$ solution. It seems to be the reason that the large concentration of $\text{Nd}(\text{NO}_3)_3$ solution enhances the rate of electrochemical reactions on the surface of zinc powder from the liquid–solid system ($\text{Nd}(\text{NO}_3)_3\text{--Zn}$), and thus the white deposits generated with a great speed have no enough time to disperse. As a result, the concentration of immersed solution has important impacts on the formation and quality of white deposits.

The EDS method certifies that white deposits on modified zinc powder consist of Nd, Zn, and O elements, which reveal the presence of neodymium compounds on modified zinc powder. Nevertheless, the dark regions on modified zinc powder do not give the Nd signal from the EDS spectra. In order to determine accu-

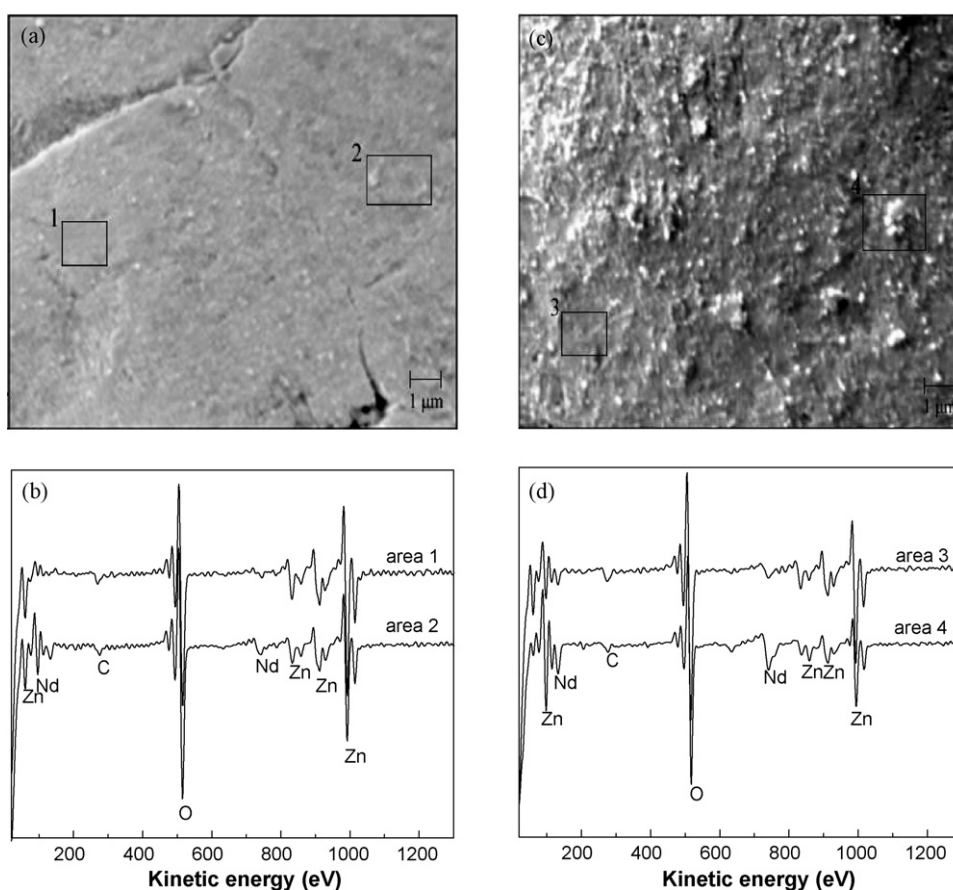


Fig. 2. (a and c) SEM images of the zinc powder modified, respectively, with 0.003 and 0.060 mol L⁻¹ Nd(NO₃)₃ solutions. (b and d) AES spectra acquired from the surface areas marked on the corresponding SEM images.

rately the surface composition and state of modified zinc powder, Fig. 2 illustrates the various small areas on the typical SEM images and the corresponding AES spectra for the zinc powder modified with 0.003 and 0.060 mol L⁻¹ Nd(NO₃)₃ solutions, respectively. The AES spectra confirm that Nd, Zn and O elements exist at every region, suggesting that neodymium conversion layers cover on the zinc powder modified with different concentrations of Nd(NO₃)₃ solutions. Simultaneously, the spectra for the zinc powder modified with 0.060 mol L⁻¹ Nd(NO₃)₃ solution (see Fig. 2(c) and (d)) exhibit the relatively stronger Nd signals than with 0.003 mol L⁻¹ Nd(NO₃)₃ solution (see Fig. 2(a) and (b)). Thus, a larger content of neodymium element on modified zinc powder can be obtained from the high concentration of Nd(NO₃)₃ solution, verifying that a greater reaction rate on the surface of zinc powder can be provided by 0.060 mol L⁻¹ Nd(NO₃)₃ solution. Moreover, fairly strong Nd peaks are detected on the area 2 and 4 containing considerable white deposits, whereas the observations of area 1 and 3 with few white deposits give relatively weak Nd signal. Combined with the above EDS analysis, it appears that the Nd-rich particles are distributed on modified zinc powder in the form of white deposits. It is, therefore, reasonable to conclude that the neodymium conversion layers generated with various concentrations of Nd(NO₃)₃ solutions comprise basal membrane and Nd-rich particles.

Fig. 3(a) reveals the typical TEM image of the zinc powder modified in 0.045 mol L⁻¹ Nd(NO₃)₃ solution, and the corresponding high-resolution micrograph (HRTEM) is represented in Fig. 3(b). The measured interplanar spacings of 3.1351 and 2.9730 Å agree with the d-spacing of the (002) plane (3.1385 Å) and the (101)

plane (3.0019 Å) according to the Joint Committee On Powder Diffraction Standards (JCPDS) card no. 83-1353 of Nd₂O₃. The interplanar spacing of 2.4524 Å is also confirmed to correspond to the (002) plane (JCPDS card no. 87-0713, 2.4735 Å) of zinc. Consequently, it can be known that the neodymium conversion films covering on modified zinc powder contain the Nd₂O₃ particles.

The XPS pattern of the neodymium conversion film on the zinc powder modified with 0.045 mol L⁻¹ Nd(NO₃)₃ solution is presented in Fig. 4(a). The emergence of a relatively small peak of C 1s is caused due to adventitious contamination. As expected, the obvious peaks of Zn, Nd, O are also found. Detailed scan in the Zn 2p_{3/2} region, as showed in Fig. 4(b), indicates the peak appears at 1021.1 eV which may be seen as an overlap of metallic Zn and ZnO peaks. Combined with Zn LMM signal analysis in the inset of Fig. 4(b), one contribution at the kinetics energy of 988.6 eV ascertains further the presence of ZnO. The Nd 3d spectrum given in Fig. 4(c) represents the 3d line is asymmetrical due to the overlap of O KLL emission lines. By peak deconvolution, the binding energies at 981.9 and 1004.4 eV correspond separately to Nd 3d_{5/2} and Nd 3d_{3/2} peaks. Simultaneously, the Nd 3d_{5/2} signal at 981.9 eV is in good agreement with reported values of 982.2 eV for the Nd3d_{5/2} peak of Nd₂O₃ [26]. Fig. 4(d) illustrates the deconvolution analysis of O 1s region, which reveals three components. The peak occurring at 530.1 eV is attributed to ZnO, while the other peaks at 530.8 and 531.6 eV are close to 530.5 eV for Nd₂O₃ and 532 eV for Nd(OH)₃ as reported elsewhere [27].

All these spectra suggest the neodymium conversion layers formed on the modified zinc powder are mainly composed of Nd₂O₃, Nd(OH)₃ and ZnO.

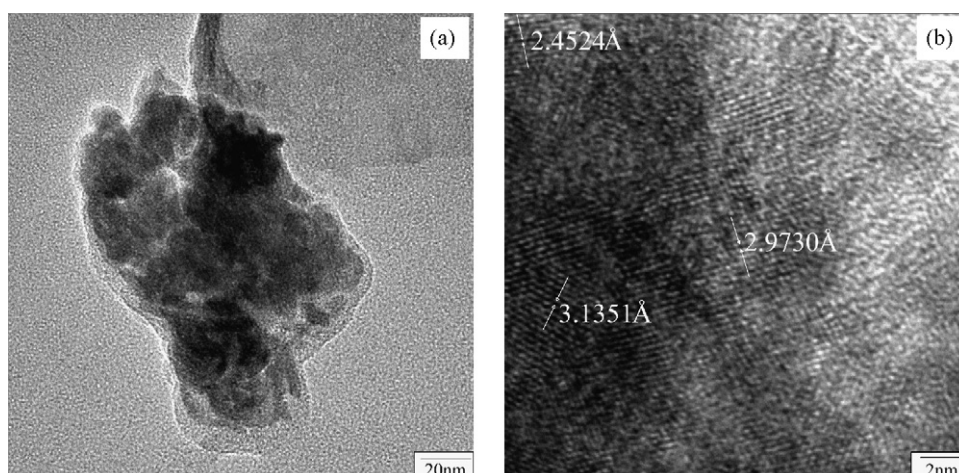


Fig. 3. (a) TEM image of modified zinc powder with $0.045 \text{ mol L}^{-1} \text{ Nd(NO}_3)_3$ solution, and (b) the corresponding HRTEM microscopy for the same sample.

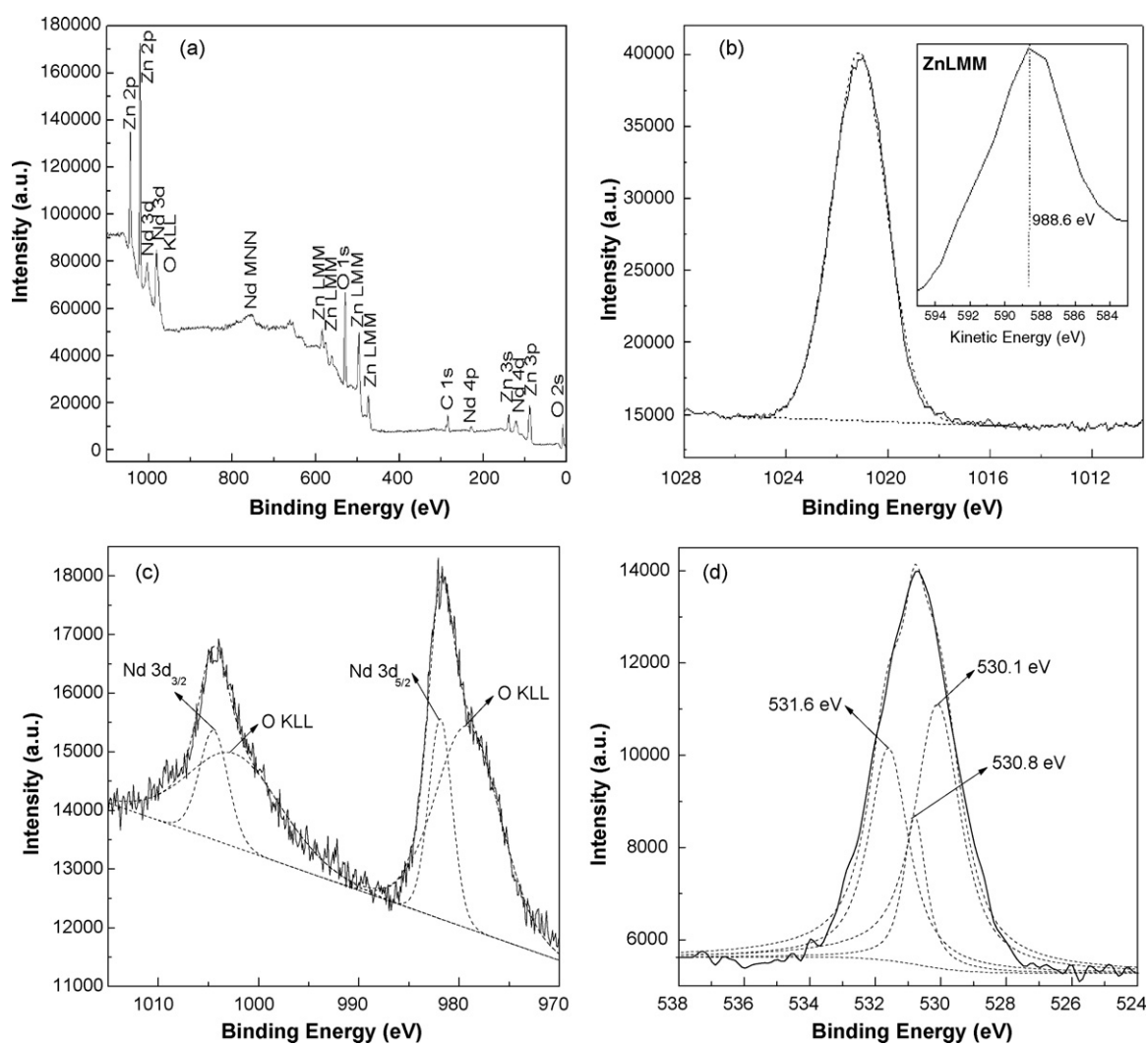


Fig. 4. XPS spectra obtained on the zinc powder modified in $0.045 \text{ mol L}^{-1} \text{ Nd(NO}_3)_3$ solution by ultrasonic immersion: (a) survey scan of the entire binding energy; (b) Zn $2p_{3/2}$ peak, and the inset exhibits the Auger spectrum of Zn LMM for the same modified sample; (c) Nd 3d region; and (d) O 1s signal. Experimental data and synthesis components are respectively shown by solid line and dashed lines.

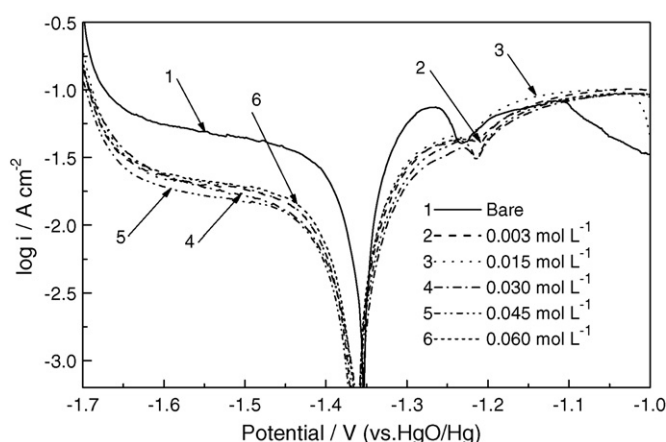
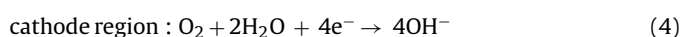
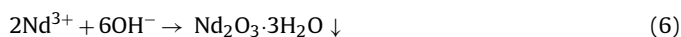


Fig. 5. Potentiodynamic polarization curves of zinc electrodes in 6 M KOH saturated with ZnO for bare zinc powder and the powder modified with different concentrations of $\text{Nd}(\text{NO}_3)_3$ solutions at a scan rate of 0.5 mV s^{-1} .

The formation of neodymium conversion films is ascribed to cathodic reaction of numerous local cells resulted from microscopic defects on the heterogeneous surface of immersed zinc powder. The relative electrochemical reactions are listed as follows:



As a result, the cathode reaction generates an alkaline environment that leads to precipitation of Nd_2O_3 and $\text{Nd}(\text{OH})_3$ on the modified zinc powder. Simultaneously, the ZnO products are incidentally generated because the Nd_2O_3 and $\text{Nd}(\text{OH})_3$ particles can preferentially grow from solubility product principle. Here are the reactions associated with the procedure,



This formation mechanism is similar with other reports that coated rare earth films on the metal electrode by simple immersion process [28–30].

It should be emphasized that ultrasound promotes the modification process because the collapse of cavitation bubbles drives high-speed jets of immersion solution to the surface of zinc powder, which is coupled with the enhancement of mass transfer rate and activation of electrochemical reactions. In addition, the growth of neodymium conversion films always begin with the defect regions of zinc powder because the surface reactions of zinc powder occur first at the high-active sites. Thus, the Nd-rich particles are easily formed on the defect sites of zinc powder due to relative rapid reactions. Therefore, it is reasonable to assume that neodymium conversion films containing Nd-rich particles can improve the electrochemical performance of zinc electrodes, because the defect sites of zinc powder are responsible for the corrosion and dendritic formation of zinc.

3.2. Effect of neodymium conversion films on the corrosion of zinc

The corrosion behavior of zinc electrodes containing bare zinc powder or the powder modified with ultrasonic immersion process in different concentrations of $\text{Nd}(\text{NO}_3)_3$ solutions is investigated by potentiodynamic polarization curves as shown in Fig. 5. The corresponding results are listed in Table 1 where corrosion potential (E_{corr}) and corrosion current density (i_{corr}) are determined by

Table 1

Corrosion studies of zinc electrodes in 6 M KOH saturated with ZnO for comparing bare zinc powder and the powder modified with different concentrations of $\text{Nd}(\text{NO}_3)_3$ solutions

Concentration of $\text{Nd}(\text{NO}_3)_3$ (mol L ⁻¹)	E_{corr} (±0.003 V)	i_{corr} (±0.66 mA cm ⁻²)	P (%)
Bare	−1.353	67.50	–
0.003	−1.362	13.83	79.5
0.015	−1.362	13.28	80.3
0.030	−1.358	12.96	80.8
0.045	−1.362	10.62	84.3
0.060	−1.361	20.16	70.1

extrapolation of the anodic and cathodic Tafel lines as well as protective efficiency (P) is obtained by an equation,

$$P = 1 - \left(\frac{i_{\text{corr}}}{i_{\text{corr}}^0} \right) \times 100\% \quad (8)$$

Here i_{corr}^0 and i_{corr} denote, respectively, corrosion current density of the electrodes with bare and modified zinc powder.

The E_{corr} value of various zinc electrodes composed of modified zinc powder has slightly shifted towards a negative direction as compared with that made of bare zinc powder, whereas the i_{corr} value has exhibited a marked reduction. All these imply that the modification of zinc powder generating neodymium conversion films can enhance the property of corrosion resistance of zinc electrode in alkaline electrolyte. In the case of the zinc powder modified in 0.045 mol L^{-1} $\text{Nd}(\text{NO}_3)_3$ solution, the polarized zinc electrode has a minimum i_{corr} value and a maximum P value which reaches 84.3%. This is possibly explained in terms of the effective formation and uniform distribution of Nd-rich particles growing in neodymium conversion films on the defect sites of zinc powder. As regards the zinc powder modified in 0.060 mol L^{-1} $\text{Nd}(\text{NO}_3)_3$ solution, the i_{corr} value rises as compared with that in 0.045 mol L^{-1} $\text{Nd}(\text{NO}_3)_3$ solution. This fact is likely relative to the non-uniform distribution of larger size of Nd-rich particles in neodymium conversion films resulting from the severe accumulation. Hence, it may be concluded that the neodymium conversion layers gained in 0.045 mol L^{-1} $\text{Nd}(\text{NO}_3)_3$ solution would be most effective in impeding the corrosion of zinc electrode.

3.3. Influence of neodymium conversion layers on the dendritic growth of zinc

The dendritic growth of zinc would increase surface area of zinc electrode, and thus the current flowing pass the electrode would gradually ascend as the polarization time extends because of constant polarization potential. Consequently, increased rate of current ($\Delta I = (I_{\text{max}} - I_{\text{min}})/I_{\text{min}}$) determined by potentiostatic polarization measurement can reflect the degree of dendritic formation. Fig. 6 gives some contrasts of the increased rate of current among bare zinc powder and the powder modified with ultrasonic immersion method in variable concentrations of $\text{Nd}(\text{NO}_3)_3$ solutions. In the initial step double layer is charged, and the current has speedily moved in a negative direction till it attains to a minimum value that is I_{min} . Subsequently, the current ascends along with the aggravation of concentration polarization, and the dendritic deposits of zinc are multiplied simultaneously. When the polarization time achieves 2000 s, the current is defined as I_{max} . Table 2 presents I_{min} , I_{max} and ΔI gained from the curves of potentiostatic polarization.

As expected, it is found that all increased rates of current for different samples of zinc powder coated with neodymium conversion films are smaller than that for bare zinc powder. This indicates that the neodymium conversion coating can suppress the dendritic growth of zinc electrode to some extent. It seems to be the reason

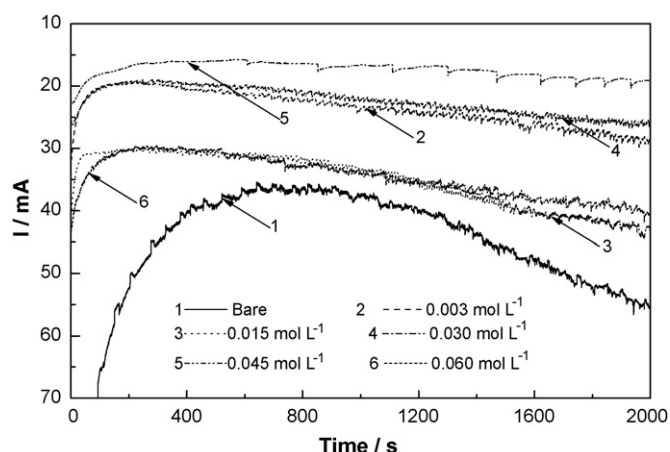


Fig. 6. Degree comparison of dendrite formation for zinc electrodes polarized in 6 M KOH saturated with ZnO at a constant overpotential of -150 mV among bare zinc powder and the powder modified by various concentrations of $\text{Nd}(\text{NO}_3)_3$ solutions.

Table 2

Parameters elicited from polarization behavior of zinc electrodes containing bare zinc powder or the powder modified by different concentrations of $\text{Nd}(\text{NO}_3)_3$ solutions at a constant overpotential of -150 mV

Concentration of $\text{Nd}(\text{NO}_3)_3$ (mol L^{-1})	$I_{\max}$ (± 1.1 mA)	$I_{\min}$ (± 0.8 mA)	$(I_{\max} - I_{\min})/I_{\min}$ (%)
Bare	55.4	35.4	56.50
0.003	28.7	19.4	47.9
0.015	43.3	30.1	43.8
0.030	26.1	19.0	37.4
0.045	19.1	15.8	20.8
0.060	39.7	29.6	34.1

that the defect sites on the surface of zinc powder are responsible for dendritic formation, as well as the Nd-rich particles form preferentially at these sites and thus they can excellently improve the deposition state of zinc during the charging. In particular, when the zinc powder is modified in 0.045 mol L^{-1} $\text{Nd}(\text{NO}_3)_3$ solution, the ΔI value that is only 20.8% has been exhibited the least one as compared with other samples. That is to say the neodymium conversion layers formed in 0.045 mol L^{-1} $\text{Nd}(\text{NO}_3)_3$ solution inhibit significantly the dendritic growth of zinc. Nevertheless, the ΔI value for zinc electrode containing the zinc powder modified in 0.060 mol L^{-1} $\text{Nd}(\text{NO}_3)_3$ solution moves up to 34.1% as compared with that in 0.045 mol L^{-1} $\text{Nd}(\text{NO}_3)_3$ solution. It is possible to discern directly that the distribution status of neodymium conversion films on modified zinc powder is greatly responsible for electrochemical performance of zinc electrode. Therefore, it is obvious from Fig. 6 and Table 2 that 0.045 mol L^{-1} $\text{Nd}(\text{NO}_3)_3$ solution is a superior process for the beneficial role of neodymium conversion coatings in dendritic inhibition of zinc electrodes once it is compared with other $\text{Nd}(\text{NO}_3)_3$ solutions.

3.4. Cycle performance of zinc electrodes

The first and twentieth cycle curves of zinc electrodes with bare zinc powder or the powder modified by means of ultrasonic immersion in 0.045 mol L^{-1} $\text{Nd}(\text{NO}_3)_3$ solution are revealed in Fig. 7. During the potentiodynamic scan starting from -600 mV, an irreversible anodic current peak has appeared around -1000 mV due possibly to re-establish oxidation product of zinc. Afterwards, a cathodic peak (C) formed in -1500 to -1800 mV is related to the reduction of accumulated $\text{ZnO}/\text{Zn}(\text{OH})_2$. It should be note that the area of cathodic peak is attributed to the amounts of $\text{ZnO}/\text{Zn}(\text{OH})_2$

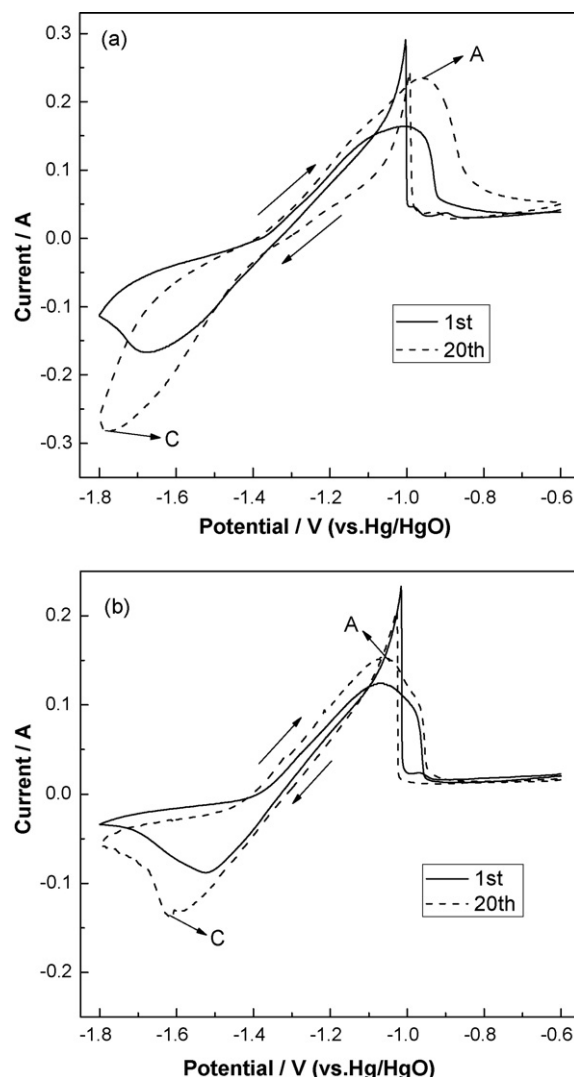


Fig. 7. Cyclic voltammograms of zinc electrodes with different zinc powder in 6 M KOH saturated with ZnO at a scan rate of 10 mV s^{-1} . (a) The 1st and 20th cycle curves of bare zinc powder; and (b) the 1st and 20th cycle curves of the zinc powder modified in 0.045 mol L^{-1} $\text{Nd}(\text{NO}_3)_3$ solution. C: cathodic peak; A: anodic peak.

that retain in the electrode surface and are not dissolved in the electrolyte [21,31]. During the back-going scan, a reversible anodic peak (A) appearing in the potential range of -950 to -1100 mV corresponds to the oxidation of Zn into $\text{ZnO}/\text{Zn}(\text{OH})_2$. Thus, the anodic and cathodic peak (A and C) and their potentials (E_A and E_C), the anodic and cathodic peak currents (i_A and i_C) obtained from the cycle curves are revealed for comparing bare zinc powder and the powder modified in 0.045 mol L^{-1} $\text{Nd}(\text{NO}_3)_3$ solution in Table 3. At the same time, the differential values between anode and cathodic peak potentials

Table 3

Data obtained from the 1st and 20th cycle behavior of zinc electrodes in 6 M KOH saturated with ZnO for bare zinc powder or the powder modified in 0.045 mol L^{-1} $\text{Nd}(\text{NO}_3)_3$ solution by ultrasonic immersion

Zinc powder	Cycle number	E_A (± 2 mV)	E_C (± 3 mV)	i_A (± 1 mA)	i_C (± 1 mA)	ΔE_P (mV)
Bare	1	-997	-1683	164	-167	686
	20	-956	-1784	235	-282	828
Modified	1	-1061	-1522	124	-88	461
	20	-1057	-1612	153	-138	555

($\Delta E_p = E_A - E_C$), which is a measure of reversibility of the electrode reaction, are also listed in Table 3.

Compared with bare zinc powder, zinc electrode with the powder modified in $0.045 \text{ mol L}^{-1} \text{ Nd}(\text{NO}_3)_3$ solution has a much larger area of cathodic peak during cycle scan. This reflects that neodymium conversion coatings formed on the modified zinc powder can effectively prevent the dissolution and diffusion of $\text{ZnO/Zn}(\text{OH})_2$ in the alkaline electrolyte. Therefore, the neodymium conversion films play a significant role in reducing capacity-loss of the electrodes and impeding dendrite growth of zinc. Furthermore, the i_A and i_C values ascend slowly as the scan number increases. This fact indicates that zinc would uniformly deposit and dissolve during the charging and discharging. Also the ΔE_p value is obviously smaller, illustrating that the reversibility of zinc electrode is greatly enhanced by the presence of neodymium conversion films on modified zinc powder. All these results lead to a smooth and even surface of the zinc electrode containing modified zinc powder after the scan terminates. Simultaneously, these facts demonstrate that zinc electrode using the zinc powder modified in $0.045 \text{ mol L}^{-1} \text{ Nd}(\text{NO}_3)_3$ solution by ultrasonic immersion is provided with outstanding reversibility, low capacity-loss and high stability because of fine growth of neodymium conversion films on the surface of zinc powder.

4. Conclusions

Neodymium conversion films containing Nd_2O_3 , $\text{Nd}(\text{OH})_3$ and ZnO are directly coated on the surface of zinc powder by means of ultrasonic immersion. The results of polarization experiments for zinc electrodes containing the zinc powder modified with different concentrations of $\text{Nd}(\text{NO}_3)_3$ solutions confirm the availability of neodymium conversion films in giving corrosion protection and suppressing dendrite growth. Especially, as far as the zinc powder modified in $0.045 \text{ mol L}^{-1} \text{ Nd}(\text{NO}_3)_3$ solution is concerned, protective efficiency of zinc electrode attains to 84.3%, indicating that the generated neodymium conversion layers have a best impact on enhancing the property of corrosion resistance of zinc electrode. Moreover, the neodymium conversion films can evidently reduce dendritic growth of zinc electrode with increased rate of current of 20.8%. The great improvements over electrochemical performance of zinc electrode may be attributed to the favorable growth and uniform distribution of Nd-rich particles existing in neodymium conversion films on the defect sites of zinc powder. Simultaneously, the neodymium conversion films obtained with $0.045 \text{ mol L}^{-1} \text{ Nd}(\text{NO}_3)_3$ solution suppress the dissolution and

diffusion of $\text{ZnO/Zn}(\text{OH})_2$, as well as improve the stability and reversibility in the alkaline electrolyte during the cycle scan.

Hence, modified zinc powder with neodymium conversion films onto it could well be used as active materials of zinc electrodes for secondary alkaline batteries.

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