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Comparative Study on the Morphology and Electrochemical Performance of Self-made and Commercial LiNi_{0.5}Mn_{1.5}O₄ Electrode

Jinjing Du^{1,2,}, Meng Zhou¹, Xingliang Zhang¹, Zhao Fang^{1,2}, Bin Wang¹, Qian Li¹, Yuehao Guo¹, Zhuoqi Liu¹*

¹ School of Metallurgy Engineering, Xi'an University of Architecture and Technology
² Research Center of Metallurgical Engineering and Technology of Shaanxi, Xi'an 710055, China
*E-mail: <u>djzxauat@gmail.com</u>

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The LiNi_{0.5}Mn_{1.5}O₄ high voltage cathode for lithium ion batteries is prepared via simple coprecipitation method. The effect of the precipitation temperature, pH, and calcination temperature on the phase transformation, microstructure and electrochemical performance was investigated. On this basis, a comparative study on the morphology and electrochemical properties of the prepared and commercial LiNi_{0.5}Mn_{1.5}O₄ cathodes was also conducted. The results indicate that the high-purity precursor was obtained with preparation pH and temperature is 11.5 and 50 °C, and then was mixed and ground with LiOH thoroughly, and then the mixture was calcined at 800 °C for 15 hours to obtain LiNi_{0.5}Mn_{1.5}O₄ material, which demonstrated superior performance. Both the commercial and selfmade lithium nickel manganate cathode materials present typical spinel structure. Obvious particle agglomeration for poor dispersion could be observed in the commercial lithium nickel-manganate cathode material. The particles are dispersed uniformly, but some large-sized particles appeared in prepared cathode material. The initial discharge capacity is about 128.2 mAh/g at a rate of 1 C. After 100 cycles, the capacity retention of the prepared lithium nickel-manganate cathode material is 93.8%, while a lower capacity retention of 92.5% for the commercial cathode material.

Keywords: Lithium-ion batteries; Spinel LiNi_{0.5}Mn_{1.5}O₄; Cathode; Electrochemical performance

1. INTRODUCTION

Lithium-ion batteries (LIBs) have attracted much attention for applications in electric vehicles, hybrid electric vehicles and large-scale energy storage systems (ESSs). To meet the demand for these applications, cathode materials with high voltage and capacity along with environmental friendliness are highly required, which play an important role in the electrochemical performance of lithium ion battery [1-4].

The spinel lithium manganese oxide (LiMn₂O₄) as a promising cathode material for LIBs has been paid much attention due to its low cost and abundant manganese resources. Although LiMn₂O₄ cathode with a voltage platform of 4V, the poor cycle performance of LiMn₂O₄ will be caused by the John Taylor distortion and the dissolution of Mn³⁺ [5-6], which will result in the restrictions on the EV application. It is found that substitution of partial manganese ion in spinel LiMn₂O₄ by other metallic ions, such as Zn, Ni, Mg, Al, Si, Ti, is conducive to the stabilization of the LiMn₂O₄ spinel structure [7-13]. Among these doping materials, Ni-doped LiNi_{0.5}Mn_{1.5}O₄ with its high theoretical capacity of 146.7 mAh/g has drawn much attention due to its high operating voltage (~4.7 V), the high intrinsic rate capability offered by the 3D lithium ion diffusion in the spinel lattice and considerable structural stability [14-18]. Therefore, LiNi_{0.5}Mn_{1.5}O₄ can be applied as high-voltage cathode material for highperformance lithium ion batteries.

The effect of influence factors during the preparation process on the phase transformation, microstructure and electrochemical performance is investigated here. To figure out the difference in the morphology and electrochemical performance of self-made and commercial $LiNi_{0.5}Mn_{1.5}O_4$ cathodes, an in-depth comparative research will be conducted in this paper.

2. EXPERIMENTAL

2.1 Preparation

The powders of NiSO₄·6H₂O and MnSO₄·H₂O (industrial grade) with a molar ratio of 1:3 were dissolved in 100 ml distilled water to form solution A with metal ion concentration ratio of 0.25mol/L. Solution A was transferred to a four-necked flask for thermostatic stirring. Meanwhile, 50ml NH₃·H₂O (0.376mol/L) was slowly dripped into the four-necked flask. Besides, 0.5mol/L NaOH solution was adopted to adjust the pH of the mixed liquids. After constant stirring for 12h, the mixed solution was cooled down to room temperature and then filtration operation was conducted. The obtained (Ni_{0.5}Mn_{1.5})(OH)₄ precursor was washed several times with deionized water and dehydrated alcohol, then dried at 80°C for 10h. The obtained precursor and stoichiometric amounts of LiOH·H₂O (excess 5%) was mixed thoroughly and then placed in a vacuum tube furnace. The mixed powder was heated at 480 °C for 15 h, and finally cooled inside the furnace to the ambient temperature, yielding the LiNi_{0.5}Mn_{1.5}O₄ (LNMO) powder. Additionally, analytical grade LiNi_{0.5}Mn_{1.5}O₄ was purchased from Guangdong Candlelight New Energy Technology Co., Ltd.

2.2 Cathode preparation and battery assembly

 $LiNi_{0.5}Mn_{1.5}O_4$, polyvinylidene fluoride (PVDF) and acetylene black conductor were mixed at a mass ratio of 8:1:1. Then appropriate amount of N-methylpyrrolidone (NMP) was adopted to the mixture for preparation of the cathode slurry. The slurry was coated on aluminum foil and dried at 55°C for 12 h in electricity heat drum wind drying oven. It was fabricated into a cathode disc with a diameter of 14mm. And the cathode disc was placed in an argon-protected glove box. The cathode is metal lithium (Φ 16mm×0.3mm), the separator is Celgard 2400 microporous polypropylene membrane, and the electrolyte is traditional LiPF₆.

2.3 Materials characterization and electrochemical measurements

The phase composition of precursor, the self-prepared and commercial $\text{LiNi}_{0.5}\text{Mn}_{1.5}\text{O}_4$ powder products was analyzed by X-ray diffractometer (Bruker D8) with Cu K α radiation, pip voltage 40 kV and current 100 mA. The morphology of LNMO was observed with scanning electron microscope (Gemini SEM 300). Elemental distribution of the products was determined by energy dispersive spectroscopy (EDS). The constant current charge and discharge, and rate performance of batteries was tested by LAND-CT2001A battery test system at room temperature.

3. RESULTS AND DISCUSSION

3.1 Phase composition and micro-morphology

The influence of precipitation temperature and pH on the composition and morphology of precursor materials was investigated here. The XRD patterns of the precursor materials prepared with different conditions, are shown in Fig. 1. It can be seen that the characteristic diffraction peaks of the precipitate quite match with that of Mn₃O₄, along with a small quantity of MnO(OH)₂ and MnO₂. It indicated that no pure complex hydroxide was synthesized, partial manganese element has been oxidized to generate manganese tetroxide. Besides, it is found that it is still difficult to obtain highly pure manganese hydroxide precipitation in a completely sealed reactor with shielding gas. Taken together, when the value of precipitation temperature and pH was selected as 50°C and 11.5, more pure precursor material can be obtained.



Figure 1. XRD patterns of the precursor prepared with coprecipitation process (a) pH; (b) temperature

It can be seen from Fig. 2 (a) that the primary particle agglomeration of the (Ni_{0.5}Mn_{1.5})(OH)₄ precursor with PH range of 9.5~11.5 is very obvious. The particle size is not uniform and presents an irregular shape, which may be due to the characteristics of coprecipitation method [19]. With increasing the value of pH, the precursor particle is denser with smooth surface and the packing density is also increased. It maybe because higher pH is beneficial to the formation of precipitation nucleation here. With pH=11.5, it can be found that uneven particle distribution and agglomeration still exist. As increasing precipitation temperature, the bulk density of the precursor increased, which can be seen from Fig. 2 (b). The appearance of expected spherical precursor particles was not be observed, technological parameter should be optimized to obtain micro-nano sized spherical particles in the subsequent study.



Figure 2. SEM images of the obtained precursor with different (a) pH, a1 = 9.5, a2 =10.5, a3 =11.5; (b) precipitation temperatures, b1 = 30°C, b2 = 50°C, b3 = 70°C

The influence of pH and precipitation temperature on the composition and morphology of the prepared LiNi_{0.5}Mn_{1.5}O₄ was also studied. The XRD patterns of self-made LiNi_{0.5}Mn_{1.5}O₄ with different pH, are shown in Fig. 3. At about 38°, 44°/2θ, the appearance of impurities can be observed [20]. When pH is 9.5, the diffraction peaks of Li_xNi_{1-x}O and LiNi_{0.5-y}Mn_{1.5+y}O₄ impurity phases can be detected obviously. The existence of the two impurities will reduce the purity of the LiNi_{0.5}Mn_{1.5}O₄ cathode, which will also attenuate the electrochemical performance [21]. With pH value of 11.5, the peaks are well-defined LiNi_{0.5}Mn_{1.5}O₄ with typical spinel structure, no obvious impurities was observed. It is indicated that the prepared LiNi_{0.5}Mn_{1.5}O₄ material with pH 11.5 has better crystallinity and more ordered lattice arrangement.



Figure 3. XRD patterns of the prepared LiNi_{0.5}Mn_{1.5}O₄ with different precipitation pH



Figure 4. XRD patterns of the prepared LiNi_{0.5}Mn_{1.5}O₄ with different precipitation temperatures

The diffraction peaks of $LiNi_{0.5}Mn_{1.5}O_4$ materials prepared with different precipitation temperatures are sharp (as shown in Fig. 4), and the characteristic peaks of spinel structure can be observed, indicating that the material has high crystallinity. The diffraction peak intensity of the synthesized materials at different temperatures is slightly different. The $LiNi_{0.5}Mn_{1.5}O_4$ cathode material prepared by the precursor synthesized at T=50 °C has the highest diffraction peak intensity

and no obvious heterogeneous diffraction peak. It is indicated that the impurity phase in the precursor does not affect the synthesis of LiNi_{0.5}Mn_{1.5}O₄ material. At T=30 °C, obvious heterogeneous Li_xNiO_{1-x} and LiNi_{0.5-y}Mn_{1.5+y}O₄ heterophases were observed. And at T=70 °C, Li_xNiO_{1-x} is the main impurity. It can be seen that Li_xNiO_{1-x} is the major impurity, which is often generated by oxygen loss when calcination temperature is above 650°C [22].

Besides, the influence of sintering temperature on the morphology of the $LiNi_{0.5}Mn_{1.5}O_4$ cathode material was also investigated. SEM images of the $LiNi_{0.5}Mn_{1.5}O_4$ cathode material prepared under different sintering temperatures are shown in Fig. 5.



Figure 5. SEM images of the LiNi_{0.5}Mn_{1.5}O₄ cathode material prepared under different calcination temperatures (a)- 800°C; (b) - 850°C; (c) - 900°C

It can be seen from Fig. 5 that a similar morphology with spinel-type octahedral structure of the lithium nickel manganate cathode materials prepared at 800 °C and 850 °C can be observed separately. The crystal morphology of the LiNi_{0.5}Mn_{1.5}O₄ material is very complete and the grain boundary among the particles is very obvious. It is illustrated that the precursor reacts very well with the lithium source at 800 °C and 850 °C, and the LiNi_{0.5}Mn_{1.5}O₄ cathode material has a wide sintering temperature range. Besides, it is interesting to note that the particles have good dispersion and the surface of the particles sintered under 800°C is very smooth without small debris. The morphology of prepared LiNi_{0.5}Mn_{1.5}O₄ cathode material here is similar to that prepared with sol-gel method, but the corresponding precursor

presents quite different morphology, especially grain size[23], and micro-sized precursor is our further work target.

However, the LiNi_{0.5}Mn_{1.5}O₄ cathode materials prepared at 900 °C have completely lost their spinel structure. And the particle surface is relatively rough. It is indicated that the crystal structure of LiNi_{0.5}Mn_{1.5}O₄ cathode materials has transferred from spinel structure to irregular polyhedron shape with little clastic particles at 900 °C [24].

It may be because lithium nickel manganese oxide is decomposed under high temperature conditions, and small debris on the surface of the particles is likely to be a partial decomposition product, which leads to the irregular polyhedron morphology. Another possibility is that lithium nickel-manganate produces anoxic compounds at high temperature, which causes the material to undergo secondary crystallization, resulting in larger-sized grain [25].

It can be seen from Fig. 6 that both the commercial and self-made lithium nickel manganate cathode materials present typical spinel structure. The commercial lithium nickel-manganate cathode material has obvious agglomeration phenomenon for poor particle dispersion with relatively larger grains. While no similar agglomeration occurred in the self-made lithium nickel manganate cathode material. The particles are dispersed uniformly, but less large-sized particles appeared in the matrix, which may be caused by the too tight compaction between the precursor powder and the lithium source. It will result in temperature gradient in the mixture during calcination process. The reaction forms spinel crystals on the surface firstly, along with the appearance of larger lithium nickel manganate particles in the product [26].



Figure 6. SEM images of (a) the commercial and (b) self-made LiNi_{0.5}Mn_{1.5}O₄ cathode material

3.2 Electrochemical performance

The effect of precipitation temperature, pH, and calcination temperature on the electrochemical performance of self-made LiNi_{0.5}Mn_{1.5}O₄ cathode material was also studied here.



Figure 7. The electrochemical performance curves of LiNi_{0.5}Mn_{1.5}O₄ cathode material prepared with precipitation PH of 9.5, 10.5, 11.5. (a) the rate performance; (b) the initial charge-discharge curves; (c) the cycling performance curves

Comparative experiments of electrochemical performance for the commercial and self-made LiNi_{0.5}Mn_{1.5}O₄ cathode material were conducted.

The rate performances are shown in Fig. 7a. The discharge capacity remains relatively stable at 0.1 C, 0.5 C, 1 C. When the current densities are improved to 2 C, 5C and 10 C, the discharge capacities decay rapidly. It is found that when pH value is adjusted to 11.5, the discharge capacity of 121.02 mAh/g, 121.24 mAh/g, 116.48 mAh/g, 95.7 mAh/g, 40.76 mAh/g and 6.72 mAh/g can be obtained, respectively. When the current density suddenly returns from 10 C to 0.5 C, the discharge capacity of 125.98 mAh/g is slightly higher than the original capacity, which is probably due to the lithium ion consumption caused by the formation of CEI film on the surface of the cathode material and the capacity loss caused by the reaction between the lithium hexafororide phosphate electrolyte and the active substance during the initial charge-discharge process. With the cycle progress, the specific capacity of the material increased after activation, indicating that the material synthesized by co-precipitation with pH=11.5 showed better performance of magnification and strong resistance to large-ratio charge and discharge. Fig. 7b presents the initial charge-discharge curves of the LiNi_{0.5}Mn_{1.5}O₄ cathode material prepared with coprecipitation method. When pH value is 9.5, 10.5, 11.5, the initial discharge capacity is 102.4 mAh/g, 115.8 mAh/g and 120.0 mAh/g, respectively. For the three tested samples, the appearance of the voltage platform at about 4.7V corresponding to the redox reaction of Ni²⁺/Ni⁴⁺ and another voltage platform at about 4.0V corresponding to the redox reaction of Mn³⁺/Mn⁴⁺ can be observed in the charging-discharging cycles. It is indicated that a certain amount of Mn³⁺ existed in the prepared cathode materials, and the initial charge-discharge curve is

consistent with the discharge curve characteristics of spinel-type lithium nickel manganese oxide. The cycle performance of the three products at a rate of 1 C at room temperature is shown in Fig. 7c. As can be seen in Fig. 7c, the initial specific capacities of the cathode materials prepared with pH of 9.5, 10.5 and 11.5 are 102.4, 115.8 and 120.0 mAh/g at 1 C, respectively. And the capacity retentions are up to 95.7% \sim 79.8% and 98.6% after 100 cycles, respectively. It is illustrated a better cycle performance of the lithium nickel manganese oxide cathode material with the precursor prepared with precipitation pH of 11.5, can be obtained, which is contributed to the higher purity [27].



Figure 8. The electrochemical performance curves of LiNi_{0.5}Mn_{1.5}O₄ cathode material prepared with precipitation temperature of 30°C, 50°C, 70°C: (a) the rate performance; (b) the initial charge-discharge curves; (c) the cycling performance curves

When precipitation temperature of 50°C is selected to prepare lithium nickel-manganate precursor, a better rate performance of the subsequent cathode material can be obtained (Fig. 8a). The initial discharge capacity is about 118.7 mAh/g at a rate of 0.1 C, which is quite different from that of the spherical LiNi0.5Mn1.5O4 synthesized by coprecipitation [28]. The first charging specific capacity of the spherical LiNi0.5Mn1.5O4 is higher than theoretical capacity. Similarly, the discharge capacities decay rapidly with increasing current densities. When the current density suddenly returns from 5 C to 0.5 C, the discharge capacity is 139.1 mAh/g, which is slightly higher than the original capacity. The presumable reason is aging time is too short to obtain enough battery activation with

lower current densities. And after multiple high-rate charge and discharge, the battery operating state is adequately activated, thereby excellent electrochemical performance could be exhibited.

Besides, the voltage platform at about 4.7V is very stable (Fig. 8b), and another voltage platform at about 4.0V corresponding to the redox reaction of Mn³⁺/Mn⁴⁺ is not obvious. It is indicated that less Mn³⁺ existed in the prepared lithium nickel manganate cathode material, and subsequent Mn³⁺ dissolution and Jahn-Teller effect have little influence on battery performance [29]. Through comparative analysis on cycle performance (Fig. 8c), it is found that a higher initial discharge capacity of 136.7 mAh/g can be obtained with precipitation temperature of 50°C. And the capacity retention is up to 93.8% after 100 cycles at room temperature. Besides, the influence of calcination temperature on the electrochemical performance was also researched here. And the results are shown in Fig. 9.



Figure 9. The electrochemical performance curves of LiNi_{0.5}Mn_{1.5}O₄ cathode material prepared with sintering temperature of 800°C, 850°C, 900°C: (a) the rate performance; (b) the initial charge-discharge curves; (c) the cycling performance curves

It can be seen from Fig. 9(a) that the discharge capacity at 0.1 C, 0.5 C, 1 C for the $LiNi_{0.5}Mn_{1.5}O_4$ cathode material calcined under 800°C is 118.2 mAh/g, 127.1 mAh/g, 117.5 mAh/g, which is higher than that of 105.7 mAh/g, 114.4 mAh/g, 107.2 mAh/g for the cathode material calcined under 850°C. It also can be found that the cathode material calcined under 900°C performed worst, and the discharge capacity of ~ 51.3 mAh/g at 0.5 C, which is about 40.4% of that sintered under 800 °C and 44.8% of that sintered under 850°C. It can also be seen that although the specific discharge capacity of the electrode material sintered at 800 °C is higher than that of the electrode

materials sintered at 850 °C with low rate, the electrode material sintered at 850 °C shows excellent performance as the current density increases. The discharge specific capacity under charge and discharge condition at 5 C is 1.73 times that of 800 °C. The first discharge curves with different calcination temperatures exhibit the discharge curve characteristics of high-voltage spinel LiNi0.5Mn1.5O4 cathode materials, which can be seen from Fig. 9(b). It can be observed from the curve that high similarity exists in the charge and discharge curves of materials sintered at 800 °C and 850 °C. And the first discharge specific capacities are very close, 113.6 mAh/g vs. 111.9 mAh/g. While the materials sintered at 900 °C almost have no 4.7 V discharge platform, the voltage attenuation is very serious, and the first discharge specific capacity is only 42.6 mAh/g. It may be due to the high calcination temperature, resulting in the inactivation of lithium nickel manganate material [30]. The cycle performance curves of the lithium nickel manganate cathode materials prepared at three different calcination temperatures for 100 cycles at 1 C ratio were shown in Fig. 9c. It can be seen that the materials calcined under 900 °C have the worst cycling performance, and the highest discharge specific capacity is 42.6 mAh/g, which is only 28.9% of the theoretical discharge capacity. It may be due to the possible decomposition or generation of anoxic forms at high temperature, resulting in the electrode material inactive. The cycling performance of materials sintered at 800 °C and 850 °C is similar. The first discharge specific capacities at 1 C rate are 109.8 mAh/g and 109.5 mAh/g, respectively. After 100 cycles, the specific discharge capacities are 100.8 mAh/g and 98.1mAh/g, respectively. And the corresponding cycle retention rate is 91.8% and 89.6%.

Therefore, the LiNi_{0.5}Mn_{1.5}O₄ electrode materials sintered at 800 °C and 850 °C have no significant difference in specific capacity of 100 cycles at normal temperature with a rate of 1 C. However, the LiNi_{0.5}Mn_{1.5}O₄ electrode materials sintered at 850 °C showed a better resistance to overshoot and over-discharge. The specific discharge capacity at high rates of 2 C and 5 C is higher than that of lithium nickel manganate materials sintered at 800 °C with good cycling performance. It is indicated that properly increasing calcination temperature will not destroy the crystal structure of the material, but also improve the cycling performance of the lithium nickel manganate material at high rates. Based on this, the comparative study on the electrochemical performance of the prepared and the commercial lithium nickel manganate material was also conducted.





Figure 10. The electrochemical performance curves of commercial and prepared LiNi_{0.5}Mn_{1.5}O₄ cathode material: (a) the cycling performance curves; (b) the rate performance

As can be seen from Fig. 10(a), the first discharge specific capacity of self-made lithium nickel-manganate cathode material is 136.7mAh/g at a rate of 1 C. After 100 cycles, the specific discharge capacity is 128.2 mAh / g and the capacity retention rate is 93.8%. However, the first discharge specific capacity of the commercial lithium nickel-manganate cathode material is 132.3 mAh/g at the same rate. After 100 cycles, the discharge specific capacity is 122.4 mAh/g, and the capacity retention rate is 92.5%. It can be seen that the specific discharge capacity of the self-made lithium nickel manganate cathode material is superior to that of the commercial cathode materials. Fig. 10(b) shows the cycle performance curves of the prepared and commercial lithium nickel manganate cathode materials at different rates. It can be seen that the first discharge specific capacities of prepared lithium nickel-manganate cathode materials at 0.1C, 0.5C, 1c, 2C and 5Cwere 124.0, 117.6, 76.4, 24.3 and 2.5mAh/g, respectively. While under the same rate condition, the first discharge specific capacities are 120.3, 108.1, 95.2, 55.9 and 3 mAh/g for the commercial cathode materials, respectively. When the high-rate test is restored to 0.5 C, the discharge capacity of the prepared lithium nickel manganate cathode material can still be restored to the initial level, of ~119.2 mAh/g, but only 111.4 mAh / g for the commercial matrial. It can be seen that the self-made lithium nickel manganate cathode material has a higher discharge specific capacity than that of the commercial material at room temperature with low current density. But it is interesting to note that the commercial lithium nickel manganate cathode material can still exhibit superior discharge specific capacity at high rates. It is known from Fig.6 that the particle size of the self-made lithium nickel manganate material is significantly smaller than that of the commercial cathode material, and the particle size distribution is more uniform. It will enhance the specific surface and allow the electrolyte to fully contact and wet the active particles of the positive electrode material, which can expand the tunnels for Li-ions diffusion. So the self-made lithium nickel manganate material has significantly higher cycling performance than the commercial material. Additionally, with increasing circle ratio, the discharge current density also increases gradually. Due to the smaller particles of the self-made lithium nickel manganate material, lithium ions cannot migrate to the inside of the cathode material. It will result in a higher degree of delithiation and polarization phenomenon. As the lithium ion concentration on the upper surface decreases, the internal stress of the

prepared cathode material particles gradually accumulates, which eventually leads to particle breakage and deformation of material crystal structure. And the three-dimensional diffusion channels for the lithium ions could be blocked or collapsed, resulting in a rapid capacity attenuation of the prepared lithium nickel manganate material.

4. CONCLUSIONS

The lithium nickel-manganate cathode material for lithium ion batteries is prepared with simple co-precipitation method. The influence of affecting factors, such as precipitation temperature, pH, and calcination temperature, on the phase transformation, microstructure and electrochemical performance was investigated. Besides, a comparative study on the morphology and electrochemical properties of the prepared and commercial LiNi_{0.5}Mn_{1.5}O₄ cathodes was also conducted. It is found that the high-purity precursor was obtained with preparation pH of 11.5 and temperature of 50 °C. Then the high-purity precursor was mixed and ground with LiOH thoroughly, and then was calcined at 800 °C for 15 hours to prepare LiNi_{0.5}Mn_{1.5}O₄ material, which demonstrated superior performance. Both the commercial and self-made lithium nickel manganate cathode materials present typical spinel structure. Obvious agglomeration phenomenon for poor dispersion among particles could be observed in the purchased lithium nickel-manganate cathode material. But for the prepared cathode material, the particles are dispersed uniformly, but some large-sized particles could be observed. The initial discharge capacity is about 128.2 mAh/g at a rate of 1 C. After 100 cycles, the capacity retention of the prepared lithium nickel-manganate cathode material is 93.8%, while a lower capacity retention of 92.5% for the commercial cathode material.

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References

- 1. S. P. Feng, X. Kong, H. Y. Sun, B. S. Wang, T. B. Luo, and G. Y. Liu, *J. Alloy. Compd.*, 749 (2018) 1009.
- Y. L. Liu, J. Lia, M. Zeng, Y. J. Huang, X. Xu, M. Yan, J. Q. Guo, J. N. Deng, and J. Z. Yang, *Ceram. Int.*, 44 (2018) 20043.
- 3. A. M. Wang, and N. Bai, Solid State Ionics, 336 (2019) 19.
- 4. M. Bini, P. Boni, P. Mustarelli, I. Quinzeni, G. Bruni, and D. Capsoni, *Solid State Ionics*, 320 (2018) 1.
- 5. X. L. Ren, Y. R. Wang, Q. Z. Xiao, G. T. Lei, and Z. H. Li, Mater. Lett., 248 (2019) 97.
- 6. P. F. Zhang, H. Q. Fan, Y. F. Fu, Z. Li, and Y. L. Deng, Rare Metals, 25 (2006) 100.
- H. Y. Zhao, F. Li, X. H. Shu, J. T. Liu, T. T. Wu, Z. K. Wang, Y. F. Li, and J. X. Su, *Ceram. Int.*, 44 (2018) 20575.

- 8. W. Q. Xu, Q. L. Li, J. M. Guo, H. L. Bai, C. W. Su, R. S. Ruan, and J. H. Peng, *Ceram. Int.*, 5 (2016) 5693.
- H. M. Wu, J. P. Tu, X. T. Chen, Y. Li, X. B. Zhao, and G. S. Cao, J. Solid State Electr., 11 (2005) 173.
- 10. J. J. Huang, F. L. Yang, Y. J. Guo, C. C. Peng, H. L. Bai, J. H. Peng, and J. M. Guo, *Ceram. Int.*, 41 (2015) 9662.
- 11. D.L. Guo, B. Li, Z. R. Chang, H. W. Tang, X. H. Xu, K. Chang, E. B. Shangguan, X. Z. Yuan, and H. J. Wang, *Electrochim. Acta*, 134 (2014) 338.
- 12. H. Zhao, S. Liu, Z. Wang, Y. Cai, M. Tan, and X. Liu, Ceram. Int., 42 (2016) 13442.
- 13. L. L. Xiong, Y. L. Xu, C. Zhang, Z. W. Zhang, and J. B. Li, J. Solid State Electr., 15 (2010) 1263.
- 14. J. Liu, A. Huq, Z. Moorhead-Rosenberg, A. Manthiram, and K. Page, *Chem. Mater.*, 28 (2016) 6817.
- 15. H. Duncan, D. Duguay, Y. Abu-Lebdeh, and I. J. Davidson, J. Electrochem. Soc., 158 (2011) A537.
- 16. T. Kozawa, J. Power Sources, 419 (2019) 52.
- 17. A. Manthiram, K. Chemelewski, E. S. Lee, Energ. Environ. Sci., 7 (2014) 1339.
- 18. M. X. Lin, L. B. Ben, Y. Sun, H. Wang, Z. Z. Yang, L. Gu, X. Q. Yu, X. Q. Yang, H. F. Zhao, R. C. Yu, M. Armand, and X. J. Huang, *Chem. Mater.*, 27 (2015) 292.
- 19. Z. R. Chang, D. M. Dai, H. W. Tang, X. Yu, X. Z. Yuan, and H. J. Wang, *Electrochim. Acta*, 55(2010) 5506.
- 20. K. M. Shaju, and P. G. Bruce, Dalton Trans., 40 (2008) 5471.
- 21. Y. Z. Lv, Y. Z. Jin, Y. Xue, J. Wu, X. G. Zhang, and Z. B. Wang, RSC Adv., 4(50) (2014) 26022.
- 22. B. Zong, Z. Y. Deng, S. H. Yan, Y. Q. Lang, J. J. Gong, J. L. Guo, L. Wang, and G. C. Liang, *Powder Technol.*, 364 (2020) 725.
- 23. Y. D. Shen, X. K. Ju, J. Z. Zhang, T. Z. Xie, F. Y. Zong, D. Y. Xue, X. P. Lin, J. M. Zhang, and Q. H. Li, Mater. Chem. *Phys.*, 240 (2020) 122137.
- 24. E. Q. Zhao, L. Wei, Y. D. Guo, Y. J. Xu, W. C. Yan, D. Y. Sun, and Y. C. Jin, *J. Alloy. Compd.*, 695(2017) 3393.
- 25. Q. L. Zhao, N. Q. Ye, L. Li, and F. Yan, Rare Metal Mat. Eng., 39(10)(2010) 1715.
- 26. N. D. Rosedhi, N. H. Idris, M. M. Rahman, M. F. Md Din and J. L. Wang, *Electrochim. Acta*, 206(2016) 374.
- 27. Xiao J, Chen X, P. V. Sushko, M.L. Sushko, L. Kovarik, J. Feng, Z. Deng, J. Zheng, and G. L. Graff, et al., *Adv. Mater.*, 24(16)(2012) 2109.
- 28. J. Gao, J. J. Li, F. Song, J. X. Lin, X. G. He, and C. Y. Jiang, Mater. Chem. Phys., 152 (2015) 177.
- 29. N. P. W. Pieczonka, Z. Liu, and P. Lu, J. Phys. Chem. C, 117(31) (2013) 15947.
- 30. C. M. Jiao, L. Wang, Y. X. Zuo, P. Ni, and G. C. Liang, Solid State Ionics, 277(2015) 50.

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