

Synthesis of nickel nanostructured microfibers to increase the electrochemical activity of nickel electrodes

© Mikhail V. Morozov^a✉, Ravil N. Mansurov^b, Sergey V. Drobyshev^a

^a Kazan National Research Technical University named after A. N. Tupolev – KAI,
10, Karl Marx St., Kazan, 423111, Russian Federation,

^b A. E. Arbuzov Institute of Organic and Physical Chemistry KazNC RAS,
8, Akademika Arbuzova St., Kazan, 423088, Russian Federation

✉ misha617@mail.ru

Abstract: At present, the investigation of the properties of nanostructured materials for electrochemical applications, in particular for the development of promising supercapacitors, is of current interest. In this regard, a special interest is directed to the study of new methods for the synthesis of nickel microfibers nanostructured materials. The research focuses on the fact that the existing synthesis methods are complicated and require either specialized equipment or a large number of chemical reagents for the synthesis of nickel nanostructured materials. The aim of this work is to determine the influence of the reagents, nickel chloride as an oxidizer and hydrazine hydrate as a reducing agent, on the parameters of nickel microfibers – length and surface development. Using this technique, nickel nanostructured microfibers were obtained depending on the oxidizer concentration. The morphology of the obtained products was characterized by optical microscopy and scanning electron microscopy. It was shown that the morphology of the microfibers changes smoothly with changes of the oxidizer concentration, which provides controllability of the product characteristics, adjustment of the required length of nickel microfibers in the range from 20 to 150 μm. The method of X-ray phase analysis confirmed that the final products of the synthesis are nickel microfibers without any side impurities. The high electrochemical activity of nickel electrodes modified by the synthesized structures in alkaline electrolyte was shown. The results obtained can be used in the electrochemical current sources, including batteries and supercapacitors, as well as in other applications where a developed surface is required, for example, in sensors and catalysis.

Keywords: nickel microfiber; synthesis of nanostructured nickel; nickel chloride; hydrazine hydrate; nickel electrodes; oxidizer concentration; electrochemical activity of the electrode; supercapacitor.

For citation: Morozov MV, Mansurov RN, Drobyshev SV. Synthesis of nickel nanostructured microfibers to increase the electrochemical activity of nickel electrodes. *Journal of Advanced Materials and Technologies*. 2023;8(4):260-269. DOI: 10.17277/jamt.2023.04.pp.260-269

Синтез никелевых наноструктурированных микроволокон для повышения электрохимической активности никелевых электродов

© М. В. Морозов^a✉, Р. Н. Мансуров^b, С. В. Дробышев^a

^a Казанский национальный исследовательский технический университет им. А. Н. Туполева – КАИ,
ул. Карла Маркса, 10, Казань, 423111, Российская Федерация,

^b Институт органической и физической химии имени А. Е. Арбузова КазНЦ РАН,
ул. Академика Арбузова, 8, Казань, 423088, Российская Федерация

✉ misha617@mail.ru

Аннотация: В настоящее время актуальными являются исследования свойств наноструктурированных материалов для электрохимических приложений, в частности, для разработки перспективных суперконденсаторов. В связи с этим особый интерес направлен на исследование новых способов синтеза никелевых микроволоконных наноструктурированных материалов. Проблема исследования заключается в том, что существующие способы синтеза сложны и требуют или специализированного оборудования, или большого количества химических

реактивов для синтеза никелевых наноструктурированных материалов. Цель работы – определение влияния реагентов хлорида никеля в качестве окислителя и гидразингидрата в качестве восстановителя на параметры никелевых микроволокон – длину и развитость поверхности. С помощью данной методики получены никелевые наноструктурированные микроволокна в зависимости от концентрации окислителя. Морфология полученных продуктов охарактеризована методами оптической микроскопии и сканирующей электронной микроскопии. Показано, что морфология микроволокон плавно меняется с изменением концентрации окислителя, что обеспечивает управляемость характеристиками продукта, настройку требуемой длины никелевых микроволокон в диапазоне от 20 до 150 мкм. Методом рентгенофазового анализа подтверждено, что конечными продуктами синтеза являются никелевые микроволокна без каких-либо побочных примесей. Показана высокая электрохимическая активность никелевых электродов, модифицированных синтезированными структурами, в щелочном электролите. Полученные результаты могут быть использованы в электрохимических источниках тока, в том числе аккумуляторах и суперконденсаторах, а также в других приложениях, там, где требуется развитая поверхность, например, в сенсорах и катализе.

Ключевые слова: никелевое микроволокно; синтез наноструктурированного никеля; хлорид никеля; гидразин гидрат; никелевые электроды; концентрация окислителя; электрохимическая активность электрода; суперконденсаторы.

Для цитирования: Morozov MV, Mansurov RN, Drobyshch SV. Synthesis of nickel nanostructured microfibers to increase the electrochemical activity of nickel electrodes. *Journal of Advanced Materials and Technologies*. 2023;8(4):260-269. DOI: 10.17277/jamt.2023.04.pp.260-269

1. Introduction

The ever-increasing requirements for unique combinations of properties of substances, including thermal and electrical conductivity, strength and ductility, stability and reactivity are the main driving force in the field of architecturing new materials. This necessitates both the synthesis of new materials and the investigation of conditions for the fabrication of new products based on them [1, 2]. In the creation of electrodes for modern chemical sources of current, nickel and nickel-oxide materials for lithium-ion batteries are of particular interest [3–5]. Nanostructuring of nickel materials allows increasing their specific surface area, which is especially important in the development of supercapacitors because it increases their capacity and power [6–15].

The problem with the synthesis of nickel materials with developed surface area is that the existing synthesis methods are complex and require either specialized equipment or a large number of chemical reagents for the synthesis of nickel nanostructured materials, and thus it is a relevant issue. On the other hand, the application of porous electrode frameworks in chemical current sources (CCS) has been efficient. This shows that an important parameter is the particle length, which is necessary to create porous electrode frameworks from these particles, so it is important to learn how to produce long nickel microfibers resistant to alkaline environment. At the same time, the mechanism of synthesis of nanostructured nickel coatings is rather complex, and it is necessary to study reactions with a minimum set of reagents, which will also reduce the

amount of impurities in the synthesized product. Therefore, the aim of this work is to determine the effect of reagents including nickel chloride as an oxidizing agent and hydrazine hydrate as a reducing agent on the parameters of nickel microfibers – length and surface development under the condition of a minimum set of reagents. Next, we consider promising methods for the synthesis of nickel materials requiring a small set of reagents and low temperatures with a developed surface [16–20].

In [18], 80 % $\text{N}_2\text{H}_4 \cdot 6\text{H}_2\text{O}$ solution was mixed into the 1.9 M of NiCl_2 aqueous solution, which led to the formation of Ni complexes between NiCl_2 and N_2H_4 (pale purple precipitate), and the temperature of the solution increased due to the exothermic reaction. These complex compounds that gave this colour were identified as $[\text{Ni}(\text{NH}_3)_6]\text{Cl}_2$ and $[\text{Ni}(\text{N}_2\text{H}_4)_2]\text{Cl}_2$ [21]. It is also known that $[\text{Ni}(\text{NH}_3)_6]\text{Cl}_2$ is formed when $[\text{Ni}(\text{N}_2\text{H}_4)_2]\text{Cl}_2$ is heated to high temperature ($\sim 65^\circ\text{C}$) [22]. The decomposition of Ni complex compounds in a strongly alkaline environment ($\text{pH} \sim 13$) will lead to the formation of $\text{Ni}(\text{OH})_2$ [23, 24], and it can be reduced by N_2H_4 [25–28]. Thus, under the above synthesis conditions, intermediate nickel complexes and nickel hydroxide are formed due to the presence of alkali in the reagents, and excessive amount of hydrazine is needed for its reduction. The final product of the reaction is nickel, and the synthesized nanoparticles are of spherical shape, which is inefficient for the use in CCS.

In [19], a precursor solution was firstly prepared by adding the corresponding NiCl_2 , ammonium

citrate and sodium hydroxide to the reactor. Polyvinylpyrrolidone and silver nitrate were added to the above solution as a protecting agent and nucleating agent to enhance the reaction rate. The reduction reaction took place immediately after the addition of N_2H_4 and precipitation of black Ni particles. The results of X-ray phase analysis showed that nickel hydroxide was formed first and then it was reduced to metallic nickel by N_2H_4 . In view of these experimental results, it is believed that the reactions of $\text{Ni}(\text{OH})_2$ formation and its reduction to nickel particles by hydrazine are two competing reactions [19]. Thus, under these conditions, nickel hydroxide, which is an undesirable reaction product, is also formed, and the shape of nickel particles is spherical, making it inefficient for the application in CCS.

Template-based approaches have been widely used for the synthesis of magnetic metallic micro/nanofibers and wires. Many magnetic metallic fibers have been synthesized using porous anodic aluminium oxide or polycarbonate membrane as matrix [29, 30]. However, this method involves a complex manufacturing process and results in low product yields. Nickel microfiber can also be obtained by oxalate precursor precipitation-thermal decomposition-reduction process using ammonia as a coordinating agent [31]. Obtaining oxalate precursor occurs at high pH (≈ 9), which will lead to equipment deterioration and environmental pollution.

A chemical method for the synthesis of nickel microfibers in an acidic environment can be considered, but this synthesis takes place at high temperature and requires additional equipment, which increases the cost of synthesis [32]. The method of synthesis in an alkaline environment is known [33], but the use of chemical reagents, in addition to oxidizing and reducing agents, in the synthesis of nickel materials leads to the formation of side reactions [18, 19, 25–28]. For example, when NaOH is used, the by-product $\text{Ni}(\text{OH})_2$ appears; this involves an additional amount of hydrazine hydrate, which increases the cost of the synthesis itself. From [34] it is known that surfactants (surfactants) are used in the synthesis of nickel microfibers, but the cost of surfactants is high, which again affects the cost of synthesis of nickel materials. Therefore, the existing synthesis methods do not solve the identified research problem because they are complex and require either specialized equipment or a large number of chemical reagents for the synthesis of nickel nanostructured materials. In order to solve the problem of synthesis of nickel microfibers with developed surface, the present study has been carried out.

2. Materials and Methods

2.1. Synthesis of microfibre structures and electrodes

Nickel microfiber structures were prepared by mixing solutions of NiCl_2 (oxidant) and hydrazine hydrate (reducing agent). Four samples were synthesized using 600, 900, 1200 and 1500 mg of nickel chloride. Nickel (II) chloride was dissolved in 40 mL of water and heated to 60 °C, then hydrazine hydrate solution was injected into the resulting solution dropwise at a rate of $3 \text{ mL} \cdot \text{min}^{-1}$ to form a homogeneous solution obtained by dissolving 5 mL of hydrazine hydrate in 40 mL of distilled water. This reaction solution was thermostated for 40 minutes at 95 °C. After this time, the reaction was stopped, the products were removed from the solution and washed with distilled water several times and dried in an oven at 70 °C for at least 12 hours. Separately, for the samples using 1200 and 1500 mg of nickel chloride, the reaction was carried out with a thermostat time of 60 minutes to determine the completion time of the synthesis under these conditions.

Nickel electrodes modified with nickel microfiber were obtained by mixing solutions of nickel (II) chloride and hydrazine hydrate. 240 mg of nickel (II) chloride was dissolved in 40 mL of water and heated to 60 °C, then an industrial-type porous nickel foil electrode was placed in the solution and hydrazine hydrate solution was injected dropwise at a rate of $3 \text{ mL} \cdot \text{min}^{-1}$ to form a homogeneous solution obtained by dissolving 5 mL of hydrazine hydrate in 40 mL of distilled water. The final solution was thermostated for 1 hour at 95 °C. After one hour, the reaction was stopped and the electrode with nickel microfibers was removed from the solution and washed with distilled water several times and dried in an oven at 70 °C for at least 12 hours.

2.2. Analytic Methods

The morphology of the products obtained during the synthesis, including their overall structure and surface area, was examined by scanning electron microscopy (SEM) on an Auriga Crossbeam workstation (Carl Zeiss, Germany) with a thermal field emission cathode. Also the overall structure of the microfibers was investigated by optical microscopy on an Axio Imager.Z2m microscope (Carl Zeiss, Germany). The phase composition of the products was investigated by X-ray phase analysis on a research grade Shimadzu XRD-7000 X-ray

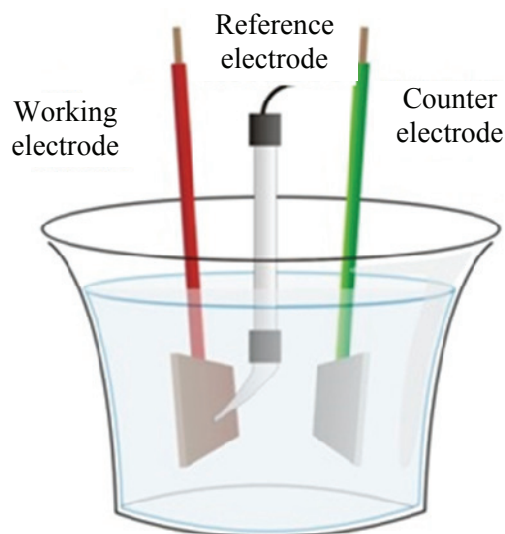


Fig. 1. Three-electrode cell

diffractometer (Shimadzu Corporation, Japan) with a vertical θ - θ goniometer. Energy dispersive X-ray analysis spectra were obtained on the Auriga Crossbeam workstation for elemental analysis of products.

2.3. Electrochemical measurements

A series of cyclic voltammetry experiments were carried out to characterize the relationship between the surface development of the synthesized materials and the electrochemical activity of nickel electrodes modified with the synthesized structures, in alkaline electrolyte. For this purpose, a three-electrode cell setup was used (Fig. 1).

An electrode with synthesized microfiber structures with dimensions of 3×3 cm or a porous

nickel foil electrode of industrial type without microfiber structures was used as a working electrode. A silver chloride electrode was used as a reference electrode and a platinum wire was used as a counter electrode. After that, voltammograms of the electrodes in alkaline electrolyte in 0.1 M caustic potassium solution were taken in the potential range from -1 to 1 V at a sweep speed from 5 to 60 $\text{mV}\cdot\text{s}^{-1}$ on an Autolab PGSTAT302N potentiostat/galvanostat (MetrohmAutolab, Netherlands).

3. Results and Discussion

3.1. Synthesis of nickel microfiber structures at different reagent concentrations

Table 1 shows the optical microscope images of washed and dried microfibers.

The results of the microfiber length study are presented in Table 2.

From the optical microscopy data, it is observed that the length of microfibers decreases with the increasing oxidizer concentration (Table 1). The same is observed visually and shown in Table 2. At lower concentrations of nickel chloride, the fibers grow in solid and large pieces, unlike at higher concentrations [3].

Table 3 shows the SEM images of microfibers in dependence of the oxidizer concentration.

Analyzing the images from Table 3, it can be concluded that with the increase of the oxidizer concentration, the length of microfibers decreases and the obtained structures are agglomerates of particles, which corresponds to the conclusions of [3].

Table 1. Microfiber images obtained using an optical microscope, depending on the mass of the oxidizer

Mass of the oxidizer, mg	Overview	Images of separate fibres
600		


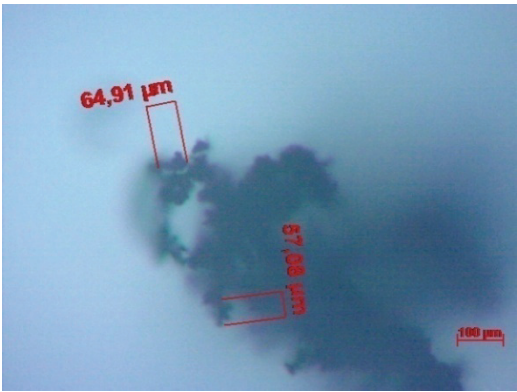
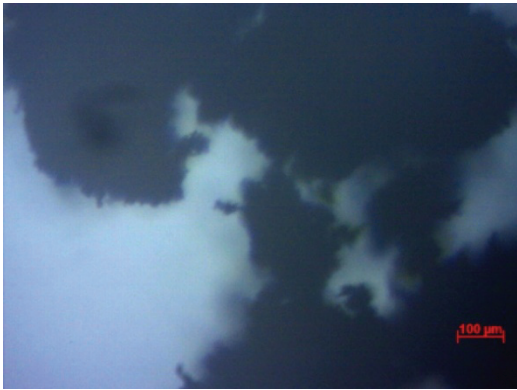
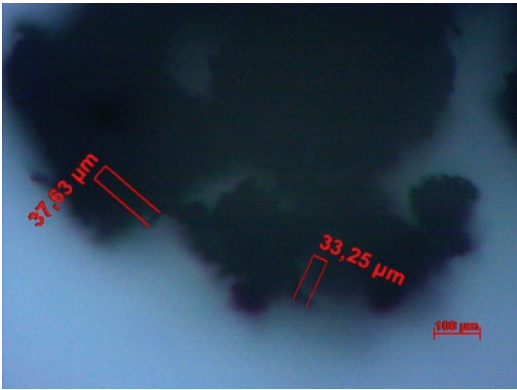

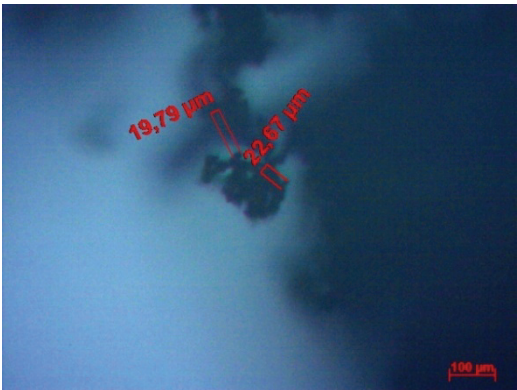
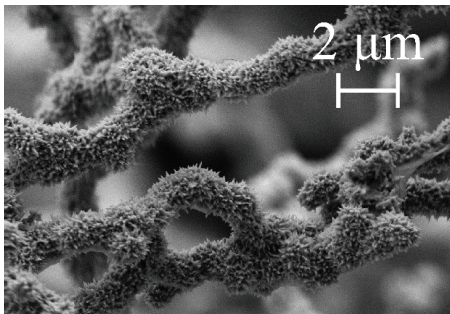
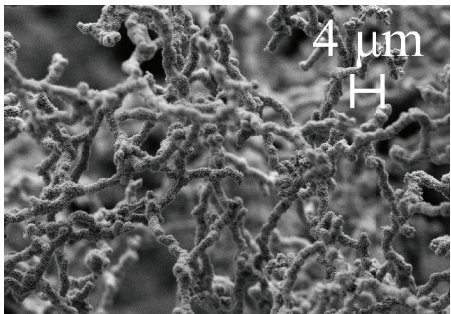
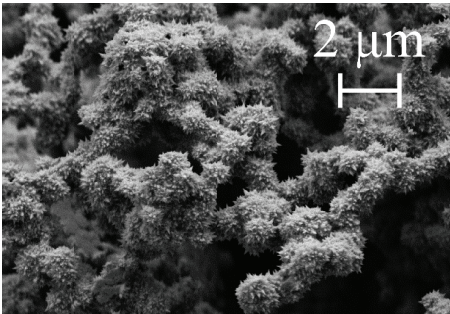
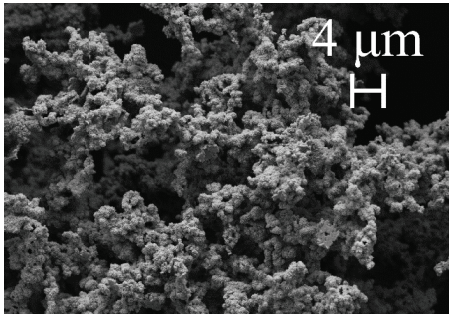
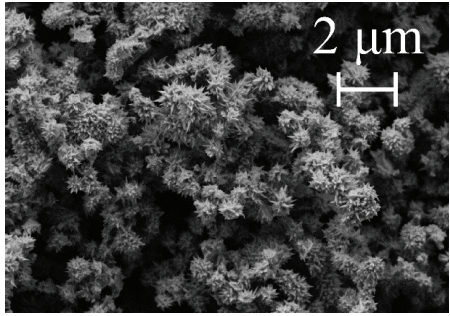
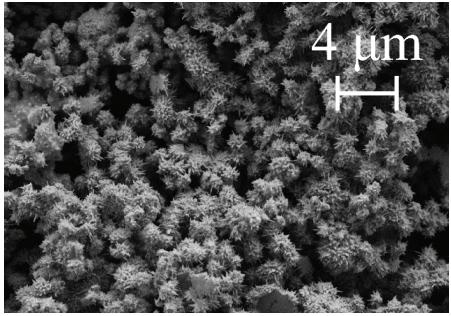
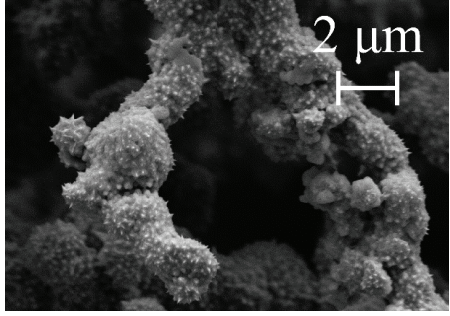
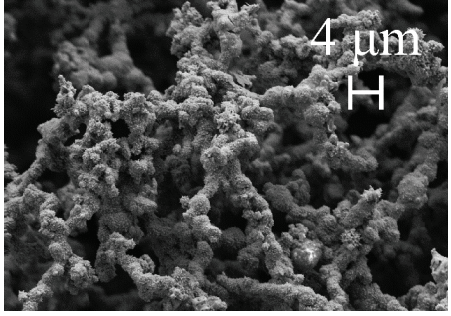
Mass of the oxidizer, mg	Overview	Images of separate fibres
900		
1200		
1500		

Table 2. Results of optical microscopy image analysis

Sample number	Hydrazine hydrate ($\text{N}_2\text{H}_4 \cdot \text{H}_2\text{O}$), mL	Nickel chloride ($\text{N}_2\text{H}_4 \cdot 6\text{H}_2\text{O}$), mg	Microfiber length range, μm
1	5	600	145 ± 10
2		900	65 ± 10
3		1200	38 ± 8
4		1500	22 ± 5

Table 3. SEM images of nickel microfibers, depending on the mass of the reactant

Sample number	Smaller scale image (magnification 20 000)	Larger scale image (magnification 5000)
1		
2		
3		
4		

The synthesized microfibers (Fig. 2) have a developed surface covered with nanospikes, which indicates that their use in supercapacitors is promising [6–15]. The length of the nanospikes as estimated from Fig. 2 is 100–250 nm, and their dimensions in the transverse direction are much smaller than those in the longitudinal direction. Thus, the nanospikes provide a developed surface for electrodes based on synthesized nickel nanostructured microfibers.

In the experiments in which a large amount of oxidant (1200 and 1500 mg) was used, it was observed that some powder inclusions did not react completely and remained after the completion of the synthesis. SEM images show that the inclusions are non-electrically conducting hollow spherical particles (Fig. 3), which appear as a light blue powder in the microfiber structure. Energy dispersive X-ray analysis shows that this substance consists of at least nitrogen, chlorine and nickel (Fig. 4).

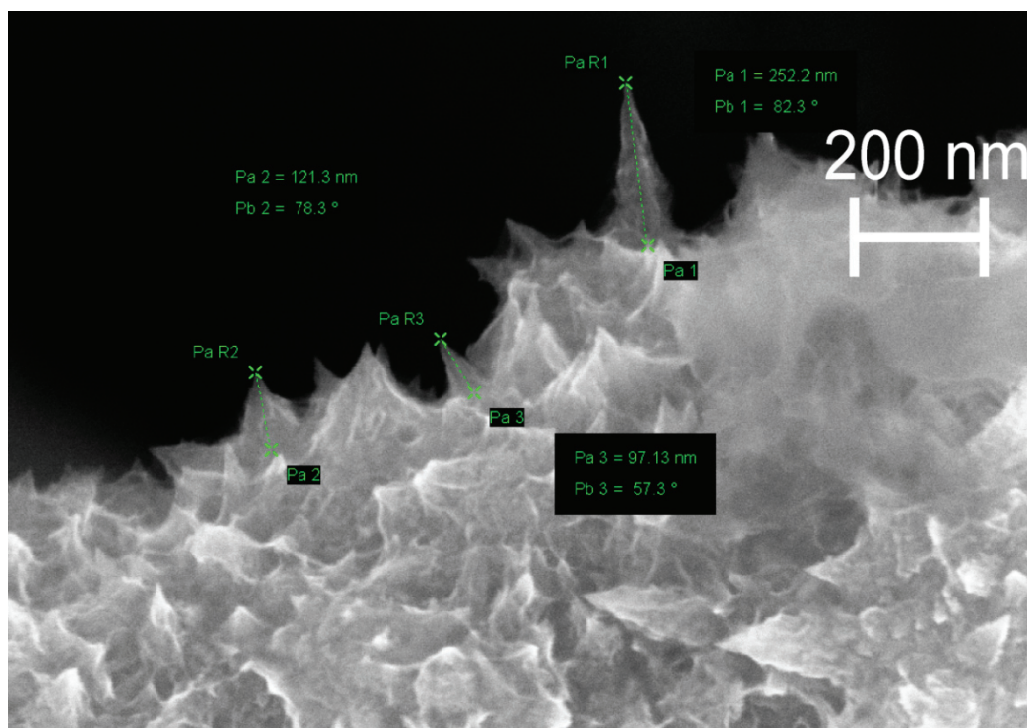


Fig. 2. Enlarged SEM image of the nickel microfibre surface (sample 1, magnification 190 000)

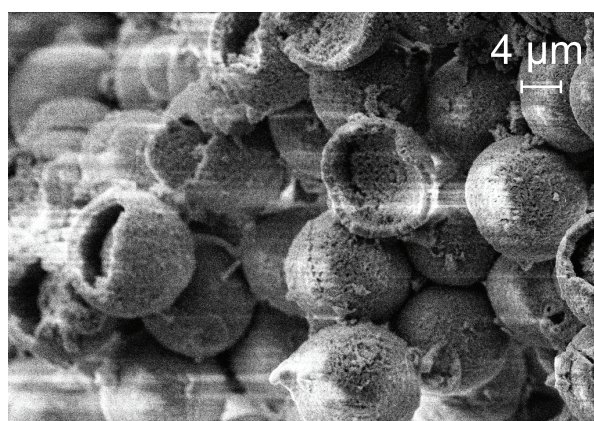


Fig. 3. SEM images of powder inclusions at magnification 7000

Sources [35] indicate that nanostructured nickel is formed by the decomposition of $\text{Ni}(\text{NH}_3)_6\text{Cl}_2$. Presumably, this substance in the form of light blue particles is observed in the obtained SEM images, which is confirmed by the presence of chlorine, nitrogen and nickel in the particles according to the results of energy dispersive X-ray analysis.

To determine the phase composition experiments were repeated with samples 1, 2, 3 and 4 using X-ray phase analysis (XRD). For samples 3 and 4, it was decided to increase the experiment time to complete the synthesis (maintaining at 95 °C for 60 min) and intermediate powder samples were taken to identify the inclusions.

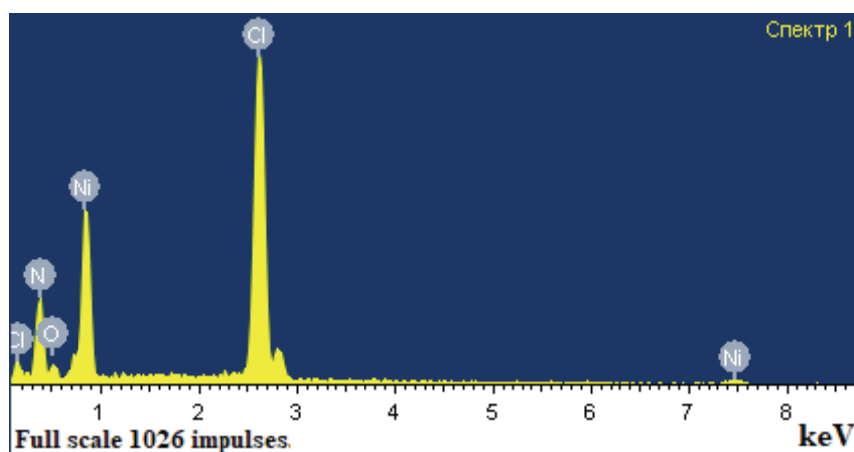


Fig. 4. Results of energy dispersive X-ray spectroscopy of powder inclusions

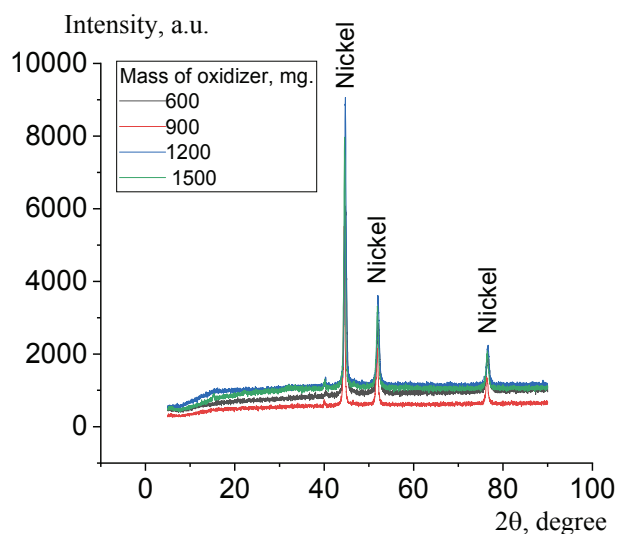


Fig. 5. Diffractogram of samples with different oxidizer mass after the completion of synthesis

As can be seen in Fig. 5, all samples consist of only nanostructured nickel and contain no other phases. Meanwhile, samples 3 and 4 obtained after 1 hour of thermostating at 95 °C do not contain any inclusion.

3.2. Investigation of the electrochemical activity of the synthesised nickel-based electrodes in alkaline electrolyte

Figure 6 shows cyclic voltammetry obtained for nickel foil and electrode with microfiber structures in 0.1 M KOH solution in the potential range $[-1.0-1.0]$ V at potential sweep rate $\nu = 20 \text{ mV}\cdot\text{s}^{-1}$. It was noted in [36] that in the considered potential range nickel oxide NiO and β -nickel hydroxide ($\beta\text{-Ni}(\text{OH})_2$) can be formed. Presumably, the presence of a cathodic peak in the 0.1 V region for the electrode with microfiber structures is because the developed nickel surface is transformed and additional nickel hydroxides are formed on the electrode surface, which can be reduced at the cathodic peak. Accordingly, the more developed the surface is, the more intensive is the process of hydroxide formation [36]. The absence of this peak for nickel foil is explained by the absence of a developed nanostructured surface on it, and microstructured nickel particles are much less susceptible to conversion to hydroxides. It should be noted that the bend on the cyclic voltammetry image at potentials of 1 V and more corresponds to the region of oxygen release, and the bend at potentials less than -1 V corresponds to the region of hydrogen release [36].

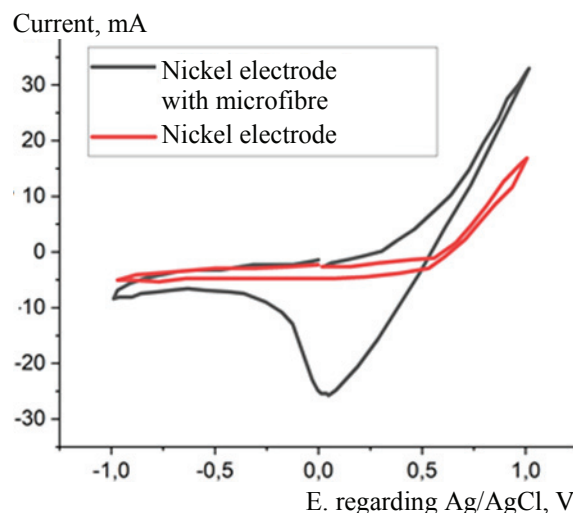


Fig. 6. Cyclic voltammograms obtained for nickel foil and electrode with microfiber structures in 0.1 M KOH solution in the range of potentials $[-1.0-1.0]$ V at the potential sweep rate $\nu = 20 \text{ mV}\cdot\text{s}^{-1}$

4. Conclusion

In this work, the synthesis of nickel nanostructured microfibers was carried out at different concentrations of reagents. The synthesis of coatings was carried out using a technique with a minimum set of initial reagents to reduce the cost of synthesis technology and avoid the occurrence of residual impurities. To obtain nickel materials with developed surface using the proposed methodology, it is necessary to carry out the synthesis for at least one hour. The hydrazine hydrate solution should be added dropwise at a rate of $3 \text{ mL}\cdot\text{min}^{-1}$ to create a homogeneous solution. By methods of optical microscopy and scanning electron microscopy the morphology of the obtained intermediate and final products of synthesis was investigated. It was found that a decrease in oxidant concentration is required to increase the length of the microfibers, which provides length tuning in the range from 20 to 150 μm . It was confirmed by X-ray phase analysis that the final products of the synthesis are nickel microfibers. The electrochemical activity of nickel foil electrodes modified by the synthesized structures exceeds the activity of the original foil electrodes by about five times. In the future it is planned to investigate in detail the electrochemical activity of the synthesized structures, to determine the optimal synthesis conditions and to develop a method of creating supercapacitor electrodes with nickel nanostructured materials. Also, the results obtained can be used in the creation of batteries, as well as in other applications, where a developed surface is required, for example, in sensors and catalysis.

5. Funding

The study was funded by the government assignment for the Federal Research Center “Kazan Scientific Center of the Russian Academy of Sciences”.

6. Conflict of interests

The authors declare no conflict of interests.

References

1. Török TI, Pázmán J, Szabó M, et al. Laboratory preparation and characterization of electroless nickel coated powders of industrially produced aluminium and iron(III) oxides. *Materials Science Forum*. 2013;752:284-293. DOI:10.4028/www.scientific.net/msf.752.284
2. Gromov AA, Nalivaiko AY, Ambaryan GN, et al. Aluminum–alumina composites: Part 1: Obtaining and characterization of powders. *Materials*. 2019;12(19):3180. DOI:10.3390/ma12193180
3. Morozov M, Ivanov S, Kadirov M, et al. Facile synthesis of a binder-free 3D Ni/NiO microwire network with a nanostructured fiber surface for a negative electrode in Li-ion battery. *Journal of Applied Electrochemistry*. 2021;51(5):815-828. DOI:10.1007/s10800-021-01541-5
4. Liu C, Li C, Ahmed K, et al. Template free and binder less NiO nanowire foam for Li-ion battery anodes with long cycle life and ultrahigh rate capability. *Scientific Reports*. 2016;6(1). DOI:10.1038/srep29183
5. Holzer L, Iwanschitz B, Hocker T, et al. Microstructure degradation of cermet anodes for solid oxide fuel cells: Quantification of nickel grain growth in dry and in humid atmospheres. *Journal of Power Sources*. 2011;196(3):1279-1294. DOI:10.1016/j.jpowsour.2010.08.017
6. Nam K-W, Kim K-H, Lee E-S, et al. Pseudocapacitive properties of electrochemically prepared nickel oxides on 3-dimensional carbon nanotube film substrates. *Journal of Power Sources*. 2008;182(2):642-652. DOI:10.1016/j.jpowsour.2008.03.090
7. Wu M-S, Hsu W-H. Nickel nanoparticles embedded in partially graphitic porous carbon fabricated by direct carbonization of nickel-organic framework for high-performance supercapacitors. *Journal of Power Sources*. 2015;274:1055-1062. DOI:10.1016/j.jpowsour.2014.10.133
8. Yuan G- hui, Jiang Z- hua, Aramata A, et al. Electrochemical behavior of activated-carbon capacitor material loaded with nickel oxide. *Carbon*. 2005;43(14): 2913-2917. DOI:10.1016/j.carbon.2005.06.027
9. Cheng Y-K, Zhang F, Tang L-L, et al. Pregnancy associated nasopharyngeal carcinoma: A retrospective case-control analysis of maternal survival outcomes. *Radiotherapy and Oncology*. 2015;116(1):125-130. DOI:10.1016/j.radonc.2015.06.008
10. Dong S, Ji X, Yu M, et al. Direct synthesis of interconnected porous carbon nanosheet/nickel foam composite for high-performance supercapacitors by microwave-assisted heating. *Journal of Porous Materials*. 2017;25(3):923-933. DOI:10.1007/s10934-017-0504-0
11. Liu Y, Lu Q, Huang Z, et al. Electrodeposition of Ni–Co–S nanosheet arrays on N-doped porous carbon nanofibers for flexible asymmetric supercapacitors. *Journal of Alloys and Compounds*. 2018;762:301-311. DOI:10.1016/j.jallcom.2018.05.239
12. Nagaraju G, Cha SM, Yu JS. Ultrathin nickel hydroxide nanosheet arrays grafted biomass-derived honeycomb-like porous carbon with improved electrochemical performance as a supercapacitive material. *Scientific Reports*. 2017;7(1). DOI:10.1038/srep45201
13. Wu M-S, Zheng Z-B, Lai Y-S, et al. Nickel cobaltite nanograss grown around porous carbon nanotube-wrapped stainless steel wire mesh as a flexible electrode for high-performance supercapacitor application. *Electrochimica Acta*. 2015;182:31-38. DOI:10.1016/j.electacta.2015.09.049
14. Feng J, Zhao J, Tang B, et al. The electrochemical performance of ordered mesoporous carbon/nickel compounds composite material for supercapacitor. *Journal of Solid State Chemistry*. 2010;183(12):2932-2936. DOI:10.1016/j.jssc.2010.09.043
15. Yang H-X, Zhao D-L, Meng W-J, et al. Nickel nanoparticles incorporated into N-doped porous carbon derived from N-containing nickel-MOF for high-performance supercapacitors. *Journal of Alloys and Compounds*. 2019;782:905-914. DOI:10.1016/j.jallcom.2018.12.259
16. Muench F, Oezaslan M, Rauber M, et al. Electroless synthesis of nanostructured nickel and nickel–boron tubes and their performance as unsupported ethanol electrooxidation catalysts. *Journal of Power Sources*. 2013;222:243-252. DOI:10.1016/j.jpowsour.2012.08.067
17. Zhao X, Muench F, Schaefer S, et al. Electroless decoration of macroscale foam with nickel nano-spikes: A scalable route toward efficient catalyst electrodes. *Electrochemistry Communications*. 2016;65:39-43. DOI:10.1016/j.elecom.2016.02.002
18. Choi J-Y, Lee Y-K, Yoon S-M, et al. A chemical route to large-scale preparation of spherical and monodisperse Ni powders. *Journal of the American Ceramic Society*. 2005;88(11):3020-3023. DOI:10.1111/j.1551-2916.2005.00582.x
19. Chou L-H, Hung W-C, Lee M-T. On the preparation of nickel nanoparticles by chemical reduction method: X-ray absorption spectroscopy. *Materials Science*. 2016;22(2). DOI:10.5755/j01.ms.22.2.12921
20. Eluri R, Paul B. Synthesis of nickel nanoparticles by hydrazine reduction: mechanistic study and continuous flow synthesis. *Journal of Nanoparticle Research*. 2012;14(4). DOI:10.1007/s11051-012-0800-1
21. Nicholls D, Swindells R. Hydrazine complexes of nickel(II) chloride. *Journal of Inorganic and Nuclear Chemistry*. 1968;30(8):2211-2217. DOI:10.1016/0022-1902(68)80219-2
22. Guo L, Liu C, Wang R, et al. Large-scale synthesis of uniform nanotubes of a nickel complex by a solution chemical route. *ChemInform*. 2004;35(25). DOI:10.1002/chin.200425241
23. Li Y, Li C, Wang H, et al. Preparation of nickel ultrafine powder and crystalline film by chemical control

reduction. *Materials Chemistry and Physics*. 1999;59(1):88-90. DOI:10.1016/s0254-0584(99)00015-2

24. Gao J, Guan F, Zhao Y, et al. Preparation of ultrafine nickel powder and its catalytic dehydrogenation activity. *Materials Chemistry and Physics*. 2001;71(2): 215-219. DOI:10.1016/s0254-0584(01)00275-9

25. Chen D-H, Wu S-H. Synthesis of Nickel Nanoparticles in Water-in-Oil Microemulsions. *Chemistry of Materials*. 2000;12(5):1354-1360. DOI:10.1021/cm991167y

26. Boudjahem A-G, Monteverdi S, Mercy M, et al. Study of support effects on the reduction of Ni^{2+} ions in aqueous hydrazine. *Langmuir*. 2003;20(1):208-213. DOI:10.1021/la035120

27. Zheng H-G, Liang J-H, Zeng J-H, et al. Preparation of nickel nanopowders in ethanol-water system (EWS). *Materials Research Bulletin*. 2001;36(5):947-952. DOI:10.1016/s0025-5408(01)00569-4

28. Park JW, Chae EH, Kim SH, et al. Preparation of fine Ni powders from nickel hydrazine complex. *Materials Chemistry and Physics*. 2006;97(2):371-378. DOI:10.1016/j.matchemphys.2005.08.028

29. Qiao L, Han X, Gao B, et al. Microwave absorption properties of the hierarchically branched Ni nanowire composites. *Journal of Applied Physics*. 2009;105(5): 053911. DOI:10.1063/1.3081649

30. Xue S, Li M, Wang Y, et al. Electrochemically synthesized binary alloy FeNi nanorod and nanotube arrays in polycarbonate membranes. *Thin Solid Films*. 2009;517(20):5922-5926. DOI:10.1016/j.tsf.2007.08.011

31. Okamoto T, Ichino R, Okido M, et al. Effect of ammonia on the crystal morphology of nickel oxalate

precipitates and their thermal decomposition into metallic nickel. *Materials Transactions*. 2005;46(2):171-174. DOI:10.2320/matertrans.46.171

32. Zhang C, Yao Y, Zhan J, et al. Template-free synthesis of Ni microfibres and their electromagnetic wave absorbing properties. *Journal of Physics D: Applied Physics*. 2013;46(49):495308. DOI:10.1088/0022-3727/46/49/495308

33. Zhang X, Zhang Z, Han X. Synthesis of coral-like nickel nanocrystallites via a dipolar-interaction-directed self-assembly process. *Journal of Crystal Growth*. 2005;274(1):113-117. DOI:10.1016/j.jcrysgro.2004.09.075

34. Niu H, Chen Q, Ning M, et al. Synthesis and one-dimensional self-assembly of acicular nickel nanocrystallites under magnetic fields. *The Journal of Physical Chemistry B*. 2004;108(13):3996-3999. DOI:10.1021/jp0361172

35. Yue HY, Song SS, Huang S, et al. Preparation of three-dimensional hollow graphene balls and simultaneous electrochemical determination of dopamine and uric acid. *Journal of Materials Science: Materials in Electronics*. 2018;29(14):12330-12339. DOI:10.1007/s10854-018-9346-z

36. Oshchepkov AG, Bonnefont A, Pronkin SN, et al. Nanostructured nickel nanoparticles supported on vulcan carbon as a highly active catalyst for the hydrogen oxidation reaction in alkaline media. *Journal of Power Sources*. 2018;402:447-452. DOI:10.1016/j.jpowsour.2018.09.051

Information about the authors / Информация об авторах

Mikhail V. Morozov, Cand. Sc. (Eng.), Associate Professor, Department of the Nanotechnology in Electronics, Kazan National Research Technical University named after A.N. Tupolev – KAI (KNRTU-KAI), Kazan, Russian Federation; ORCID 0000-0003-1434-830X; e-mail: misha617@mail.ru

Ravil N. Mansurov, Junior Researcher, A.E. Arbuzov Institute of Organic and Physical Chemistry, Kazan, Russian Federation; ORCID 0000-0002-4003-0525; e-mail: ravil545@bk.ru

Sergey V. Drobyshev, Assistant, Department of the Nanotechnology in Electronics, KNRTU-KAI, Kazan, Russian Federation; ORCID 0000-0002-1655-4492; e-mail: warlordik_009@mail.ru

Морозов Михаил Валерьевич, кандидат технических наук, доцент кафедры «Нанотехнологии в электронике (НТвЭ)», Казанский национальный исследовательский технический университет им. А. Н. Туполева – КАИ (КНИТУ-КАИ), Казань, Российская Федерация; ORCID 0000-0003-1434-830X; e-mail: misha617@mail.ru

Мансуров Равиль Нафисович, младший научный сотрудник, Институт органической и физической химии имени А. Е. Арбузова КазНЦ РАН, Казань, Российская Федерация; ORCID 0000-0002-4003-0525; e-mail: ravil545@bk.ru

Дробышев Сергей Викторович, ассистент, кафедра НТвЭ, КНИТУ-КАИ, Казань, Российская Федерация; ORCID 0000-0002-1655-4492; e-mail: warlordik_009@mail.ru

Received 16 August 2023; Accepted 28 September 2023; Published 15 December 2023



Copyright: © Morozov MV, Mansurov RN, Drobyshev SV, 2023. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).