Advances in Nickel Hydroxide: Structures and Modern Applications (review)

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Abstract. This review article summarises decades of research on nickel hydroxide. Nickel hydroxide is an important material in both physics and chemistry, especially in technical applications such as batteries. First, the structures of two known polymorphs, α-Ni(OH)$_2$ and β-Ni(OH)$_2$, are described. The article also examines common types of disorder in nickel hydroxide, such as hydration, stacking faults, mechanical stresses and the presence of ionic impurities. Related materials such as intercalated α-derivatives and basic nickel salts are also discussed. Various synthetic methods of nickel hydroxide synthesis are reviewed, including chemical and electrochemical precipitation, sol-gel synthesis, chemical ageing, hydrothermal and solvothermal processes, electrochemical oxidation, microwave-assisted techniques and sonochemical methods. The article discusses the physical properties of nickel hydroxide, including its magnetic, vibrational, optical, electrical and mechanical properties. Finally, the article highlights the promising properties of these materials and approaches for the identification and characterization of unknown nickel hydroxide-based samples.

Keywords: Nickel hydroxide, Battery technologies, Electrocatalysis, Photocatalysis, Nanostructures, Supercapacitors, Electrochemical sensors, Structural disorder, Synthesis methods, Microwave-assisted synthesis, Sonochemistry, Electrochromic devices.

Introduction

When we began to write this review of nickel hydroxides, our goal was to identify the most valuable aspects of these industrially important materials for the scientific community. At that time, research was mainly concerned with water, hydroxyl and oxyhydroxyl concentrations in nickel oxide thin and bulk films [1]. This led to concepts such as bound water, structural water, compositional water, and adsorbed water, all of which are essential for understanding corrosion and battery performance. However, advanced analytical techniques were not yet available. Recent developments have significantly improved the understanding of these materials. A simple online search using the keyword "nickel hydroxide" reveals thousands of publications, highlighting their importance. This wealth of literature can be daunting, especially for new students or researchers unfamiliar with the experimental methods in question [2, 3].

Materials and methods

Nickel hydroxides have a wide range of applications in chemistry, physics and engineering. They have been used since the early 20th century as electrode materials in battery technologies. They also play an essential role in the electrochemical processes of nickel and nickel-based alloys or in surface layers formed during corrosion [4, 5]. Research in the late 20th century focused mainly on these two areas. In the late 1960's, Bode et al. proposed a simple model to explain the electrochemical oxidation of nickel hydroxides to nickel(III) oxyhydroxide and subsequent reduction to nickel(II) hydroxide. This model includes two nickel hydroxide phases, α- and β-$Ni(OH)_2$, and two oxidized phases, β- and γ-NiOOH. Although the complete mechanism is more complex, this model and some modifications (such as the transition from γ-NiOOH to β-$Ni(OH)_2$ still provide a useful framework for understanding the processes occurring in nickel hydroxide battery electrodes[6, 7].

Nickel-based batteries, including nickel-cadmium (NiCd) and nickel-metal hydride (NiMH), are widely used in modern technology [8, 9]. Recently, McBreen examined the importance of nickel hydroxides in contemporary battery applications. However, the use of nickel hydroxides has expanded beyond traditional battery and corrosion research into areas such as photocatalysis, electrocatalysis, electrosynthesis, supercapacitors, electrochromic devices and electrochemical sensors. Extensive research has deepened the understanding of these materials beyond the basic two-phase model [10]. Innovations in nanotechnology have led to the development of complex structures such as nanoflowers and nanoribbons, and hundreds of synthesis methods are now available, including advanced techniques such as microwave-assisted synthesis and stereochemistry.

This increasing complexity makes nickel hydroxides both fascinating and challenging. Detailed understanding of structures and properties can be difficult, and choosing the right synthesis method for particular chemical or physical attributes at an appropriate scale can be overwhelming [11]. To help overcome these challenges, this review provides an overview of nickel hydroxide materials and their modern applications, aimed at an interdisciplinary audience that does not require specialized knowledge. It begins by discussing the different nickel hydroxide structures and common structural disorders, followed by a categorization of common synthesis methods with advice on their appropriate use. Finally, the physical properties and analytical characterization of nickel hydroxides are evaluated [9, 12].

Results and discussion

The structure of nickel hydroxides, especially nickel (II) hydroxide ($Ni(OH)_2$), has attracted considerable interest due to its unique properties and applications in a variety of fields including catalysis, energy storage, and environmental remediation. Nickel hydroxides can exist in various polymorphic forms, primarily α-$Ni(OH)_2$ and β-$Ni(OH)_2$, each with unique structural characteristics and stability [13, 14].

β-$Ni(OH)_2$ is isostructurally related to brucite ($Mg(OH)_2$) and occurs naturally as the mineral theophrastite. This phase is characterized by trigonal symmetry, meaning that the **a** and **b** axes are not orthogonal, forming an angle of 120°. The unit cell parameters for β-$Ni(OH)_2$ are determined using X-ray and neutron diffraction. The β-phase structure consists of layers of nickel hydroxide that are arranged in a specific manner, giving it unique properties [6, 7].

α-$Ni(OH)_2$ x H_2O is a polymorph consisting of layers of β-$Ni(OH)_2$ intercalated with water molecules. The degree of hydration (x) can vary, typically ranging from 0.41 to 0.7. Although the material is initially hydrated, water molecules are often omitted from the formula, resulting in the designation α-$Ni(OH)_2$. The α-Phase is known for its structural disorganization, which can affect its physical properties [15, 16].
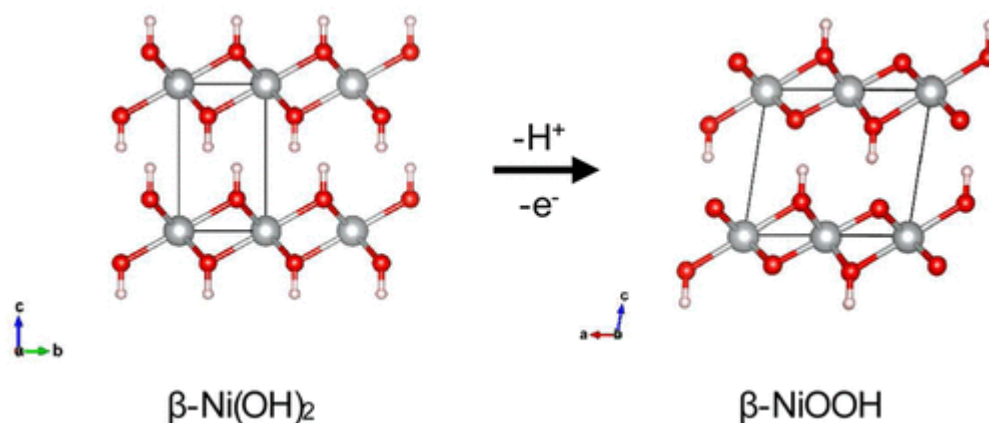

Figure 1. Structure of α- and β- forms of nickel hydroxide [17]

These differences in the structures of the α- and β-forms of nickel hydroxide determine their stability and characteristics, making them important for applications in various technologies [18].

Both forms of nickel hydroxides, α-$Ni(OH)_2$ and β-$Ni(OH)_2$, have unique structural characteristics and behavior, making them important for various applications, especially in the fields of energy storage and catalysts. Structural disorder in nickel hydroxides refers to the various types of irregularities and variations in the crystal structure that can occur in the α and β phases, and this disorder can significantly affect the properties and behavior of the material [19].

The main aspects of structural disorder include the inclusion of foreign ions, variable hydration, and crystal defects. The presence of impurities or foreign ions can disrupt the regular arrangement of nickel and hydroxyl ions in the crystal lattice. The degree of hydration can vary, leading to differences in the arrangement of water molecules within the structure, affecting the stability and reactivity of the material. Crystalline defects, such as irregularities in the crystalline layer stacking sequence, can lead to broadening of X-ray diffraction peaks and affect the overall crystallinity of the material [20].

X-ray diffraction (XRD) analyses showed that the presence of a structural disorder results in peak widths, indicating inhomogeneities in the crystal structure. Neutron diffraction further confirmed the presence of these crystal defects and revealed the arrangement and distribution of atoms in the different phases (Figure 2). Different notations, such as α_am, α*, α', IS, and β_bc, are used to describe the disorder types in nickel hydroxides, which helps identify the parent structure and the disorder types observed. For example, some samples identified as β_bc were found to be β-Ni(OH)$_2$ with a layer stacking disorder [20–22]. These designations help researchers identify the parent structure and characteristic types of disorder that can affect the physical and chemical properties of a material.

The designations have the following meaning: α_am indicates amorphous or partially crystalline forms of α-Ni(OH)$_2$, α* may indicate specific variations in the structure of α-Ni(OH)$_2$ that may be related to changes in hydration or impurities, α' is often used to indicate modifications of α-Ni(OH)$_2$ with specific structural changes, IS can indicate intercalated structures where ions or molecules are located between layers, and β_bc indicates β-Ni(OH)$_2$ with disorder in the stacking of the layers, which can affect its electrolytic properties.

For each of these designations, differences in the XRD spectra can be expected. For example, samples identified as β_bc may show broader peaks compared to well crystallised β-Ni(OH)$_2$, indicating the presence of structural disorder. Variations in the intensity and width of the peaks can be observed in the spectra, which may be due to differences in crystal structure and the presence of defects.

For a more detailed analysis, specific XRD spectra for the samples identified as α_am, α*, α', IS and β_bc should be given. This will allow a visual comparison of their characteristics such as peak positions, peak widths and intensities. For example, the spectrum of β_bc may show peaks that are wider and less intense compared to pure β-Ni(OH)$_2$, indicating the presence of layer stacking disorder.

Thus, a comparative analysis of XRD results for different labelling can provide valuable information on the structural characteristics of nickel hydroxides and their potential applications. For a deeper understanding, it is necessary to perform experimental studies and compare the obtained data with the known characterisation of different forms of Ni(OH)$_2$.
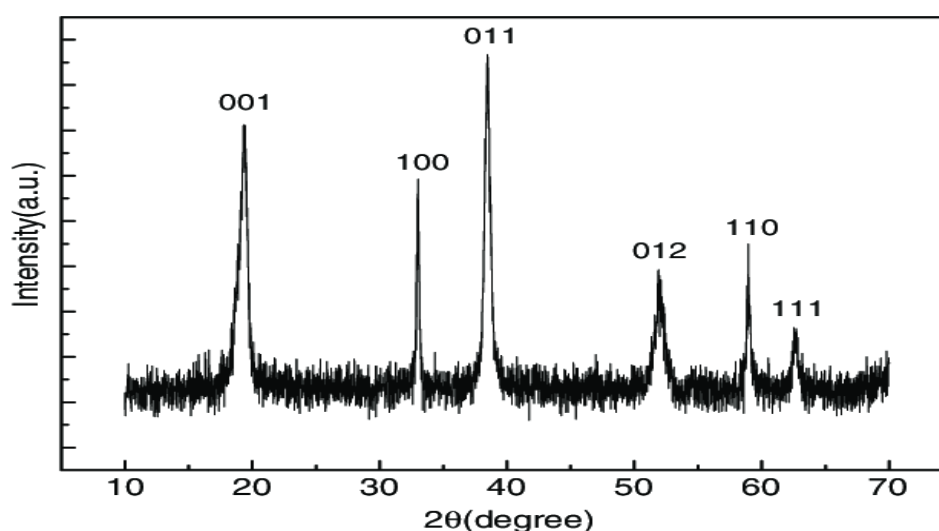
Figure 2. XRD pattern of the as-prepared Ni(OH)$_2$ [23]

The peaks in the XRD spectrum correspond to certain planes of the crystal lattice. For β-Ni(OH)$_2$, for example, one can expect peaks corresponding to planes (003), (006), (009) and others, which indicate periodicity in the crystal structure. The width of the peaks may indicate the presence of structural disorder. Wider peaks often indicate less crystal homogeneity and more defects in the crystal lattice. This may be due to mechanical stresses, hydration or the presence of impurities.
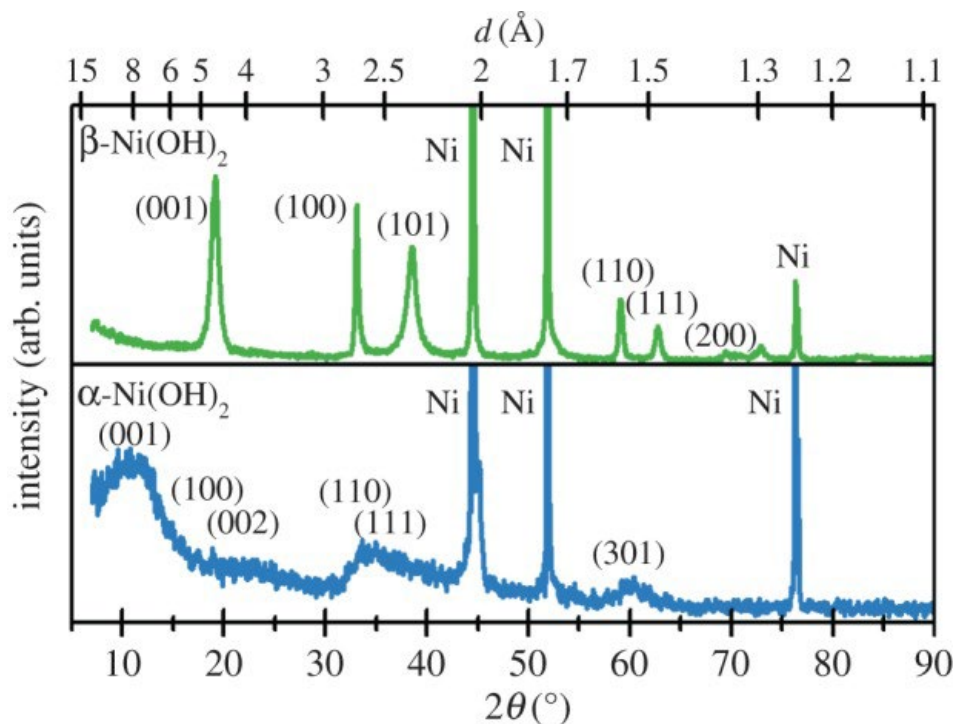

Figure 3. X-ray diffraction patterns of Ni(OH)$_2$ films on Ni substrates collected using a Cu K$_\alpha$ X-ray source [24]

The intensity of the peaks can vary depending on the degree of crystallinity and the presence of different phases in the sample. For example, if both α- and β-forms of Ni(OH)$_2$ are present in the sample, this can lead to variations in the intensity of certain peaks. For a more accurate analysis, it is important to compare the peaks obtained with reference data for Ni(OH)$_2$ to determine which peaks correspond to specific planes and how they change depending on the synthesis conditions.

The presence of structural disorder in nickel hydroxides can lead to significant changes in the physical and chemical properties, including their electrochemical behavior, stability, and reactivity. Understanding and controlling this disorder is key to optimizing the performance of nickel hydroxides in applications such as batteries and catalysts. Overall, structural disorder is an important factor in the study of nickel hydroxides, influencing their synthesis, characterization, and applications in various fields.

These effects have important practical implications. For example, well-crystallized β-Ni(OH)$_2$ exhibits lower electrochemical activity compared to disorganized β-Ni(OH)$_2$ materials. However, the relationship between structural disorder and measured properties is not always clear. Replacing nickel sites with cobalt improves the proton conductivity of β-Ni(OH)$_2$, but it is unclear whether this is due to an increase in proton vacancies or to an increase in stacking distortion, which also affects the electrochemical activity of nickel hydroxide electrodes [21, 25–27]. It is therefore important to identify all possible forms of the distortion.

Stacking distortion in nickel hydroxides is a significant structural phenomenon that affects the properties and performance of the material, especially in electrochemical applications such as batteries and supercapacitors. Stacking implies the presence of disturbances in the arrangement of crystalline layers, which can disrupt the ideal stacking sequence of hydroxide layers in the crystal structure [21]. In nickel hydroxides, especially in the β-phase, the structure consists of stacked layers of $Ni(OH)_2$ [28]. Ideally, these layers are arranged in a specific sequence, but stacking distortion can introduce variations such as rotations or displacements of the layers. For example, stacking can occur when a layer rotates around the c-axis or is displaced in the ab-plane, resulting in a disordered arrangement. This disorder can be characterized by different stacking motifs that can be visualized by X-ray diffraction (XRD), showing peak broadening due to the loss of long-range order [20, 29].

The presence of stacking defects can significantly affect the physical and chemical properties of nickel hydroxides. For example, they can alter the ionic conductivity and electrochemical performance of the material by changing the pathways available for ion transport. In addition, stacking disruptors can lead to changes in the vibrational modes of the material that can be detected using spectroscopic techniques such as Raman and infrared spectroscopy. These techniques often reveal additional O−H stretching modes associated with the disruptor, providing insight into the structural changes occurring in the material [30, 31].

Stacking distortion can also affect the stability and reactivity of nickel hydroxides. The presence of defects can improve the material's ability to accommodate foreign ions or facilitate the hydration process, which can be beneficial in certain applications. However, excessive stacking distortion can lead to decreased crystallinity and poor electrochemical performance [26, 32, 33]. Overall, stacking distortion is an important aspect of the structural performance of nickel hydroxides. Understanding this distortion is critical to optimizing the design and functionality of nickel hydroxide-based materials, especially in energy storage and conversion applications where structural integrity and electrochemical efficiency are of utmost importance [34–36].

Hydration is a critical aspect that significantly affects the structural and electrochemical properties of nickel hydroxides. Hydrated nickel hydroxides, especially β-$Ni(OH)_2$, play important roles in various applications, especially in energy storage systems such as batteries. The hydrated form of nickel hydroxide can be represented as $Ni(H_2O)x_2$, where x typically ranges from 0.1 to 0.4, indicating the presence of water molecules loosely bound to the nickel cations [19].

The hydration process affects the interlayer spacing in the crystal structure of nickel hydroxides. When water molecules are incorporated, the interlayer spacing can increase by approximately 0.1 Å. This widening is critical to the electrochemical activity of the material, as it facilitates ion transport during redox reactions. However, the role of stacking disruptors in these measurements is not fully understood, complicating the interpretation of hydration effects [30, 33, 37, 38].

Thermogravimetric analysis (TGA) is a common method used to assess hydration levels in nickel hydroxides [39]. This technique involves measuring the mass of a sample while gradually increasing the temperature. For β-$Ni(OH)_2$, TGA shows that surface water can be removed at relatively low temperatures (around 80–90°C), while embedded water is completely removed at higher temperatures (around 160°C). Water removal through thermal dehydration can result in a 10–14% reduction in the charging capacity of nickel hydroxide battery electrodes, highlighting the importance of hydration in maintaining the performance of these materials.

Thermogravimetric analysis (TGA) can show how the mass of a sample changes with heating. For example, for α-$Ni(OH)_2$, one would expect to see a loss of water associated with dehydration at around 100-200°C, which would be seen as a sharp decrease in mass. Upon further heating,

e.g., to 300-400°C, the decomposition of nickel hydroxide to form nickel oxide (NiO) may be observed, which would also be reflected in the TGA as an additional mass loss [40].

Nickel hydroxide ($Ni(OH)_2$) exists in two polymorphic forms: alpha (α) and beta (β), each with specific properties and reactivity. The alpha form of $Ni(OH)_2$ is often used as the positive electrode in nickel metal hydride (NiMH) and nickel-cadmium (NiCd) batteries due to its high electrochemical activity resulting from its larger surface area and better conductivity compared to the beta form. Also, α-$Ni(OH)_2$ serves as a catalyst for the oxidation of organic compounds and can be used in hydrogenation reactions, accelerating the processes due to its layered structure. Another important application of nickel alpha hydroxide is in carbon dioxide absorption, where reaction with CO_2 produces nickel carbonate, which finds application in environmental carbon capture projects.

The beta form $Ni(OH)_2$ is more stable in alkaline environments and is often used to produce nickel oxide (NiO) when heated, which is then used in catalysis and as a pigment. Although α-$Ni(OH)_2$ is generally preferred in batteries, β-$Ni(OH)_2$ can also be used, especially in systems with lower capacity requirements and reversible processes. The beta form demonstrates its reactivity in acidic environments, where it reacts with acids to form nickel salts and water, emphasising its flexibility in chemical processes when the pH changes.

Thus, α-$Ni(OH)_2$ is more reactive and finds applications in batteries, catalysis and carbon dioxide capture, while β-$Ni(OH)_2$ is more stable and is used in the production of nickel oxide and other applications requiring reactions in acidic environments [16].

The presence of embedded water can also be detected using vibrational spectroscopic techniques such as X-ray and infrared (IR) spectroscopy. These techniques allow the identification of additional O−H vibrational modes associated with hydration, providing insight into the structural changes that occur during hydration and dehydration [41]. Hydration is thus a key characteristic of nickel hydroxides that affects their structural integrity, electrochemical performance, and overall functionality in various applications, especially in energy storage technologies. Understanding the hydration dynamics is critical to optimize the performance of nickel hydroxide-based materials [42].

Infrared spectroscopy (IR) can be used to identify functional groups in a sample. For example, in the IR spectrum for α-$Ni(OH)_2$ one can expect to see characteristic absorption bands in the 3200-3600 cm^{-1} region, which is associated with O-H bond vibrations, as well as bands in the 500-600 cm^{-1} region corresponding to Ni-O vibrations. For β-$Ni(OH)_2$, similar bands can be observed, but with differences in intensity and width, which may indicate differences in crystal structure and degree of hydration [43].

Ion exchange and foreign ion incorporation are key processes that significantly affect the structural, electrochemical, and functional properties of nickel hydroxides, especially in applications such as batteries, supercapacitors, and catalysts [42]. These processes involve the replacement of nickel ions in the hydroxide lattice by other cations or the introduction of anions into the interlayer spaces, which results in a variety of structural modifications and increases in material performance.

Ionic substitution involves the replacement of nickel ions (Ni^{2+}) in the nickel hydroxide lattice by other cations such as cobalt (Co^{2+}), magnesium (Mg^{2+}), calcium (Ca^{2+}), or aluminum (Al^{3+}). This substitution can occur in varying proportions, resulting in materials with the general formula $Ni_{1-x}M_x(OH)_2$, where M represents the replaced metal and x indicates the degree of substitution. The introduction of foreign cations can lead to several beneficial effects [21]. For example, replacing nickel with cobalt improves the electrochemical activity of nickel hydroxides, probably due to increased proton conductivity or increased layer stacking distortion, which facilitates ion transport.

Ion substitution effects are often associated with changes in the crystal structure and lattice parameters. For example, the interplanar spacing (c-axis) can decrease with increasing cobalt

content due to the smaller ionic radius of Co^{2+} compared to Ni^{2+} [44]. This change can affect the electrochemical properties of the material, such as charge capacity and cycle stability. In addition, the presence of foreign cations can introduce new active sites for redox reactions, which further improves the electrochemical performance of the material [13].

Insertion of foreign ions involves the introduction of anions or other ionic species into the interlayer spaces of nickel hydroxides. This process can significantly change the structural and functional characteristics of the material. Common anions that can be incorporated include nitrate (NO_3^-), sulfate (SO_4^{2-}), carbonate (CO_3^{2-}), and various organic anions [11]. Incorporation of these anions can result in an increase in the interlayer distance, often referred to as the "gallery height", which can facilitate ion transport and improve the electrochemical performance of the material. For example, replacing hydroxide ions with sulfate ions can significantly increase the interlayer distance, which improves ion access to active sites during reactions.

The stability of the incorporated anions is influenced by their size and charge. Larger anions tend to occupy the interlayer spaces more stably, leading to significant structural expansion. For instance, the incorporation of adipate anions can result in an interlayer spacing increase of up to 65% compared to the parent structure. This expansion can enhance the accessibility of the hydroxide layers for ion exchange and improve the overall electrochemical activity [7].

Moreover, ionic substitution and foreign ion incorporation can also affect the thermal stability and mechanical properties of nickel hydroxides. The presence of foreign ions can lead to changes in the bonding characteristics within the lattice, potentially enhancing the material's resistance to thermal degradation. In summary, ionic substitution and foreign ion incorporation are essential processes that modify the structural and functional properties of nickel hydroxides [16]. These modifications can lead to enhanced electrochemical performance, improved stability, and greater versatility in applications. Understanding these processes is crucial for the design and optimization of nickel hydroxide-based materials, particularly in the context of energy storage and conversion technologies, where performance and efficiency are paramount. By tailoring the ionic composition of nickel hydroxides, researchers can develop advanced materials that meet the demands of modern energy applications [16].

Internal mechanical stress can arise from several factors. One significant cause is the incorporation of large polyatomic anions, such as nitrate, into the lattice sites or intercalation spaces of α-Ni(OH)$_2$, which is likely to induce mechanical stress. During the chemical aging process from α- to β-Ni(OH)$_2$, internal stress develops due to the changes in the unit cell c-parameter (from 8.0 to 4.6 Å), resulting in compressive and tensile forces along the c-direction in the α- and β-phases, respectively [6]. Mechanical stress has also been observed in dried nickel hydroxide films, where the shifting of lattice vibrational modes indicates that water removal alters the material's density and induces internal stresses. Furthermore, mechanical stress occurs during the redox cycling of nickel hydroxide electrodes in batteries due to the density differences between nickel hydroxide and nickel oxyhydroxide [21, 25–27].

α-Derivative structures of nickel hydroxide (α-Ni(OH)$_2$) are modified versions of the original α-phase. They are characterized by the incorporation of various guest species, such as surfactants or anions, into the interlayer spaces of the nickel hydroxide lattice. While these derivatives maintain the fundamental structure of α-Ni(OH)$_2$, they exhibit altered physical and chemical properties as a result of the presence of these intercalated species [10].

One common type of α-derivative structure involves surfactant-intercalated α-Ni(OH)$_2$, where surfactant molecules replace interlayer water. This modification results in a hydrophobic interlayer space, which can influence the material's electrochemical behavior and stability [45]. Surfactants such as cetyltrimethylammonium bromide and dodecyl sulfate have been used to create these structures, enhancing their applicability in various fields, including catalysis and energy storage [45–47].

Another important aspect of α-derivative structures is their potential for enhanced performance in electrochemical applications [48]. The incorporation of different anions or surfactants can improve the conductivity and electrochemical activity of the material, making them suitable for use in batteries, supercapacitors, and sensors[49, 50]. Moreover, the structural diversity of α-derivative nickel hydroxides allows for the tuning of their properties, such as morphology, porosity, and surface area, which are critical for optimizing their performance in specific applications. Overall, α-derivative structures represent a significant advancement in the study of nickel hydroxides, offering new avenues for research and development in materials science and electrochemistry [34, 46, 51].

Exfoliated α-derivatives of nickel hydroxide (α-Ni(OH)$_2$) represent a unique class of materials derived from the parent α-phase through the separation of its layered structure into individual sheets. This process, known as exfoliation, significantly alters the properties of the material, making it distinct from both α-Ni(OH)$_2$ and β-Ni(OH)$_2$ [9, 52].

The exfoliation of α-Ni(OH)$_2$ can be achieved through two primary methods. The first involves intercalating surfactants into the interlayer space, rendering the material organophilic. When an organic solvent is introduced, such as formamide or 1-butanol, the surfactant-stabilized layers can be spontaneously exfoliated, resulting in a colloidal suspension of individual nickel hydroxide sheets [18, 52, 53]. This method enhances the material's surface area and reactivity, making it suitable for various applications, including catalysis and energy storage. The second method utilizes amphoteric molecules, which possess both acidic and basic functional groups. For example, p-aminobenzoic acid can be intercalated into the α-derivative structure. When the pH of the solution is altered, the molecule transitions to a zwitterionic form, leading to Coulombic repulsion between adjacent layers and driving the exfoliation process [7].

Exfoliated α-derivatives exhibit unique properties, such as increased electrical conductivity and enhanced electrochemical performance, making them promising candidates for use in batteries, supercapacitors, and other advanced materials applications. Their ability to maintain structural integrity while providing high surface area and reactivity positions exfoliated α-derivatives as valuable materials in the fields of nanotechnology and energy storage.

Conclusion

Nickel hydroxides, particularly in their α-derivative and exfoliated forms, represent a significant area of research due to their versatile properties and wide-ranging applications. The structural modifications achieved through intercalation and exfoliation not only enhance the material's electrochemical performance but also expand its potential uses in energy storage, catalysis, and advanced materials development. The ability to tailor the properties of these derivatives by incorporating various guest species allows for the optimization of their functionality in specific applications. As research continues to explore the synthesis and characterization of nickel hydroxides and their derivatives, the insights gained will likely lead to innovative solutions in technology and materials science. The ongoing advancements in understanding the synthesis methods, structural characteristics, and properties of these materials underscore their importance in addressing contemporary challenges in energy efficiency and sustainable technologies. Overall, the study of nickel hydroxides, particularly the α-derivatives and their exfoliated forms, holds great promise for future developments in various scientific and industrial fields.

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References

1   Grams J., Ruppert A.M. Development of heterogeneous catalysts for thermo-chemical conversion of lignocellulosic biomass // Energies. - 2017. - Vol. 10, № 4. https://doi.org/10.3390/EN10040545

2   Blanco P.H., Wu C., Williams P.T. Influence of Ni/SiO2 catalyst preparation methods on hydrogen production from the pyrolysis/reforming of refuse derived fuel // International Journal of Hydrogen Energy. - 2014. - Vol. 39, № 11. - P. 5723–5732. https://doi.org/10.1016/j.ijhydene.2014.01.150

3   Chen X., Jiang J., Yan F., Li K., Tian S., Gao Y., Zhou H. Dry Reforming of Model Biogas on a Ni/SiO2 Catalyst: Overall Performance and Mechanisms of Sulfur Poisoning and Regeneration // ACS Sustainable Chemistry and Engineering. - 2017. - Vol. 5, № 11. - P. 10248–10257. https://doi.org/10.1021/ACSSUSCHEMENG.7B02251

4   Yun Y.H., Kim K., Lee C., An B.S., Kwon J.H., Lee S., Kim M.J., Seo J., Park J.H., Kim B.H., Cho H.S. Electrochemical partial reduction of Ni(OH)2 to Ni(OH)2/Ni via coupled oxidation of an interfacing NiAl intermetallic compound for robust hydrogen evolution // Journal of Energy Chemistry. - 2023. - Vol. 82. - P. 560–571. https://doi.org/10.1016/J.JECHEM.2023.03.023

5   Li J., Jing Z., Bai H., Chen Z., Osman A.I., Farghali M., Rooney D.W., Yap P.S. Optimizing hydrogen production by alkaline water decomposition with transition metal-based electrocatalysts // Environmental Chemistry Letters. - 2023. - Vol. 21, № 5. - P. 2583–2617. https://doi.org/10.1007/S10311-023-01616-Z

6   Kanhaiya K., Nathanson M., in 't Veld P.J., Zhu C., Nikiforov I., Tadmor E.B., Choi Y.K., Im W., Mishra R.K., Heinz H. Accurate Force Fields for Atomistic Simulations of Oxides, Hydroxides, and Organic Hybrid Materials up to the Micrometer Scale // Journal of Chemical Theory and Computation. - 2023. - Vol. 19, № 22. - P. 8293–8322. https://doi.org/10.1021/ACS.JCTC.3C00750

7   Kretzmer I., Stuve E.M. Electrochemical Oxide Growth on Nickel and Commercial Nickel Alloys: Influence of Chromium and Molybdenum // Journal of The Electrochemical Society. - 2023. - Vol. 170, № 6. - P. 066502. https://doi.org/10.1149/1945-7111/ACD7A6

8   Bogomolov K., Ein-Eli Y. Alkaline Ni–Zn Rechargeable Batteries for Sustainable Energy Storage: Battery Components, Deterioration Mechanisms, and Impact of Additives // ChemSusChem. - 2024. - Vol. 17, № 1. https://doi.org/10.1002/CSSC.202300940

9   Kovalenko V., Kotok V. Nickel Hydroxides: Requirements, Targeted Construction and Choice of Characteristics and Industrially Applicable Synthesis for Targeted Use in Electrochemical Devices // ChemistrySelect. - 2024. - Vol. 9, № 4. https://doi.org/10.1002/SLCT.202303302

10   Yang J.Y., Ahn J.G., Ko B., Park T., Hong S.J., Han D.K., Lee D., Li C.A., Song S.H. Green and sustainable bifunctional carbonized wood electrodes decorated with controlled nickel/α(β)-nickel(ii) hydroxide to boost overall water splitting // Journal of Materials Chemistry A. - 2023. - Vol. 11, № 48. - P. 26672–26680. https://doi.org/10.1039/D3TA05519A

11   Yang H., Deng J., Li R., Zhang R., Tang X., Chen Y. Hierarchical α-Ni(OH)2 with tunable by interlayer anion exchange for degradation of hydroxypropyl guar gum synergistic H2O2 // Sustainable Materials and Technologies. - 2024. - Vol. 41. https://doi.org/10.1016/J.SUSMAT.2024.E01075

12   Shelte A.R., Patil R.D., Karan S., Bhadu G.R., Pratihar S. Nanoscale Ni-NiO-ZnO Heterojunctions for Switchable Dehydrogenation and Hydrogenation through Modulation of Active Sites // ACS Applied

Materials and Interfaces. - 2023. - Vol. 15, № 20. - P. 24329–24345. https://doi.org/10.1021/ACSAMI.3C00985

13   Sasamura Y., Kojima T., Uekawa N. Preparation of electrochromic nickel hydroxide (II) thin film by drying sol obtained by dialysis of solution with precipitate formed from nickel nitrate aqueous solution with ammonia and sorbitol // Journal of Sol-Gel Science and Technology. - 2023. - Vol. 108, № 3. - P. 588–597. https://doi.org/10.1007/S10971-023-06244-1

14   Hashemi N., Nandy S., Aleshkevych P., Chae K.H., Najafpour M.M. Reaction between Nickel Hydroxide and Cerium(IV) Ammonium Nitrate in Aqueous Solution // Inorganic Chemistry. - 2023. - Vol. 62, № 30. - P. 12157–12165. https://doi.org/10.1021/ACS.INORGCHEM.3C01868

15   Ebrahimi S., Rezvani Jalal M., Pishdast M. Synthesis of α-Ni(OH)2 nanocrystals using air-plasma electrolysis method and its characterization // Bulletin of Materials Science. - 2024. - Vol. 47, № 3. https://doi.org/10.1007/S12034-024-03272-7

16   Sanchis-Gual R., Jaramillo-Hernández C., Hunt D., Seijas-Da Silva Á., Mizrahi M., Marini C., Oestreicher V., Abellán G. Influence of Crystallographic Structure and Metal Vacancies on the Oxygen Evolution Reaction Performance of Ni-based Layered Hydroxides // Chemistry - A European Journal. - 2024. - Vol. 30, № 5. https://doi.org/10.1002/CHEM.202303146

17   Tkalych A.J., Yu K., Carter E.A. Structural and Electronic Features of β-Ni(OH)$_2$ and β-NiOOH from First Principles // The Journal of Physical Chemistry C. - 2015. - Vol. 119, № 43. - P. 24315–24322. https://doi.org/10.1021/acs.jpcc.5b08481

18   Lee M., Jang Y., Yoon G., Lee S., Ryu G.H. Synthesis and electrochemical evaluation of nickel hydroxide nanosheets with phase transition to nickel oxide // RSC Advances. - 2024. - Vol. 14, № 15. - P. 10172–10181. https://doi.org/10.1039/D4RA01120A

19   Yi X., Celorrio V., Zhang H., Robertson N., Kirk C. α/β-Ni(OH)$_2$ phase control by F-ion incorporation to optimise hybrid supercapacitor performance // Journal of Materials Chemistry A. - 2023. - Vol. 11, № 41. - P. 22275–22287. https://doi.org/10.1039/D3TA04731H

20   Luis-Sunga M., González-Orive A., Calderón J.C., Gamba I., Ródenas A., de Los Arcos T., Hernández-Creus A., Grundmeier G., Pastor E., García G. Nickel-Induced Reduced Graphene Oxide Nanoribbon Formation on Highly Ordered Pyrolytic Graphite for Electronic and Magnetic Applications // ACS Applied Nano Materials. - 2024. - Vol. 7, № 10. - P. 11088–11096. https://doi.org/10.1021/ACSANM.3C05949

21   Ulu I., Ulgut B., Dag Ö. Fabrication of mesoporous nickel pyrophosphate electrodes and their transformation to nickel hydroxide with decent capacitance in alkaline media // Journal of Materials Chemistry A. - 2023. - Vol. 11, № 41. - P. 22384–22395. https://doi.org/10.1039/D3TA05578G

22   Bassil S., Caillot T., Cadete Santos Aires F.J., Meunier F.C., Kaddouri A. Methane steam reforming over Ni/YSZ cermet anode materials synthesized by different methods // Reaction Chemistry and Engineering. - 2024. - Vol. 9, № 5. - P. 1251–1260. https://doi.org/10.1039/D3RE00679D

23   Wang D., Xu R., Wang X., Li Y. NiO nanorings and their unexpected catalytic property for CO oxidation // Nanotechnology. - 2006. - Vol. 17, № 4. - P. 979–983. https://doi.org/10.1088/0957-4484/17/4/023

24   Hall D.S., Lockwood D.J., Bock C., MacDougall B.R. Nickel hydroxides and related materials: a review of their structures, synthesis and properties // Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences. - 2015. - Vol. 471, № 2174. https://doi.org/10.1098/RSPA.2014.0792

25   Kimmel S.W., DeBlock R.H., Manley J.A., Silguero C.M., Rolison D.R., Rhodes C.P. The role of cathode architecture and anion interactions on the performance of Al-substituted α-Ni(OH)$_2$ in rechargeable Ni–Zn cells // Materials Today Energy. - 2024. - Vol. 44. https://doi.org/10.1016/J.MTENER.2024.101609

26   Govindarajan D., Etesami M., Nootong K., Kirubaharan K., Murugadoss G., Theerthagiri J., Choi M.Y., Kheawhom S. Nano-tablets and rods-shaped Fe and Ni oxide/hydroxide encapsulated graphene for asymmetric supercapacitor and OER applications // Journal of Energy Storage. - 2023. - Vol. 74. https://doi.org/10.1016/J.EST.2023.109435

27   Chu Q., Su Y., Xu Q., Wang X., Zhou Y., Liu X. Anisotropic strain induced fracture of Ni(OH)$_2$ nanosheet electrodes for supercapacitors through a charge-ordered mixed-valent intermediate // Materials Science and Engineering: B. - 2023. - Vol. 296. https://doi.org/10.1016/J.MSEB.2023.116671

28   Zhang X., Liu Y., Noréus D. Phosphide-Enhanced Hierarchical NiMoO$_4$ Composite in Binder-Free

Ni-Electrodes for High-Capacity Aqueous Rechargeable NiZn Batteries // ACS Applied Energy Materials. - 2024. - Vol. 7, № 2. - P. 517–527. https://doi.org/10.1021/ACSAEM.3C02450

29   Debnath A., Bera S., Mahapatra G., Kapuria A., Saha S.K. Giant enhancement of coercivity in β-Ni(OH)$_2$ decorated Ti$_3$C$_2$T$_x$ MXene nanosheets // Journal of Physics D: Applied Physics. - 2024. - Vol. 57, № 35. https://doi.org/10.1088/1361-6463/AD518A

30   Naduvil Kovilakath M.S., Alex C., Rao N.N., Bagchi D., Tayal A., Peter S.C., John N.S. Unfolding the Significance of Regenerative Active Species in Nickel Hydroxide-Based Systems for Sustained Urea Electro-Oxidation // Chemistry of Materials. - 2024. - Vol. 36, № 11. - P. 5343–5355. https://doi.org/10.1021/ACS.CHEMMATER.3C03062

31   Chen J., Shen Y. Effects of Manganese Doping into Nickel Hydroxides for the Electrochemical Conversion of KA Oil // ACS Sustainable Chemistry and Engineering. - 2024. - Vol. 12, № 15. - P. 5907–5916. https://doi.org/10.1021/ACSSUSCHEMENG.3C08543

32   Loiacono A., Díaz-Coello S., García G., Lacconi G.I., Luis Rodriguez J., Pastor E., Franceschini E.A. Nickel-based composites using tungsten carbides as enhancers for electroactivity for the hydrogen evolution reaction // Journal of Electroanalytical Chemistry. - 2024. - Vol. 952. https://doi.org/10.1016/J.JELECHEM.2023.117973

33   Watson N.I., Keegan M., van den Bosch B., Yan N., Rothenberg G. The Influence of Metal Impurities on NiOOH Electrocatalytic Activity in the Oxygen Evolution Reaction // ChemElectroChem. - 2024. - Vol. 11, № 13. https://doi.org/10.1002/CELC.202400223

34   Streichhan N., Goonetilleke D., Li H., Soleymanibrojeni M., Hoffrogge P.W., Schneider D., Nestler B., Wenzel W. Surface energies control the anisotropic growth of β-Ni(OH)$_2$ nanoparticles in stirred reactors // Surfaces and Interfaces. - 2024. - Vol. 51. https://doi.org/10.1016/J.SURFIN.2024.104736

35   Gui Z., Jia Y., Liao X., Yan T., Gao B., Zhang W., Chen L., Gao Q., Zhang Y., Tang Y. Redox regulation of Ni hydroxides with controllable phase composition towards biomass-derived polyol electro-refinery // Chemical Science. - 2024. - Vol. 15, № 21. - P. 8145–8155. https://doi.org/10.1039/D4SC01221F

36   Abdelrahim A.M., Abd El-Moghny M.G., El-Deab M.S. Interface construction of Ni(OH)$_2$/Fe$_3$O$_4$ heterostructure decorating in-situ defected graphite felt for enhanced overall water splitting // International Journal of Hydrogen Energy. - 2024. - Vol. 81. - P. 173–186. https://doi.org/10.1016/J.IJHYDENE.2024.07.266

37   Hajilo M., Taherinia D. Electrodeposited CoNi-LDH nanosheets supported on halloysite nanotubes as a robust and highly efficient electrocatalyst for water oxidation // New Journal of Chemistry. - 2024. - Vol. 48, № 15. - P. 6997–7006. https://doi.org/10.1039/D3NJ05370A

38   Marquez R.A., Kalokowski E., Espinosa M., Bender J.T., Son Y.J., Kawashima K., Chukwuneke C.E., Smith L.A., Celio H., Dolocan A., Zhan X., Miller N., Milliron D.J., Resasco J., Mullins C.B. Transition metal incorporation: electrochemical, structure, and chemical composition effects on nickel oxyhydroxide oxygen-evolution electrocatalysts // Energy and Environmental Science. - 2024. - Vol. 17, № 5. - P. 2028–2045. https://doi.org/10.1039/D3EE03617K

39   Gao N., Sipra A.T., Quan C. Thermogravimetric analysis and pyrolysis product characterization of municipal solid waste using sludge fly ash as additive // Fuel. - 2020. - Vol. 281. - P. 118572. https://doi.org/10.1016/J.FUEL.2020.118572

40   Ziminska M., Wilson J.J., McErlean E., Dunne N., McCarthy H.O. Synthesis and Evaluation of a Thermoresponsive Degradable Chitosan-Grafted PNIPAAm Hydrogel as a "Smart" Gene Delivery System // Materials. - 2020. - Vol. 13, № 11. - P. 2530. https://doi.org/10.3390/ma13112530

41   Manso R.H., Hong J., Wang W., Acharya P., Hoffman A.S., Tong X., Wang F., Greenlee L.F., Zhu Y., Bare S.R., Chen J. Revealing Structural Evolution of Nickel Phosphide-Iron Oxide Core-Shell Nanocatalysts in Alkaline Medium for the Oxygen Evolution Reaction // Chemistry of Materials. - 2024. - Vol. 36, № 13. - P. 6440–6453. https://doi.org/10.1021/ACS.CHEMMATER.4C00379

42   Fujita S., Baranton S., Coutanceau C., Jerkiewicz G. Design, Synthesis, and Characterization of Carbon-Supported β-Ni(OH)$_2$ Nanosheets for Miniaturized Nickel–Metal Hydride Batteries // Energy Technology. - 2024. - Vol. 12, № 4. https://doi.org/10.1002/ENTE.202301268

43   Kanaujia P.K., Sharma Y.K., Garg M.O., Tripathi D., Singh R. Review of analytical strategies in the production and upgrading of bio-oils derived from lignocellulosic biomass // Journal of Analytical and Applied Pyrolysis. - 2014. - Vol. 105. - P. 55–74. https://doi.org/10.1016/J.JAAP.2013.10.004

44   Rea A.J.G., Pauls A.L., Taylor A.K., Gates B.D. Enhancing the Performance of Nickel Electrocatalysts for the Oxygen Evolution Reaction Using Arrays of Self-Cleaning Linear Ridges // ACS

Applied Energy Materials. - 2024. - Vol. 7, № 8. - P. 3187–3200. https://doi.org/10.1021/ACSAEM.3C03187

45 Mitchell J.B., Chagnot M., Augustyn V. Hydrous Transition Metal Oxides for Electrochemical Energy and Environmental Applications // Annual Review of Materials Research. - 2023. - Vol. 53. - P. 1–23. https://doi.org/10.1146/ANNUREV-MATSCI-080819-124955

46 Abe K., Kubota T., Jian Z. Conduction-type conversion in Ni(OH)$_2$ by intercalation of eosin Y // MRS Advances. - 2024. https://doi.org/10.1557/S43580-024-00881-6

47 Mavrič A., Valant M. In Situ Techniques for Characterization of Layered Double Hydroxide-Based Oxygen Evolution Catalysts // Inorganics. - 2023. - Vol. 11, № 7. https://doi.org/10.3390/INORGANICS11070296

48 Zheng D.J., Görlin M., McCormack K., Kim J., Peng J., Xu H., Ma X., LeBeau J.M., Fischer R.A., Román-Leshkov Y., Shao-Horn Y. Linker-Dependent Stability of Metal-Hydroxide Organic Frameworks for Oxygen Evolution // Chemistry of Materials. - 2023. - Vol. 35, № 13. - P. 5017–5031. https://doi.org/10.1021/ACS.CHEMMATER.3C00316

49 Boicea V.A. Energy storage technologies: The past and the present // Proceedings of the IEEE. - 2014. - Vol. 102, № 11. - P. 1777–1794. https://doi.org/10.1109/JPROC.2014.2359545

50 Chawla A., Sudhaik A., Sonu, Kumar R., Raizada P., Khan A.A.P., Ahamad T., Nguyen V.H., Selvasembian R., Kaushik A., Singh P. Recent advances in synthesis methods and surface structure manipulating strategies of copper selenide (CuSe) nanoparticles for photocatalytic environmental and energy applications // J. Environ. Chem. Eng. - 2024. - Vol. 12, № 4. - P. 113125. https://doi.org/10.1016/j.jece.2024.113125

51 Xu K., Wang L., Ge C., Wang L., Wang B., Wang Z., Zhang C., Liu G. Surface Deposition of Ni(OH)$_2$ and Lattice Distortion Induce the Electrochromic Performance Decay of NiO Films in Alkaline Electrolyte // Energy and Environmental Materials. - 2024. - Vol. 7, № 3. https://doi.org/10.1002/EEM2.12652

52 Wang J., Hong Y., Pan Y., Zhu J., Xu X., Choi W.M., Yang J. Ni-foam supported Ni(OH)$_2$ sheets decorated by MXene quantum dots for high performance supercapacitors // Materials Chemistry and Physics. - 2024. - Vol. 312. https://doi.org/10.1016/J.MATCHEMPHYS.2023.128634

53 Gao H., Xue C., Hu G., Zhu K. Production of graphene quantum dots by ultrasound-assisted exfoliation in supercritical CO$_2$/H$_2$O medium // Ultrason. Sonochem. - 2017. - Vol. 37. - P. 120. https://doi.org/10.1016/j.ultsonch.2017.01.001

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Никель гидроксидіндегі жетістіктер: құрылымдар және заманауи қолданбалар (шолу)

Аңдатпа. Бұл шолу мақаласында соңғы бірнеше онжылдықта никель гидроксиді бойынша жүргізілген зерттеулерге шолу жасалады, бұл физикада да, химияда да маңызды инженерлік қолданбалы, әсіресе батареяларда маңызды материал. Ол екі белгілі полиморфтардың, α-Ni(OH)$_2$ және β-Ni(OH)$_2$ құрылымдарын сипаттаудан басталады. Мақалада сонымен қатар никель гидроксидінде жиі кездесетін гидратация, қабаттасу ақаулары, механикалық кернеулер және иондық қоспалардың қосылуы сияқты әртүрлі бұзылулар зерттеледі. Байланысты материалдар, соның ішінде интеркалирленген α-туындылары мен негізгі никель тұздары да талқыланады. Шолу никель гидроксидін синтездеудің химиялық және электрохимиялық тұндыру, золь-гель синтезі, химиялық қартаю, гидротермиялық және солвотермиялық синтез, электрохимиялық тотығу, микротолқын көмегімен синтездеу және сонохимиялық әдістер сияқты бірнеше әдістерін жинақтайды. Соңында никель гидроксидінің белгілі физикалық қасиеттері - магниттік, дірілдік, оптикалық, электрлік және механикалық - зерттеледі. Қорытынды бөлім осы материалдардың әлеуетті құнды қасиеттерінің қысқаша мазмұнын және никель гидроксиді негізіндегі белгісіз үлгілерді анықтау және сипаттау әдістерін ұсынады.

Түйін сөздер: никель гидроксиді, аккумуляторлық технологиялар, электрокатализ, фотокатализ, наноқұрылымдар, суперконденсаторлар, электрохимиялық датчиктер,

құрылымдық бұзылулар, синтез әдістері, микротолқынды синтез, сонохимия, электрохромдық құрылғылар.

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Достижения в области гидроксида никеля: структуры и современные применения (обзор)

Аннотация: В этой обзорной статье представлен обзор исследований, проведенных за последние несколько десятилетий по гидроксиду никеля, важнейшему материалу как в физике, так и в химии с заметными инженерными приложениями, особенно в аккумуляторах. Она начинается с описания структур двух известных полиморфов, α-Ni(OH)$_2$ и β-Ni(OH)$_2$. В статье также рассматриваются различные типы беспорядка, обычно встречающиеся в гидроксиде никеля, такие как гидратация, дефекты упаковки, механические напряжения и включение ионных примесей. Также обсуждаются связанные материалы, включая интеркалированные α-производные и основные соли никеля. Далее в обзоре обобщаются несколько методов синтеза гидроксида никеля, таких как химическое и электрохимическое осаждение, золь-гель синтез, химическое старение, гидротермальный и сольвотермальный синтез, электрохимическое окисление, синтез с использованием микроволн и сонохимические методы. Наконец, рассматриваются известные физические свойства гидроксида никеля — магнитные, вибрационные, оптические, электрические и механические. В заключительном разделе представлено краткое изложение потенциально ценных свойств этих материалов и методов идентификации и характеристики неизвестных образцов на основе гидроксида никеля.

Ключевые слова: Гидроксид никеля, Аккумуляторные технологии, Электрокатализ, Фотокатализ, Наноструктуры, Суперконденсаторы, Электрохимические датчики, Структурный беспорядок, Методы синтеза, Синтез с использованием микроволнового излучения, Сонохимия, Электрохромные устройства.

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