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Electrochemical synthesis of nanodispersed zinc oxide using alternating current

Aizhan Mamyrbekova[a], Aigul Mamyrbekova[a,*], M.K. Kassymova[b], A.D. Mamitova[c], G.S. Mutasheva[d]

[a] Department of Fundamental Sciences, Faculty of Medicine, Khoja Akhmet Yassawi International Kazakh-Turkish University, Turkistan 161200 Kazakhstan

[b] Department of Food Engineering, Textile and Food Engineering Higher School, M. Auezov South Kazakhstan University, Shymkent 160012 Kazakhstan

[c] Department of Life Safety and Environmental Protection, Faculty of Architecture, Construction and Transport, M. Auezov South Kazakhstan University, Shymkent 160012 Kazakhstan

[d] Department of Soil Science, Agrochemistry and Ecology, Faculty of Agrobiology, Kazakh National Agrarian Research University, Almaty 050010 Kazakhstan

[*]Corresponding author, e-mail: aigul.mamyrbekova@ayu.edu.kz

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ABSTRACT: The possibility of obtaining nanodispersed zinc oxide by electrolysis on alternating current of industrial frequency was shown. The parameters of electrolysis, influencing the electrochemical oxidation of zinc in neutral solutions and the rate of formation of the zinc oxide powder were studied. The effect of electrolyte composition on the electrode process at a zinc electrode was investigated using polarization measurements. The electrochemical behavior of the zinc electrode in neutral sodium salt solutions in the concentration range of 0.4–4.0 mol/l, at temperature range of 20–50 °C, and at 5 to 100 mV/s sweep rates was studied. The anodic potentiodynamic curves in 0.4 mol/l $NaClO_4$, CH_3COONH_4, Na_2SO_4, $NaNO_3$, and NaCl solutions were recorded. From the polarization curves, it was established that the rate of anodic ionization of zinc increases in the following series: $CH_3COONH_4 < NaClO_4 < NaNO_3 < Na_2SO_4 <$ NaCl. It has been stated that during anodic oxidation of zinc, zinc oxides and hydroxocomplexes are the by-products of the electrode process. A comprehensive study of zinc oxide powders obtained by electrosynthesis using modern physicochemical methods (electron microscopy, X-ray phase analysis, IR spectroscopy, and thermogravimetry) was carried out, which made it possible to establish their qualitative composition and particle sizes that make up these compounds.

KEYWORDS: electrolysis, alternating current, zinc oxide, nanodispersed powder, microwave radiation

INTRODUCTION

In recent years, studies on the synthesis of ultrafine metal powders with a given structure and dispersion, due to which they can be used to create new effective materials for various purposes, have attracted more and more attention. Alternating current (AC) has a wide range of applications in various fields of production [1]. Using AC, a variety of redox electrochemical reactions can be carried out in solutions with or without electrode material. In particular, electrolysis with AC can destroy metals to form nanodispersed powders. This inevitably raises the question of the electrochemical behavior of the electrode material, specifically its stability under AC [2]. Using various forms of AC allows for significant intensification of anodic dissolution processes, elimination of electrode passivation, and significant simplification of nanodispersed powders production technology. It was discovered that with the same current densities, the voltage when using AC is nearly twice as low as when using direct current (DC), making the process more energy efficient [3]. It should be noted that the following advantages of AC electrolysis over DC electrolysis: the ability to use higher current densities at a lower voltage on the electrolyzer terminals, reduced electrical energy consumption during electrochemical processes on AC, and simple hardware design. The transition from DC to AC of various forms (pulsating, asymmetric, pulsed), including AC with a regulated component, has a positive effect on the synthesis of new compounds [4].

The renewed interest in nonstationary electrolysis is due to a change in goals and objectives. Currently, electrolysis under non-stationary conditions was considered as a method for producing metal oxides with a set of obvious advantages, in particular, compared with DC electrolysis [5].

There are a small number of reviews in the literature on aspects of electrochemical synthesis and characterization of zinc oxide nanoparticles on DC. Relatively recently, the authors presented a review on electrodeposited zinc oxide nanoparticles: synthesis, characterization, and anti-cervical cancer effects [6]. The authors proposed electrochemical synthesis and characterization of zinc carbonate and zinc oxide nanoparticles. Zinc carbonate nanoparticles with different sizes were electrodeposited by electrolysis of a zinc plate as anode in sodium carbonate solution. The electrosynthesized $ZnCO_3$ nanoparticles were calcined

at the temperature of 600 °C to prepare ZnO nanoparticles [7]. By other authors, the electrodeposition of ZnO nanoparticles along the vertically aligned carbon nanotubes (VACNTs) was performed using a three-electrode set-up. A short parametric study on the electrodeposition conditions led to the choice of these parameters to obtain an unprecedented and homogeneous association of electrodeposited ZnO with dense VACNT carpets. Samples were then annealed at 450 °C during 5 min to get rid of the residual component after electrodeposition [8]. In the works described above, zinc oxide was proposed to be obtained by anodic oxidation of metal with additional heat treatment of resulting product, which is a disadvantage of the DC method.

During electrochemical oxidation using DC, organic compounds have to be added to the electrolyte, which prevent particle agglomeration. The introduction of organic compounds, usually with low electrical conductivity, leads to an increase in energy consumption for electrolysis [9]. Zinc oxide is proposed to be obtained from zinc acetylacetonates by electrolysis of acetylacetone and electrolyte in acetonitrile, using as electrodes a metal that is part of the resulting acetylacetonate. The introduction of organic compounds, usually with low electrical conductivity, leads to an increase in energy consumption for electrolysis.

Electrochemical synthesis of metal oxides using non-stationary modes made it possible to obtain metal oxides with a nominal diameter of primary particles in the range of 10^{-9} to 10^{-6} m [10]. The oxides obtained by electrochemical synthesis have a number of advantages, such as: highly developed surface and dispersion of the material, the presence of a large number of mesopores, and also the minimum content of impurities in the synthesis products [11]. The products obtained by this method are quite different from the products obtained by other chemical and physical methods. An analysis of the synthetic methods of nanodispersed zinc oxide showed that the hydrothermal synthesis method, the method of thermal deposition, and the method of chemical precipitation from solution are traditionally used [12, 13]. The size of zinc oxide particles is affected by temperature, duration of synthesis, and concentration of solution components, while it must be borne in mind that impurities can reduce the degree of aggregation. ZnO nanoparticles are synthesized by various physicochemical methods, but many of these methods have such disadvantages as high cost, the need for high temperature, high pressure, specialized equipment, the use of toxic and environmentally hazardous chemicals, which lead to high energy consumption and the formation of a large amount of waste that is dangerous to the environment [14].

One of the most important advantages of the electrochemical method is the possibility of obtaining ultrapure metal oxides. Also, the practical value of the method is increased by the fact that the regulation of the parameters of electrochemical synthesis makes it possible to produce powders with a given dispersion. Of particular relevance among the variety of methods is finding fairly simple economical and environmentally friendly methods for the synthesis of nano- and micro-sized dispersed materials based on zinc oxides. The study of electrochemical oxidation of metals using AC becomes relevant with the development of modern trends in domestic science associated with the development of high-tech multifunctional materials based on metal oxide nanopowders. Currently, zinc oxide has aroused wide research interest due to its unique properties, such as high refractive index, high electrical conductivity and others [15, 16]. The use of zinc oxide nanoparticles in the presence of other metal oxides is becoming increasingly important in biomedicine and oncology due to the physicochemical properties of these nanomaterials [17–19].

One of the promising materials for future generations of micro-, nano-electronic and sensor technology are metal oxides. A small number of works are devoted to the question of electrochemical synthesis of metal oxides using AC. Scientists have studied the effect of the composition and concentration of the electrolyte, current density and electrolysis temperature on the oxidation rate of metals (Cu, Cd, Ti, Zn, Sn, Ni, Al, Pb, Fe, Mo) during polarization with AC with a frequency of 50 Hz [20, 21]. The possibility of obtaining copper oxides with a high specific surface area by electrolysis of metallic copper using an AC of industrial frequency is shown. The phase composition and characteristics of the porous structure of electrosynthesis products were determined depending on the modes of the process [22]. Studies of the electrochemical behavior of metals and alloys during the passage of AC of various forms are given in the work [23]. It has been shown that when AC is applied, the resulting process is the dissolution of metals. This effect is especially noticeable for valve metals, which are difficult to dissolve when polarized by DC (Ti, Al, Ta, Nb, W, etc.). This effect makes it possible to obtain various valuable compounds easily. Especially important is the possibility of obtaining a variety of salts in the form of solutions or powders, the use of which is economical and multifunctional.

Despite such a significant amount of research on the electrosynthesis of metal oxides under non-stationary conditions, there are few works on the production of zinc oxides using AC. Most of the works are devoted to the synthesis of thin films of zinc oxide by hydrothermal synthesis [24–26]. Nanostructured zinc oxide particles possess unique semiconductor, piezo- and pyroelectric characteristics necessary not only for nanoelectronics and other industries but also for medicine and pharmacy [27–29].

Summarizing the review on the production of nano- and micro-sized dispersed materials based on metal oxides, we note that in many cases, unsteady

electrolysis allows achieving effects that either cannot be achieved using DC, or can be achieved under much more difficult conditions. By varying the process parameters, it is possible to obtain powders with specified properties, as well as zinc-based oxide systems, which have recently been widely used in the chemical, electrical industry, medicine and radio electronics [30, 31]. In this regard, the development of a fairly simple and environmentally safe method for the electrochemical synthesis of nanodispersed zinc oxide powders, which stands out as an independent phase, is of great scientific interest. The aim of the present study is to obtain nanodispersed zinc oxide by electrolysis under non-stationary conditions in neutral solutions, to study the phase composition of the electrosynthesis product of zinc oxide.

MATERIALS AND METHODS

Electrolysis by alternating current

Nanodispersed zinc oxides were obtained by electrochemical oxidation of metal electrodes in neutral solutions under the action of a symmetric AC of industrial frequency at 50 Hz. Two identical zinc plate electrodes with an area of S = 15 cm^2 were placed in electrolyte solutions and an AC was passed with constant stirring. During the experiment, technological parameters such as current density values, temperature, electrolysis time, and electrolyte concentration were varied in order to obtain powders with high dispersion.

The nature of the electrolyte is a key factor in the electrochemical oxidation of metals with AC [32]. Considering that metallic zinc and its oxide compounds have amphoteric properties, we have previously experimentally tested solutions of various salts as an electrolyte: $NaClO_4$, CH_3COONH_4, Na_2SO_4, $NaNO_3$ and NaCl. The experiments have shown that it is most appropriate from a technological and economic point of view to use solutions of Na_2SO_4, $NaNO_3$ and NaCl for the zinc oxide synthesis. The selected electrolytes exhibit high electrical conductivity, maintain the insolubility of metals and their oxides in solution, form a porous layer of oxidation products on the electrode surface, allow easy removal of these products from electrolyte ions, and are free of impurities.

Electrochemical oxidation was carried out in electrolyte solutions of sodium chloride and sodium nitrate, in a concentration range of 0.4 to 4 mol/l, and sodium sulfate in a concentration range of 0.2 to 1.5 mol/l. All the reagents (NaCl, Na_2SO_4, $NaNO_3$) were purchased from Sigma-Aldrich (USA) and used without further purification. The electrolysis was carried out at temperatures of 40–50 °C and a current density of 0.5–2.5 A/cm^2. The choice of the current densities in the range of 0.5–2.5 A/cm^2 is due to the fact that at higher values of current density, rapid heating of the electrolyte is observed, which leads to instability process of electrosynthesis. The limitation of the electrolysis temperature regime is explained by the intensive evaporation of electrolyte solutions. This leads to an increase in the concentration of the electrolyte solution, a decrease in the working surface of the electrodes, and an increase in current density and strong fluctuations in the current in the circuit.

The resulting suspensions of composite materials were filtered, repeatedly washed with distilled water, and dried under the influence of microwave radiation. Microwave power ranges from 200–1,100 W, with a radiation frequency of 2.5 GHz and a treatment time of 5–25 min [33]. The use of microwave radiation as a substitute for the drying and heat treatment stages is efficient because it allows for uniform distribution of electromagnetic microwave radiation across the entire volume of zinc oxide samples, affecting the quality and dimensional characteristics of zinc oxide powders.

The rate of formation of zinc oxide was determined from the rate of weight loss of electrodes per unit time. During the electrolysis, the main parameters were monitored: the values of the current density and voltage on the electrolyzer, the temperature and the changes in the potentials of electrodes over time were recorded. The potentials were measured relative to a saturated silver chloride reference electrode.

Physicochemical studies of zinc oxide powders

The structure of the resulting powders was studied by electron microscopy. The INCA Energy dispersive microanalysis system (OxfordInstruments, Great Britain) was used in conjunction with an ISM-6490LV scanning electron microscope (JEOL, Japan).

The specific surface area of zinc oxide samples were determined by low-temperature adsorption of argon on a helium-argon mixture using the Brunauer-Emmett-Teller (BET) method and a sorbtometer "Color 211" (Meta-sorbi, Russia). Zinc oxide powders were thermogravimetrically measured on a "Microthermometer TG 209 F1" (Netzsch, Germany) in the temperature range of 20 to 960 °C. The sample was heated at a rate of 10 K/min. The powders were heated in an air and argon atmosphere [34]. The spectrum was recorded with the Fourier Transform Infrared Spectrometer, Shimadzu IR-Prestige 21 (Shimadzu, Japan), within the spectral range of 400–4000 cm^{-1} and resolution of 4 cm^{-1}.

RESULTS AND DISCUSSION

Kinetics and mechanism of electrooxidation of zinc in neutral solutions

Polarization measurements in a neutral medium were performed to investigate the influence of pH environment on the mechanism of electrode processes on the zinc electrode. The cyclic cathode and anode-cathode polarization curves were recorded to elucidate the mechanism of processes occurring on the zinc electrode under the action of AC, and the AC polarization

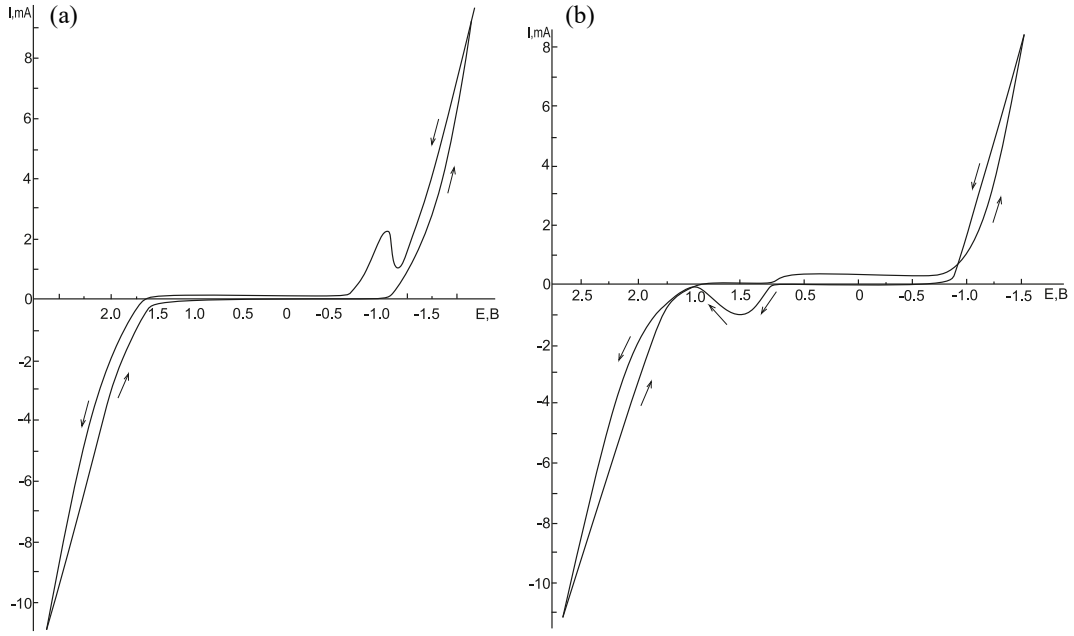


Fig. 1 Cyclic voltammetry diagram on zinc electrode in 0.5 mol/l sodium chloride: (a) cathodic and anodic; (b) anodic and cathodic.

was simulated to some extent. A feature of electrochemical oxidation under non-stationary conditions is that when AC is applied to DC, the polarity of the electrodes changes over time with a set frequency of 50 Hz, therefore, oxidation and reduction processes occur on the same electrode.

The electrochemical behavior of the zinc electrode in neutral sodium salt solutions with concentrations ranging from 0.4 to 4 mol/l was investigated at temperatures ranging from 20 to 50 °C and potential sweep rates ranging from 5 to 100 mV/s.

Fig. 1a depicts the cathode and anode cyclic polarization curves of the zinc electrode in 0.4 mol/l sodium chloride solution. When the potential in the polarogram was shifted in the cathodic direction, only the current of zinc ions reduction to the metallic state was observed according to the following reaction [35]:

$$Zn^{2+} + 2e^{-} \rightarrow Zn^{o} \tag{1}$$

When the potential shifts to a more electronegative region, the evolution of hydrogen was observed. No oxidation currents were observed in the voltammetry diagram after shifting the potential from the cathodic to the anodic region, up to the oxygen release potential. Probably, during the electrochemical oxidation of a zinc electrode under the action of AC in order to obtain metal oxide, hydrogen is formed during the cathode period of the current, diffusing into the gas phase and thereby helping to free electrode surface from the film of oxidation products. This leads to a decrease in the resistance at the electrode–solution interface and, as a result, to an increase in the intensity of the process. Hydrogen not only removes products from the electrode surface, but also contributes to their dispersion, which makes it possible to obtain product with particle size in the nanometer range with specific structure. This assumption was also confirmed by the literature data [36, 37].

According to the following equation, anode-cathode cyclic voltammetry on the electrode revealed that in a 0.5 mol/l sodium chloride solution, at the anode sweep in the region from zero to "plus" 2.5 V, there is a zinc oxidation current to zinc ions (Fig. 1b) according to the following equation [38]:

$$Zn^{o} - 2e^{-} \rightarrow Zn^{2+} \tag{2}$$

In the reverse course of the curve, no zinc ions reduction currents were observed. The absence of cathodic current of zinc ions reduction on the polarogram was connected with running of hydrogen release reaction.

To study the nature of anion electrolyte, the anodic potentiodynamic curves in 0.4 mol/l solutions of $NaClO_4$, CH_3COONH_4, Na_2SO_4, $NaNO_3$ and NaCl were taken (Fig. 2). The anodic ionization rate of zinc increases in the following series, as shown by the polarization curves.

$$CH_3COONH_4 < NaClO_4 < NaNO_3 < Na_2SO_4 < NaCl$$

The nature of the electrolyte anion influences the rate of anodic oxidation of zinc, and the process is more effective and polarized in sulphate and sodium chloride solutions. Based on the research findings, it

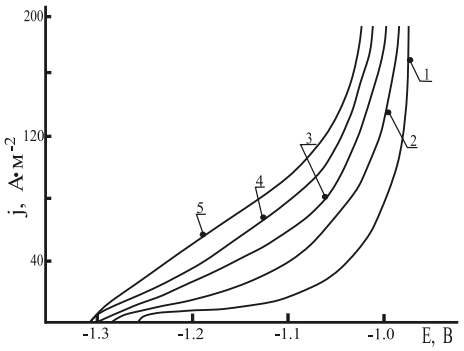


Fig. 2 Anode potentiodynamic polarization curves at electrolyte concentration of 0.4 mol/l and sweep rate of 5 mV/s: 1, CH_3COONH_4; 2, $NaClO_4$; 3, $NaNO_3$; 4, Na_2SO_4; 5, NaCl.

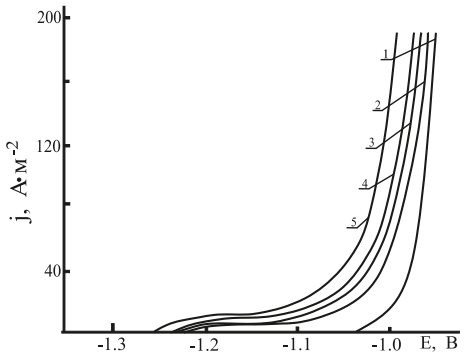


Fig. 3 Anode potentiodynamic polarization curves at electrolyte concentration of 0.4 mol/l sodium chloride and sweep rate of 5 mV/s: 1, 20 °C; 2, 30 °C; 3, 40 °C; 4, 50 °C; 5, 60 °C.

was discovered that zinc has electrochemical activity in sodium chloride solution, allowing this electrolyte to be used in electrolysis for the synthesis of zinc compounds.

The deposition of ZnO is an electrochemically induced precipitation process. Depending on the electrolyte solution, dissolved oxygen (reaction (3)) or nitrate ions (reaction (4), in the case of electrolyte $NaNO_3$) react producing OH^- close to the electrode/electrolyte interface. The electrogeneration of base leads to an increase of interfacial pH allowing the precipitation of zinc hydroxide (reaction (5)) on the surface of working electrode. Then, zinc hydroxide easily dehydrates to zinc oxide (at temperature generally > 40 °C) following reaction (6). For electrolyte solution containing NaCl at temperature above 40 °C, $ZnCl^+$ is the predominant species present in solution, thus the deposition of ZnO can be also attributed to reaction (7) [39].

$$O_2 + 2H_2O + 4e^- = 4OH^- \quad (3)$$

$$NO_3^- + H_2O + 2e^- = NO_2^- + 2OH^- \quad (4)$$

$$Zn^{2+} + 2OH^- = Zn(OH)_2 \quad (5)$$

$$Zn(OH)_2 = ZnO + H_2O \quad (6)$$

$$ZnCl^+ + 2OH^- = ZnO + H_2O + Cl^- \quad (7)$$

From these reaction mechanisms, it is clear that the deposition of ZnO depends upon many parameters such as the nature of the electrolyte and its concentration, temperature, and the presence of dissolved oxygen. Consequently, to optimize the deposition process, it was necessary to fine tune all these parameters.

The influence of temperature on electrochemical oxidation of zinc was also investigated. Polarization measurements were carried out in the temperature range of 20–60 °C. The electro-oxidation rate of zinc increased with increasing temperature up to 50–60 °C (Fig. 3).

The heterogeneous rate constants of electrochemical processes have been determined using polarization curves processing ionic transfer and diffusion coefficients. Using Matsuda and Ayabe Equation [40] and the difference of peak and half-peak potentials of voltammetry diagrams, transfer coefficients (α) of electrons for the stage of anodic process were calculated (Table 1). The Matsuda equation was used to calculate the heterogeneous rate constants of electrode processes. The heterogeneous rate constant for zinc oxidation stage in alkaline medium had a lower value k_s than in neutral medium, as shown in Table 1. According to Matsuda and Ayabe criteria, the values of rate constants of the electrode process of zinc oxidation in investigated media attested to an irreversible process on zinc electrode.

Table 1 Kinetic parameters of metallic zinc oxidation.

Reaction of medium	α	D (cm^2/s)	k_s (cm^2/s)
	$Zn^o - 2e^- \rightarrow Zn^{2+}$		
Alkaline	0.47	1.73×10^{-4}	3.6×10^{-3}
Neutral	0.53	1.62×10^{-4}	4.1×10^{-3}

The calculated values of the effective activation energy E_a for the process stage in the investigated temperature range from 20–60 °C in the alkaline and neutral media were 19.85 and 17.44 kJ/mol, respectively. The activation energy values obtained indicate that the electrochemical process is under diffusion-kinetic control.

The analysis of polarization measurements made it possible to determine the optimal conditions for electrolysis under AC. Electrolysis under non-stationary conditions was carried out in electrolyte solutions of sodium chloride and sodium nitrate in the concentration range of 0.4–4 mol/l, sodium sulphate in the concentration range of 0.2–1.5 mol/l, at temperature range of 40–50 °C, after filtering, washing, and treatment with microwave radiation.

The choice of microwave radiation was based on research that demonstrated that the range of these

Table 2 Conditions of electrolysis and microwave treatment to produce nanodispersed zinc oxide powder Please add unit of Microwave power, and put unit in all columns in ( ).

No	Electrolyte, concentration (mol/l)	Current density (A/cm^2)	Temperature (°C)	Microwave power (W)	Microwave treatment time (min)	Particle size (nm)	Specific surface (nm^2/g)
1.	NaCl, 2.0	1.0	45	1,000	5	5–10	27.0–29.0
2.	Na_2SO_4, 0.5	2.0	50	600	15	15–20	21.0–23.0
3.	$NaNO_3$, 2.5	1.4	40	800	10	10–15	23.0–25.0

values of power ensures, when compared to conventional heat treatment, high speed, uniform heating throughout the dispersion phase, and the formation of zinc oxide powder with a given structure and dispersion. The use of microwave radiation accelerates the synthesis of nanodispersed zinc oxide powders, while also significantly reducing energy costs and process time. By varying the concentration of electrolytes, the current density at low electrolysis temperatures, followed by the effect of microwave radiation on the zinc oxide powder, it is possible to obtain nanodispersed powders with a high specific surface area and a particle size.

Electrochemical oxidation of zinc by electrolysis under non-stationary conditions

Electrooxidation from neutral electrolyte solutions was carried out at low temperatures (40–50 °C) using zinc electrodes placed in parallel in the electrolyzer. The process was conducted at current densities of 0.5–2.5 A/cm^2, with polarization by symmetrical AC at a frequency of 50 Hz. During the process, a highly dispersed zinc oxide powder was formed. After the electrolysis, the powder was separated from the electrolyte by filtration, washed with distilled water, and dried under microwave radiation. The microwave power was 200–1,100 W, with a radiation frequency of 2.5 GHz, and treatment time of 5–25 min.

Table 2 shows the electrolysis and microwave treatment conditions for nanodispersed zinc oxide powder.

Specific surface, dispersity and porosity of zinc oxide powders

The product of electrochemical oxidation of zinc electrodes was subjected to differential thermal (DTA) and thermogravimetric analysis (TG) under the following conditions: sample weight == 115.0 mg, heating rate == 10 K/min, and final temperature = 960 °C. Adsorbed moisture is removed at temperatures up to 230 °C. The oxidation of zinc to zinc oxide caused a 2.5% increase in the mass of the sample at temperatures ranging from 230 to 320 °C (Fig. 4).

The results of the analysis indicate that the metal zinc oxidizes to ZnO in the specified temperature range. The exothermic effect corresponding to this process appears on the background of wide exo-effect

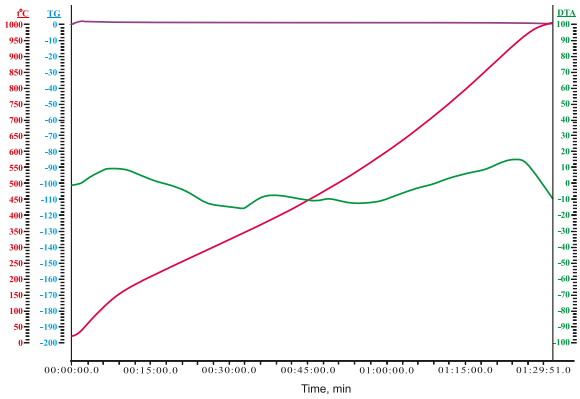


Fig. 4 TG/DTA analysis of zinc electrochemical oxidation product.

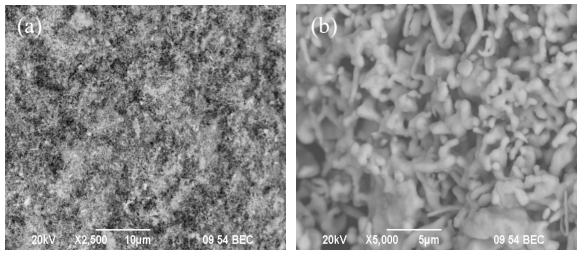
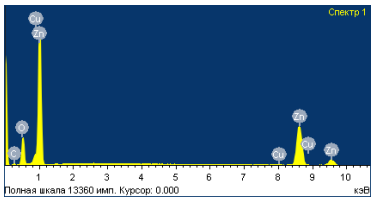


Fig. 5 Micrographs of zinc oxide powder obtained by electrolysis in a sodium nitrate solution of 2.5 mol/l and a current density of 1.4 A/cm^2: (a) ×2500; (b) ×5000.

of crystallization and recrystallization of zinc oxide. Electrolysis product electron-microscopic studies were carried out with the goal of studying the morphology of zinc oxide powder microcrystals and determining particle sizes formed during electrochemical oxidation of zinc electrodes on AC. The microphotographs obtained from the electron-microscopic analysis are shown in Fig. 5. The particles have different shapes. Some particles have rounded shapes and are aggregated, while others have elongated irregular shapes. Under magnification (×5000, Fig. 5b), the size of aggregated spherical nanoparticles is 10–15 nm, which is smaller than the particles with irregular geometric shape. The elemental composition and IR-spectrum of zinc oxide powder obtained by electrolysis in sodium

Elements	Weight, %
C	3.94
O	15.24
Cu	0.51
Zn	80.31



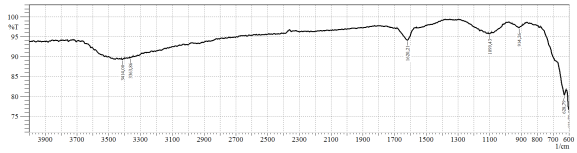


Fig. 6 Elemental composition and IR-spectrum of zinc oxide powder obtained by electrolysis in a sodium chloride solution of 2.5 mol/l and a current density of 1.4 A/cm^2.

chloride solution of 2.5 mol/l and the current density of 1.4 A/cm^2 is shown (Fig. 6).

A wide absorption band of 3300–3600 cm^{-1} indicates the interaction of zinc oxide with moisture, which probably corresponds to the presence of unbound water in the studied samples, which is not completely removed during the drying process. The IR spectra of the studied ultrafine ZnO powders also contain absorption lines at 1620.21; 1099.43 and 914.26 cm^{-1}. The characteristic modes corresponding directly to ZnO are the mode at 600 cm^{-1} and the absorption band at 628 cm^{-1}, observed with deformation lattice vibrations of Zn=O bonds.

CONCLUSION

Thus, carrying out the electrolysis process using an AC of an industrial frequency of 50 Hz allows for the electrochemical oxidation of zinc electrodes in sodium chloride and nitrate, and sodium sulfate solutions. By varying the concentration of electrolytes, the current density at low electrolysis temperatures, followed by the effect of microwave radiation on the zinc oxide powder, it is possible to obtain nanodispersed powders with a high specific surface area of 23.0–29.0 m^2/g and a particle size of 5–20 nm. The use of microwave radiation instead of the processes of drying and heat treatment of the powder after the electrolysis process leads to a reduction in energy costs and time for carrying out the processes of zinc oxide synthesis.

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