

## AUTHOR'S REFERENCE

### **of the scientific contributions in all publications of Assistant Professor Dr. Nelly Dimitrova Boshkova**

My current activity at the Institute of Physical Chemistry, Bulgarian Academy of Sciences (IPC-BAS) covers scientific and applied research in the following areas:

**Area 1 - Improving the corrosion resistance and protective ability of low carbon steel by application of electrodeposited galvanic and/or composite (hybrid) coatings; corrosion inhibitors; conversion passive films.**

**The main scientific subareas are:**

*1.1. Zinc and zinc alloy galvanic and composite (hybrid) coatings with embedded polymer nanoparticles (stabilized polymer micelles), including multilayer systems based on them;*

*1.2. Zinc composite (hybrid) coatings containing nanocontainers with corrosion inhibitor;*

*1.3. Composite (hybrid) coatings with embedded different types of inorganic or organic particles - ZnO, CuO, PANI, carbon spheres, carbon nanotubes;*

*1.4. Corrosion inhibitors;*

*1.5. Conversion surface passive films.*

**Area 2 - Preparation and corrosion characterization of protective systems based on sol-gel coatings.**

**Area 3 - Other articles.**

So far, I am a co-author of a total of 41 scientific papers on the above thematic areas. These articles have been published mainly in foreign journals, most of them with IF or SJR, as well as in full text in Proceedings of symposia, congresses and conferences with Bulgarian and international participation.

I have also published four articles with co-authors in the form of book chapters and I have one patent, also with co-authors, on the above subject.

So far I have established 80 citations of my publications by Bulgarian and foreign authors, of which 58 citations are on articles that are not included in my PhD thesis. All publications published so far correlate with one of the main thematic priorities of IPC-BAS, related to advanced materials and technologies based on electrochemically obtained metal, alloy and modified polymer coatings with protective, decorative and electrocatalytic properties.

The main contributions according to the above thematic areas of scientific interest and the research I have conducted can be summarized in groups as follows:

***Area 1 - Improving the corrosion resistance and protective ability of low carbon steel by application of electrodeposited galvanic and / or composite (hybrid) coatings; inhibitor compositions; conversion passive films.***

***Area 1, 1.1. Zinc and zinc alloy galvanic and composite (hybrid) coatings with embedded polymer nanoparticles (stabilized polymer micelles), including multilayer systems based on them***

*Zinc and zinc alloy galvanic coatings*

The conditions of electrodeposition (electrolyte composition, pH, current density, temperature) of zinc coating from weakly acid electrolyte, as well as some double alloys of this metal - Zn-Mn [12, 14, 20] and Zn- Co [20, 32, 34, 38, 39, 41] have been determined and optimized. The corrosion behavior of these coatings (including multilayer systems based on them [31]) was studied in a model medium of 5% NaCl by various methods: polarization resistance ( $R_p$ ), potentiodynamic polarization curves (PDP), electrochemical impedance (EIS) and other aiming to determine their effectiveness in relation to the classical zinc coating.

Experiments have confirmed the better corrosion resistance of both types of alloys compared to pure zinc in this medium, and the results were explained by the appearance of a corrosion product with a low product of solubility -  $10^{-14.2}$  [12, 20, 28, 34]. The latter was determined using X-ray diffraction (XRD) analysis [17, 23, 34] and X-ray photoelectron spectroscopy (XPS) [28]. This is the compound zinc hydroxychloride (ZHC), which possesses the so-called "barrier properties" and improves the corrosion resistance, impeding the penetration of the destructive process deeply inside. The protective action of the alloy component (Mn or Co) is generally associated with a local increase in the pH value of the medium, which favors the appearance of a corrosion product with a low product of solubility.

The Zn-Co alloy coating is bright and has a very good decorative appearance, as well as better corrosion characteristics than zinc at a low content of the alloying component - within 1-3

weight percent. In the case of the Zn-Mn alloy, which also demonstrates increased corrosion resistance compared to the zinc in a model solution of 5% NaCl, the alloying component content is higher (about 11 wt.%), and the coating is matte. Both types of alloys are derived from stable electrolytes. Different types of multilayer systems with good corrosion resistance in the same model environment have been also elaborated. The Zn-Mn(11 wt.%) alloy is used as a sublayer due to its not very good decorative appearance. As a finishing layer, either a bright zinc coating or a Zn-Co alloy (1-3 wt.%) with a very good appearance is applied. The systems can be treated into conversion compositions, i.e. to be with or without additional surface film, respectively [14, 19, 25, 29, 31].

Based on the obtained results, zinc and zinc alloy composite (hybrid) coatings and systems with embedded polymer nanoparticles (stabilized polymer micelles - SPM) were developed. The research was carried out as follows:

#### *Zinc composite (hybrid) coatings*

The electrochemical conditions of deposition of composite zinc coatings with four different types of polymer particles were established [17, 20, 23, 25, 28, 34, 36, 38, 39, 40, 41]. The polymer particles (PP) used are derived from two- or three-block copolymers and are of the „core-shell” type. The hydrophobic core is based on polypropylene oxide (PPO) or polystyrene (PS), and the shell is hydrophilic and is made of polyethylene oxide (PEO) or polyhydroxymethacrylate (PHEMA). Preliminary particle stabilization has been found to play an important role. It allows the core, shell or both parts to be stabilized. The stabilization process was performed by ultraviolet treatment or atomic transfer radical polymerization in the presence of various reagents (e.g. macro- or photoinitiators). The size and shape of the particles embedded in the zinc matrix were determined with a Transmission Electron Microscope (TEM), and the appearance of the resulting coatings – by application of scanning electron microscopy (SEM) [20, 23, 25, 28, 34, 36, 38].

Composite zinc coatings are deposited from the same electrolytes as the galvanic ones, but with the addition of certain amounts of PP, and the concentration of the latter is very important in order to obtain optimal corrosion resistance and protective ability [17, 20, 25, 31]. The influence of PP on the cathodic and anodic processes of deposition and dissolution was studied using cyclic voltammetry. It has been found that in the case of zinc, the presence of PP does not lead to depolarization or overpolarization, but the cathodic (and also the anodic) processes are more intensive [17, 20].

The corrosion resistance of composite zinc coatings was studied using the methods of polarization resistance ( $R_p$ ), potentiodynamic polarization curves (PDP), electrochemical

impedance (EIS), scanning vibration-electrode technique (SVET), atomic force microscopy (AFM). Studies with external anodic polarization in a model solution of 5% NaCl have shown that the strongest influence of PP was on the course of the anodic curve of the ordinary zinc, where the so-called "pseudo-passive zone" appears, the latter being generally not observed for Zn in this environment [23, 34]. Measurements by Rp and EIS methods also generally confirmed the increased protective parameters of the composite coatings compared to the conventional zinc [17, 20, 25, 28]. The concentration of the particles is essential, and with its increase the protective indicators in the model environment slightly deteriorate. The SVET method was used to investigate the appearance and development of corrosion processes on the surface of the samples, as well as the distribution of the cathodic and anodic currents. It was found that local corrosion processes are initially more intense on the surface of the composite coatings, but after some (not very long) period the trend is reversed and the rate of the processes slows down, as the affected areas on the surface partially expand, but do not penetrate into the depth. The reason for this observation is the appearance of a mixed film containing ZHC and polymer particles. The latter are stable in this environment and their presence in the film contributes to the transformation of the local corrosion into general, in contrast to the situation with the conventional galvanic zinc [23, 25, 28, 29, 36]. The presence of this mixed film was also confirmed by XRD and XPS [17, 20, 23, 28, 29, 34] as well as AFM [36].

#### *Zinc alloy composite (hybrid) coatings*

These coatings are obtained in the same way as the zinc ones – the electrolytes for galvanic alloys are used with the addition of a certain amount of PP under identical electrodeposition conditions. The influence of the polymer inclusions on the corrosion resistance of Zn-Co (1-3 wt%) and Zn-Mn (11 wt%) alloys [20, 31, 34, 38] has been established using the same methods as for ordinary zinc. In the case of the Zn-Co alloy, no significant changes were found in the course of the anodic curves for its composite variant. Studies with CVA have shown some depolarization in the cathodic zone and more intensive anodic processes compared to the conventional galvanic alloys [20]. However, in contrast to the composite zinc coating, the presence of PP in the alloy somewhat impairs the protective properties in this environment [34]. This result is due to the different structure and morphology of the alloy, where additional internal stresses in the metal matrix and texture changes occur, leading to faster separation (detachment) of some areas of the coating [34].

However, in the case of the Zn-Mn alloy (11%), the presence of PP improves the corrosion resistance in this medium [20], and the results were confirmed by measuring the polarization

resistance of the samples over a long period of time. This alloy also has an accelerated tendency for passivation in the presence of PP at conditions of external anodic polarization [20]. Investigations with CVA method have shown that overpolarization is observed in the presence of PP, but unlike Zn and the Zn-Co alloy, here the anodic processes are less pronounced than in the galvanic alloy without PP presenting in the electrolyte [20] .

***Area 1, 1.2. Zinc composite (hybrid) coatings containing nanocontainers with corrosion inhibitor***

*Zinc hybrid coatings containing polymer nanocontainers with hematite core*

Zinc composite coatings containing embedded polymer nanocontainers with inhibitor Benzotriazole were also obtained [18]. An alpha-hematite core was used, which was successively coated with two polymer layers by application of the “layer-by-layer” method. The first layer was polyacrylic acid (PAA) and was negatively charged, while the second one was polydimethyldialylammonium chloride (PDADMAC) with a positive charge. A certain amount of inhibitor was included between the two layers. Because the polymer shell is sensitive to changes in the pH value, it tears open when this parameter decreases. Therefore, as the corrosion process progresses, at some point the inhibitor is released from the polymer shell and begins to slow down the corrosion rate in the area around the nanocontainers (NC). The results obtained by PDP, Rp and EIS methods confirmed these expectations. The influence of the NC on the cathodic and anodic processes was studied with cyclic voltammetry. Their presence strongly depolarize the cathodic process and increase the rate in the anodic part. Potentiodynamic studies have shown that the zinc composite coating has a lower corrosion current in a model medium of 5% NaCl under external anodic polarization [18].

*Zinc hybrid coatings containing kaolinite core nanocontainers*

Another study investigates the possibility of producing NC with a kaolinite core [13, 16] and a Benzotriazole inhibitor. The aim was to increase the corrosion resistance and protective ability of the coating, as it is known that kaolinite has well-defined barrier properties, which are expected to prevent the penetration of the corrosive agents deeply inside. The same polymer encapsulation technique was used as for hematite. Using the CVA method, the influence of NC on the cathodic deposition processes and the anodic processes on dissolution was established. It was found that in the presence of NC the cathodic process occurs with overpolarization in comparison both with respect to conventional zinc and to the composite coating with embedded NC with hematite core [13,16]. The results obtained by the PDP, Rp and EIS methods confirmed that in a model environment of 5% NaCl the composite coating has better corrosion

resistance - longer anode curve at the conditions of external anodic polarization, higher polarization resistance at the end of 30-days test period and increased impedance characteristics. Additional clarity regarding the protective ability of this composite coating was shown by studies with XRD and XPS methods, which determined the composition of corrosive products, one of which demonstrates well-defined protective properties due to its low product of solubility value - ZHC. It should be added that here (as in the case of NC with hematite core) a mixed protective film of ZHC, residues of the polymer shell and areas where the inhibitor has spread appear. All this contributes to the increased corrosion resistance of this type of composite coating.

*Zinc hybrid coatings containing polymer nanocontainers with ZnO core*

These composite coatings contain nanocontainers with a ZnO core and inhibitor Safranin. ZnO cores are treated with polyethyleneimine (PEI) in order to further stabilize the resulting suspension, and the encapsulation of Safranin is realized using the "layer-by-layer" technique. Polyacrylic acid (PAA) and polyethyleneimine (PEI) are applied for this purpose. In contrast to the previous two cases, a thin sublayer of polymer modified ZnO is initially deposited here, followed by a finishing zinc layer. The aim was to obtain a system in which the sublayer was applied directly to the protected low-carbon steel substrate in order to have a barrier effect on the penetration of chlorine ions in depth. Corrosion studies have confirmed the improved protective characteristics of the coating - a longer anodic curve at external polarization and a higher value of the polarization resistance compared to ordinary zinc coating [5].

***Area 1, 1.3. Composite (hybrid) coatings with embedded different types of inorganic and organic particles - ZnO, CuO, PANI, carbon spheres, carbon nanotubes;***

*Zinc hybrid coatings with embedded polymer modified ZnO particles*

These composite coatings were prepared as described above, but in this case the polymer modified ZnO particles were incorporated directly into the coating without NC with inhibitor [5]. The same assessment methods were applied and it was found that even in the absence of an inhibitor, the presence of these particles leads to increased anti-corrosion performance compared to ordinary zinc coating, although not to the extent recorded in the presence of inhibitor.

*Zinc hybrid coatings with embedded polymer modified CuO particles*

These coatings were developed with a view to their possible combined application against local corrosion and biocorrosion, given the proven bactericidal properties of CuO. The same polymer modification using polyethyleneimine (PEI) was applied as in the case for the ZnO and NC

particles with polymer modified ZnO. Research is still in its initial stage, but the results obtained at this stage are encouraging and research will continue.

#### *Zinc hybrid coatings with incorporated PANI particles*

Hybrid zinc-based coatings with embedded PANI particles in the metal matrix in a one-step process by electrodeposition on low-carbon steel substrates have been obtained [11, 15]. The aim is directly to use the inhibitory properties of polyaniline (PANI) for improved corrosion protection in a medium containing chlorine ions (5% NaCl solution). Polyaniline (PANI) is known to be a corrosion inhibitor that affects cathodic and anodic processes. Its strong adsorption on metal surfaces is mainly due to the presence of delocalized  $\pi$ -electrons in the PANI macromolecules [11]. PANI particles (at a concentration of 0.025 g/l) were added to the starting zinc electrolyte in dispersed form. This is obtained by oxidative polymerization in the presence of stabilizers - polyvinylpyrrolidone (PVP) or colloidal SiO<sub>2</sub>. It was found that better results (stable dispersion and better decorative appearance of the coatings) are obtained in the second case [11].

Studies with CVA have shown that the presence of PANI particles definitely affects the cathodic and anodic processes. In the cathodic zone, a strong depolarization of about 100 mV is observed compared to the same deposition process of ordinary zinc coating, but at a lower current value. A slower process is registered in the anodic area than in the case of the zinc. Corrosion studies have confirmed the beneficial effect of these particles on the protective ability of the coatings - higher R<sub>p</sub> values after 50 days in 5% NaCl, lower corrosion current and longer anodic curve under external polarization. The XRD and XPS methods have been used to determine the composition of the newly formed mixed layer of corrosion products, where the main component is ZHC, but PANI particles are also present, which have an inhibitory effect on the development of corrosion processes [11].

Except as described above, these particles were subjected to additional polymer modifications using amphiphilic triblock copolymer Pluronic F127 [10], as well as polyethyleneimine (PEI) - [4]. In both cases, the presence of PANI particles was found to facilitate the cathodic deposition process of the coating, most likely due to its larger size occupying a larger area on the substrate. Also here, the experiments confirmed the increased protective characteristics of composite coatings compared to conventional zinc - longer anodic polarization curves, higher R<sub>p</sub> value for a period of 45 days in the model corrosive environment of 5% NaCl, higher impedance (higher value of the R<sub>p</sub> on the X axis).



### *Zinc hybrid coatings with embedded polymer modified carbon spheres*

A possible way to prepare a stable aqueous suspension of positively charged carbon spheres for simultaneous electrodeposition with zinc on a low-carbon steel substrate is described [9]. To stabilize the anti-aggregation suspension, a three-block amphiphilic copolymer Pluronic F127 is adsorbed on the surface of spherical carbon particles, which contains polyethylene oxide (PEO) blocks as hydrophilic segments and polypropylene oxide (PPO) blocks as a hydrophobic part. The stability of the resulting suspension was visually confirmed by scanning electron microscopy. The particles were embedded in the zinc coating by co-electrodeposition. The influence of the carbon spheres on the cathodic and anodic processes was evaluated by cyclic voltammetric studies. Electrochemical studies were performed in a model corrosive medium (5% NaCl solution with pH 6.7) using PDP, Rp and EIS methods and confirmed the higher protective ability of the hybrid coating compared to that of ordinary zinc [9].

### *Nickel composite coatings with embedded carbon nanotubes*

Bright and semi-bright nickel composite coatings were electrochemically obtained, which are characterized by good physical and mechanical properties, decorative appearance and increased corrosion resistance in two model corrosion media - 0.5M Na<sub>2</sub>SO<sub>4</sub> and 0.5M H<sub>3</sub>BO<sub>3</sub> [26]. A stable electrolyte was used, to which multiwall carbon nanotubes (MWCNT) were added. The protective properties and the decorative appearance of these layers are analyzed depending on the concentration, distribution and type of MWCNT used. Their influence on cathodic and anodic behavior was investigated using cyclic voltammetry (CVA) and surface morphology was observed by using SEM. The investigations show that these coatings have increased corrosion resistance and protective ability in that model environment under external polarization. These characteristic parameters are worsen when certain additives such as Saccharin or Butynediol are added to the electrolytes, most likely as a result of the incorporated sulfur (from the additives). However, these coating types can be used not only as separate protective layers, but also as a sublayer in multilayer systems.

Another study [35] showed the possibility of obtaining two types of nickel nanocomposite coatings with embedded carbon nanospheres and TiO<sub>2</sub> particles with special equipment. The obtained materials are characterized in terms of their photocatalytic properties for possible practical application.

### ***Area 1, 1.4. Corrosion inhibitors***

Nitrogen-containing heterocyclic di-cationic compounds with antioxidant properties were synthesized, which were characterized by NMR spectroscopy. Their corrosion inhibitory action



to protect steel and galvanized steel has been studied by electrochemical polarization methods to assess the potential suitability of these compounds to be included as inhibitors in hybrid zinc galvanic coatings [8]. This study found that the compounds have a well-defined protective effect against corrosion in a 5% NaCl model environment - lower corrosion current and higher polarization resistance for 70 days - making them suitable for this future purpose.

### *Area 1, 1.5. Conversion surface passive films*

In a model medium of freely aerated 5% NaCl solution, the protective ability of different types of chromate passivating films (based on conversion solutions containing  $\text{Cr}^{3+}$  compounds) on galvanic and composite zinc coatings was evaluated [19, 25, 29, 30]. Formulations based on trivalent chromium salts with potassium [14, 19] or ammonium oxalate [21] were used to treat both ordinary zinc and some of its alloys such as Zn-Co. Chromium-free variants of conversion solutions have also been used, but they do not show good protective characteristics [21]. Conversion films of different colors were obtained - transparent, gray-black and light green. The latest one demonstrates the best protective characteristics when tested in Neutral Salt Spray Chamber (NSS) – estimation mark 10 for 22 cycles [19]. In some cases, however, certain conversion films do not improve the protective performance of the composite zinc, probably due to the fact that during the stay in the conversion solution a faster dissolution of the metal appears and as a result of additional detachment of some of the PP incorporated into the coating [25, 29].

The studies confirm the possibility of obtaining  $\text{Cr}^{3+}$ -containing and chromium-free films on zinc and Zn-Co alloy with low cobalt content. To characterize these coatings and films, well-established and standardized test methods were used - PDP,  $R_p$ , EIS, Scanning-Vibration Electrode Technique (SVET), NSS [19, 21, 25, 27, 29, 30, 32]. Surface morphology was determined using SEM. The corrosion resistance of the films was studied in model environments of 3% and 5% NaCl solutions. The XPS and XRD methods show some newly appeared compounds that form a mixed layer and fill the pores of the film to some extent, further preventing the penetration of the corrosive media. They all act as barrier layers and inhibit the corrosion of the zinc [21].

Conversion films have also been obtained on zinc alloy coatings [12, 27, 32]. The results show an improvement in the protective properties of chromium-containing films in contrast to the chromium-free ones.

## ***Area 2 - Preparation and corrosion characterization of protection systems based on sol-gel coatings***

Increased corrosion resistance of low-carbon steel has been achieved through multi-layer environmentally friendly systems with barrier properties based on sol-gel coatings of ZrO<sub>2</sub> (top, surface layer) and TiO<sub>2</sub> (sublayer). The zirconium precursor solution remains constant, while the TiO<sub>2</sub> solution is modified with two different types of polymers added separately to it. Phase composition (using XRD, EDX and XPS methods), surface morphology (via SEM and AFM) and corrosion protection (with PDP) in 5% NaCl solution were analyzed. The degree of hydrophobicity was assessed by measuring the contact angle. Both types of polymer modifications demonstrate increased protective properties on the corrosion resistance of coatings under external polarization conditions compared to the unmodified titanium layer. In addition, the amorphous structure of the zirconium layer and its relatively dense and hydrophobic surface also improve the anti-corrosion characteristics of the system in this environment [3]. Similar studies have been performed for multilayer systems of the same starting components, where two different variants have been implemented: the first system consists of three sublayers of TiO<sub>2</sub> and a surface layer of ZrO<sub>2</sub> while the second contains one sublayer of TiO<sub>2</sub> and three consecutive layers of ZrO<sub>2</sub> [6]. The characterization of the systems and the applied methods are identical. The systems are amorphous and dense, demonstrating increased corrosion resistance compared to low-carbon steel in a model environment with chlorine ions.

In another study, dense, highly textured, hydrophobic coatings of ZrO<sub>2</sub>-TiO<sub>2</sub> (1:1) with an amorphous structure were obtained, respectively, using an organic or inorganic zirconium precursor [2]. Their protective ability in a selected model corrosion medium of 5% NaCl was studied. The coatings show good corrosion resistance, which is demonstrated both by the weight method and by means of potentiodynamic polarization curves. The samples were characterized by XRD, XPS [7], AFM, infrared spectroscopy (IRS), SEM, differential thermal analysis (DTA-TG), contact angle measurement. It was found that the degree of influence of some factors, such as heat treatment temperature (TT) and the type of zirconium precursor is different. The potentiodynamic curves of the samples thermotreated at 400 °C show a more pronounced effect of the zirconium precursor compared to TT, as the application of organic zirconium salt worsens the zones of anodic passivation. In contrast, coatings derived from organic and inorganic zirconium precursors show similar corrosion resistance, i.e. the influence of the precursor is minimized. Probably the influence of some complex structural and surface factors such as amorphous structure, surface smoothness and its hydrophobicity, as well as chemical

composition (low content of hydroxyl groups) contribute to the improved anti-corrosion properties of these coatings [2].

Increased corrosion resistance of low-carbon steel is achieved by a newly developed hybrid multilayer coating consisting of a zinc sublayer (1 micrometer), a middle layer of chitosan (CS) and a sol-gel coating of  $ZrO_2$  as a finishing layer. The middle chitosan layer is obtained by immersing the galvanized steel in a 3% aqueous solution of tartaric acid. Two chitosan layer systems were obtained and tested - the first was allowed to dry at room temperature for 2 weeks and the other was dried at 100 °C for one hour. After CS deposition, the samples were immersed in a solution of isopropanol sol of zirconium butoxide containing small amounts of polyethylene glycol (PEG400). The immersion and drying processes were repeated three times, after which the system was thermotreated at 180 °C. Two types of test specimens were obtained - those whose middle layer of chitosan was dried at room temperature and those where CS was treated at 100 °C. Samples were characterized using DTA-TG, XRD, XPS and AFM. The hydrophobicity of the coatings was assessed by measuring the contact angle. Two electrochemical tests - PDP and EIS - were used to determine the corrosion resistance and the protective ability of the coatings in 5% NaCl. The results showed that “sandwich” systems reliably protect the steel substrate in this corrosive environment. The newly obtained hybrid multilayer systems with an intermediate layer of CS have a dense structure and hydrophobic character. They demonstrate positive effects on the protective ability under external polarization, regardless of various characteristics such as morphology, grain size, roughness and contact angle [1].

### ***Area 3 - Other articles***

#### ***Corrosion monitoring***

Research and corrosion monitoring of austenitic (18Cr10NiTi) and low-carbon (38GN2MFA) steels used for some of the structures in Kozloduy Nuclear Power Plant (NPP) in model environments containing the most common corrosive agents in the plant's heat exchangers were conducted. The beneficial effect of monoethanolamine as a mixed inhibitor has been established. Potentiodynamic studies were performed at conditions close to the water-chemical regime used in NPP. Mossbauer and XPS analysis of corrosion products removed from the inner surface of the heat exchangers was performed [22, 33, 37]. They were found to contain mainly magnetite and small amounts of hematite, which is favorable from a corrosion point of view. A special electrode has been designed to simulate the corrosion processes in the cracks

(the size of which can be changed if necessary) and preliminary studies have been carried out [22].

*Synthesis and modeling of nanoparticle size*

Together with colleagues from the Technical University of Tbilisi, Georgia, equipment and methodology for the production of metal and oxide nanoparticles, as well as for adjusting their size using a rotating electrode (cathode) in a two-layer bath of immiscible aqueous and organic solvents. The facility provides control over various parameters, including the nucleation and growth of the resulting nanoparticles, depending on the residence time in the medium and the speed of rotation of the cathode [24].

Future investigations in my scientific research will focus on finding ways to improve the corrosion resistance and protective ability of low-carbon steels and can be systematized in several areas:

- Finding suitable compositions for environmentally friendly passive protective films;
- Selection of particles with different functional properties for obtaining of composite (hybrid) coatings;
- Environmentally friendly inhibitors for treatment of the corrosive media or their inclusion in a protective coating on steel;
- Development of thin sol-gel coatings.