# ANNOTATION

of the dissertation submitted for the degree of Doctor of Philosophy (PhD) in the educational program 8D07110 "Materials Science and Technology of New Materials"

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Electrochemical synthesis and functional properties of metal and alloy-based composition coatings

**General description of the work**

This dissertation is devoted to experimental investigations of the formation processes of composite coatings with enhanced functional properties produced by electrochemical methods, as well as to the study of crystal formation mechanisms within chromium-graphene coatings and binary alloys based on nickel and cobalt.

**Relevance of the research topic**

It is well known that many functional properties, such as corrosion resistance and wear resistance, are not always required throughout the entire volume of machine parts and equipment. However, these properties are critically important in the surface layers of structural components, where they significantly contribute to extending the service life and durability of devices and industrial equipment. Among the most effective protection methods, composite electrolytic coatings (CECs) occupy a leading position. These coatings consist of metallic matrices structured with dispersed particles, as well as binary alloy coatings, which enable targeted modification of surface properties and improved operational performance.

**Purpose of the dissertation**

To develop, optimize, and characterize electrochemically synthesized metal and alloy-based composition coatings (Chromium-Graphene, Nickel-Copper, Cobalt-Vanadium), and to establish their structure-property relationships in terms of functional characteristics.

**To achieve this objective, it is necessary to carry out these research tasks:**

- To design and optimize electrochemical deposition parameters (electrolyte composition, pH, current density, temperature) for producing uniform and adherent metal and alloy-based composite coatings on various substrates and to investigate the influence of electrochemical synthesis conditions on the nucleation, growth, and microstructural evolution of the coatings.
- To characterize the morphological, structural, and compositional features of the deposited coatings using SEM/EDS, XRD, AFM, and related surface analytical techniques and to evaluate key functional properties of the coatings such as hardness and corrosion resistance and how they correlate with the synthesis parameters and microstructure.
- To establish structure-property relationships that explain how electrochemical synthesis routes affect the coating quality and functional performance and to propose optimized electrochemical strategies for producing high-performance protective and functional coatings suitable for industrial applications.

**Research methods**

The composition and microstructure of the electrolytic coatings were studied using optical metallography, spectrometric and X-ray diffraction analysis, scanning electron microscopy, and atomic force microscopy. Potentiodynamic methods as well as electrical resistance measurements were used to study corrosion properties while mechanical properties were studied using microhardness measurements. Mathematical modeling of the electrolytic coating formation process and prediction of functional properties were conducted based on the laws of electrochemistry in electrometallurgy.

**Object of the research**

The process of formation of microstructure and functional properties of composite electrolytic coatings based on chromium, nickel and cobalt under the influence of temperature and current density.

**Subject of the research**

Electrodeposited chromium-graphene, nickel-copper and cobalt-vanadium metal and alloy-based composition coatings.

**Novelty of the dissertation**

A comprehensive study has been carried out on the processes governing microstructure formation and physicochemical properties of chromium-based composite coatings structured with graphene, as well as composite electrolytic coatings from binary Ni-Cu and Co-V alloys obtained by electrochemical synthesis on AISI 304 steel substrates.

A new approach to controlling crystal size in binary Co-V systems has been developed, based on variation of current density and deposition modes (direct current and pulsed) for multicomponent coatings. As a result of this, a new electrolyte was developed, and a utility model patent titled *Method for Depositing Cobalt-Vanadium Alloy"* was obtained (Republic of Kazakhstan Patent No. 11879, dated March 6, 2026).

For the first time, the mechanisms of co-deposition of nickel with copper and cobalt with vanadium into alloys have been established, and the influence of electrolyte composition and deposition regimes on component content, structure, properties, and efficiency of the electrodeposition process for Ni-Cu and Co-V coatings has been substantiated.

Based on quantitative analysis of experimental data on oxidation kinetics, as well as the results of physical and mechanical property tests, a phenomenological model describing the formation of the microstructure of chromium-graphene composite coatings has been proposed.

**Main provisions for defense**

1. The morphology, microhardness, and content of the dispersed phase in the synthesized chromium–graphene electrolytic coatings are determined by the deposition temperature. This is manifested in the formation of a nanocrystalline structure (25–26 nm) at deposition temperatures of 288–303 (±2) K, a nanocrystalline structure (19 nm) at 318 (±2) K, and a cracked and microporous structure at 303 (±2) K.

2. In coatings consisting of binary Ni–Cu alloys, control over crystal size, grain texture, and porosity can be achieved by varying the current density, thereby enabling the purposeful formation of nanocrystalline and amorphous–crystalline structures and optimization of mechanical properties and corrosion resistance for specified operating conditions.

3. The corrosion-electrochemical and mechanical characteristics of composite electrolytic coatings based on binary Co-V alloys depend on the deposition mode (direct current or pulsed). An increase in the content of the refractory component is associated with an increase in current efficiency and with the chemical reduction of vanadium during the pause period under pulsed electrodeposition conditions.

**Scientific and practical significance of the dissertation**

The dissertation was carried out within the framework of a grant-funded project of the Ministry of Science and Higher Education of the Republic of Kazakhstan for 2024–2026, IRN No. AP23484310, *"Composite coatings from binary and ternary alloys and hetero-oxide compounds with tailored functional properties"*, under the priority area *"Energy, Advanced Materials, and Transport"*. It contributes to the development of Kazakhstan's potential in the field of materials science by investigating electrochemical methods that are scalable, cost-effective, and suitable for integration into national industries.

The dissertation reflects priority areas outlined in the strategic documents of the State Program for the Development of Science of the Republic of Kazakhstan. This program emphasizes the development of materials science, the creation of new materials, and the implementation of advanced technologies as key priorities. The research conducted in this dissertation makes a direct contribution to the development of high-performance protective and functional coatings, the advancement of energy-efficient and environmentally friendly material modification technologies, and the strengthening of the scientific foundation for industrial innovation.

**Reliability and validity of the results**

The validity of the results of the dissertation work is confirmed by publications in national and international peer-reviewed journals with high impact factors.

**Doctoral student's contribution**

The doctoral student's personal contribution, under the guidance of scientific consultants, includes setting the goals and objectives of the research work, conducting research, cooperating with colleagues, processing and analyzing results, formulating conclusions, and writing articles.

**Approbation of the dissertation**

As part of the dissertation work and results obtained from it, the following have been published, reported and discussed.

**Articles in Scopus Database**

1 **Zellele D. M.,** Yar-Mukhamedova Gulmira Sh. and Rutkowska-Gorczyca M. A Review on Properties of Electrodeposited Nickel Composite Coatings: Ni-$Al_2O_3$, Ni-SiC, Ni- $ZrO_2$, Ni-$TiO_2$ and Ni-WC // MDPI Materials. -2024. -Vol. 17, No. 5715. https://doi.org/10.3390/ma17235715 (Q2, SJR = 0.614, Cite score = 6.4, IF = 3.5, Scopus percentile 79%)

2 Yar-Mukhamedova G. S., **Zellele D. M.**, Rutkowska-Gorczyca M., Makhambet I., Mussabek G., Atchibayev R. & Kemelzhanova A. Advancements in Coating Methods and Properties of Titanium-Based Composite Coatings: A Review // ES Materials and Manufacturing. -2025. -Vol 28, No. 1569. https://dx.doi.org/10.30919/mm1569 (Q1, SJR = 0.62, IF = 5.3, Cite score = 12.7, Percentile = 98%)

3 **Zellele D. M.**, Yar-Mukhamedova Gulmira Sh. and Rutkowska-Gorczyca M. Effect of Deposition Temperature on Morphology and Corrosion Resistance of Electrodeposited Chromium-Graphene Composite Coatings // ES Materials and Manufacturing. -2025. -Vol. 31, No. 1966. http://dx.doi.org/10.30919/mm1966 (Q1, SJR = 0.62, Cite score = 12.7, IF = 5.3, Percentile = 98%)

4 **Zellele D. M.**, Yar-Mukhamedova Gulmira S. and Rutkowska-Gorczyca M. Effects and Applications of Additives in Nickel Electrodeposition: A Review // ES Materials and Manufacturing. -2026. -Vol. 31, No. 2080. http://dx.doi.org/10.30919/mm2080 (Q1, SJR = 0.62, IF = 5.3, Cite score = 12.7, Percentile = 98%)

**Articles in journals recommended by National Center of Scientific and Technology Evaluation (Kazakhstan Citation Database)**

5 **Zelele D. M.,** & Rutkowska-Gorczyca M. Electrochemical synthesis and functional properties of metal and alloy-based composition coatings // Recent Contributions to Physics. -2024. -Vol. 88(1). -P. 41-48. https://doi.org/10.26577/RCPh.2024v88i1a06

6 Greshta V., Narivskiy O., Dzhus A., Vynar V., Yar-Mukhamedova G., Mukashev K., Beisen N., Musabek G., Imanbaeva A., **Zelele D.,** Atchibaev R., & Kemelzhanova A. Corrosion behavior of magnesium alloys NZ30K and NZ30K alloyed with silver in a model solution of the osteosynthesis process // Eurasian Physical Technical Journal. -2024. -Vol. 29. No. 3(49). -P. 29-36. https://doi.org/10.31489/2024No3/29-36

7 Nenastina T., Sakhnenko M., Oksak S., Yar-Mukhamedova G., **Zellele D.**, Mussabek G., Imanbayeva A. Study of Complexation Patterns in the System $Ni^{2+}$, $MoO_4^{2-}$, $P_2O_7^{4-}$, $Cit^{3-}$ for the Development of Poly-Ligand Electrolytes (Study of complexation patterns) // Eurasian Chemico-Technological Journal. -2024. -Vol. 26(3). -P. 155-160. https://doi.org/10.18321/ectj1638

8 Snizhnoi G., Pulina T., Solidor N., Yar-Mukhamedova G., Imanbayeva A., **Zellele D.,** & Mussabek G. Patterns and Mechanisms of Pitting of Heat Exchangers Made of AISI 321 and 08Kh18N10T Steels During their Operation in Recycled Water // Eurasian Chemico-Technological Journal. -2025. -Vol. 27(4) -P. 305-313. https://doi.org/10.18321/ectj1677

9 Yar-Mukhamedova G., Sakhnenko N., Korogodskaya A., Stepanova I., Karakurkchi A., **Zellele D.**, Wang W., Imanbayeva A. Synthesis and properties of polyfunctional coatings on aluminum and titanium alloys // Physical Sciences and Technology. -2025. -Vol. 12(3-4). -P. 41-49. https://doi.org/10.26577/phst20251224

**Conference papers, proceedings and posters**

10 **Zellele D.**, Electrodeposited iron-based composition coatings // Proceedings of the International Scientific Conference of Students and Young Scientists “Farabi Alemi”. Almaty, Kazakhstan, 3-5 April 2025. P. 447, ISBN 978-601-04-7063-7

11 Makhambet I., **Zellele D**. Development of recommendations for corrosion-resistant nano-CEC applications // Proceedings of the International Scientific Conference of Students and Young Scientists “Farabi Alemi”. Almaty, Kazakhstan, 3-5 April 2025. P. 448, ISBN 978-601-04-7063-7

12 **Zellele D**., Sakhnenko M., Nenastina T., Yar-Mukhamedova G. Electrolytic nickel alloys: Status and prospects // Proceedings of the XXXIII International Scientific-Practical Conference MicroCAD-2025. Kharkiv, Ukraine, –2025. –P. 1882. ISSN 2786-9253

13 **Zellele D**., Zhamanbayeva G., Kemelzhanova A., Atchibayev R., Kurmangaliyeva V. Microstructure, tribological and corrosion resistance properties of Ni composite coatings prepared via electrodeposition // International Multidisciplinary Scientific GeoConference SGEM. –2025. –Vol. 6, No. 1. –P. 57–64. https://doi.org/10.5593/sgem2025/6.1/s23.08

14 **Zellele D M.,** Microstructural and corrosion resistance properties of electrodeposited chromium–graphene composite coatings under varying deposition temperatures // Materials of the XVI International Symposium on Combustion Plasma and Chemistry, Physics and Chemistry of Carbon and Nano Energetic Materials. Almaty, Kazakhstan, 1-3 October. -P. 181. ISBN 978-601-323-422-9

15 Yar-Mukhamedova G., Sakhnenko N., Karakurkchi A., Yermolenko I., Kemelzhanova A., **Zellele D.** Electrochemical and Mechanical Properties of Iron-Based Nanocomposites. In: Aikin, M., et al. Advanced and Novel Technologies - Interdisciplinary Collaboration in Materials Science. ANTICM Advances in Science, Technology & Innovation // Springer Cham. -2025. https://doi.org/10.1007/978-3-032-00373-7_29

**Monograph**

16 Яр-Мухамедова Г. Ш., Ведь М. В., Сахненко Н. Д., Степанова И. И., Желавская Ю. А., Корогодская А. Н., Мукашев К., Мурадов А. Д., **Зеллеле Д**. Функциональные покрытия сплавами и нанокомпозитами для экотехнологий: синтез и свойства: монография. Алматы: Казахский национальный университет имени аль-Фараби, 2025. 110 с.

**Patent**

17 Patent 10580 Republic of Kazakhstan; Yar-Mukhamedova G., Sakhnenko N., Mukashev K., Imanbayeva A., **Zellele D.**, Nenastina T., Mussabek G., Pospelov A. Method for applying coatings with iron–cobalt–vanadium alloy, 19.02.2025, Bulletin № 22.

18 Patent 11879 Republic of Kazakhstan; Yar-Mukhamedova G., Sakhnenko N., Imanbaeva A., Kemelzhanova A., Zellele D., Atchibayev R., Pospelov A., Zhelavskaya Y., Zyubanova S., Wang Y., Shen C. Method for depositing a cobalt-vanadium alloy coating, 06.03.2026, Bulletin № 9.

**Volume and structure of the dissertation**

The dissertation work contains a list of symbols and abbreviations, an introduction, three chapters (the main part consisting of 3 subjects), a conclusion and a list of references. The work is presented on 113 pages, containing 52 figures, 16 tables and 216 bibliographical references.