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Synthesis and properties of polyfunctional coatings on aluminum and titanium alloys

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This work presents the synthesis of highly active electrode materials for the electrolytic production of hydrogen from aqueous solutions, which can also serve as photocatalysts. Composite coatings produced by plasma–electrolytic oxidation on aluminum and titanium alloy substrates, doped with vanadium and tungsten compounds, were investigated. The electrolysis processes of aqueous solutions using these composites as electrode materials were analyzed. Linear voltammetry was applied to determine the Tafel equation constants for the systems $WO_3 – V_2O_5 – Al_2O_3$ / Al and $WO_3 – V_2O_5 – TiO_2$ / Ti, which are proposed as electrode materials for hydrogen evolution reactions. The study found that the dopant content, the metallic substrate characteristics, and surface morphology strongly influence the coatings' functional properties. The Tafel coefficients *a* and *b* indicate a high level of electrocatalytic activity for the synthesized coatings, confirming their suitability as electrode materials for electrolytic hydrogen production. A comparison of photocatalytic activity in the methyl orange degradation reaction revealed higher activity of the aluminum-based coating than the titanium-based coating, highlighting the relevance of these materials for ecological technologies. The presence of nonstoichiometric oxides, compositional variability, morphological differences, and the developed surface area accounts for their exceptionally high electrocatalytic activity and, therefore, their strong potential for functional applications.

Keywords: plasma electrolytic oxidation, composite coatings, metallic substrates, vanadium and tungsten oxides, photocatalysis, electrocatalysis, hydrogen evolution reaction, degradation.
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1. Introduction

Plasma electrolytic oxidation (PEO) is a well-established surface treatment technique for the formation of oxide coatings on valve metals such as Al, Ti, Zr, Ta, and Nb. This method enables the synthesis of multicomponent surface layers incorporating transition metal oxides, thereby offering broad possibilities for tailoring functional properties [1]. A key characteristic of the PEO process is the continuous and dynamic restructuring of the coating across the entire metal surface. Under PEO anodizing conditions, dielectric breakdown events give rise to numerous transient microdischarges that are repeatedly generated over the surface of the substrate. These localized discharge channels are associated with extreme temperature gradients, reaching approximately 2000–10 000 K, which facilitate the transformation of initially amorphous oxide phases into crystalline structures. As a result, PEO-derived coatings exhibit highly tunable morphologies, strong interfacial adhesion, elevated microhardness, and excellent resistance to wear and corrosion. In recent years, significant research attention has focused on the photocatalytic performance of modified coatings based on titanium (IV) and aluminum oxides. Although alternative semiconductor materials, including α-Fe_2O_3, CdS, SnO_2, and $SrTiO_3$, have been explored for photocatalytic ap-

plications, their widespread implementation is often constrained by toxicity and environmental concerns. In contrast, titanium (IV) and aluminum oxides are non-toxic, chemically stable, cost-effective, and readily produced on an industrial scale, making them particularly attractive for sustainable and large-scale technological applications.

Photocatalytic performance of semiconductor materials can be enhanced through several approaches: doping with transition metals (Pt, Pd, Au, Ni, Cr, Mo, Nb, W, Mn, Fe, Ce, Co, etc.), modifying surfaces with polymers or dyes, or employing mixed binary and ternary metal oxide systems [2]. A critical factor in improving coating performance is the incorporation of *d*- and *p*-elements into the oxide matrix [3]. In this regard, particular attention is directed to electrode materials based on vanadium and tungsten oxides [4–7]. These systems hold great promise for diverse applications, including heterogeneous catalysis, photocatalysis, semiconductor devices, and as electrode materials for electrolytic hydrogen and oxygen evolution reactions [8–10]. This context has defined the focus of the present study. The purpose of this study is to investigate the properties of heterooxide coatings formed on titanium and aluminum substrates, with the aim of expanding their use as photocatalytic and electrode materials. This requires examining the positive effects of incorporating complex vanadium and tungsten oxides into titanium and aluminum oxide films.

It is well established that the crystal lattices of tungsten and vanadium oxides often deviate from ideal stoichiometry, resulting in oxygen deficiencies that significantly enhance their electrochemical activity [11]. The high concentration of oxygen vacancies, together with the existence of multiple structural polymorphs–including cubic, hexagonal, orthorhombic, and monoclinic phases–suggests that coatings based on these oxides can exhibit pronounced catalytic and photocatalytic behavior. The efficiency of photocatalytic processes is strongly influenced by several factors, such as the specific surface area of the catalyst, the nature and density of surface-active sites, and the spatial localization and lifetime of photogenerated charge carriers. These properties are, in turn, governed by the crystalline structure of the material, the synthesis route employed, and any subsequent post-treatment of the active layer [12,13].

2. Experimental

PEO coatings were prepared on titanium alloy VT1-0 and aluminum A0 (Al – 99 wt.%). Sample preparation for anodizing included degreasing in a sodium carbonate solution at 40–60 °C, followed by etching: titanium samples in a nitric acid–hydrofluoric acid mixture (1:3) and aluminum samples in nitric acid at room temperature. Samples were then rinsed in running and distilled water.

Previous studies [14] indicated that coatings formed in potassium pyrophosphate solutions with concentrations ≥0.5 mol/dm³ exhibit optimal functional properties. Therefore, further experiments were carried out using electrolytes with constant pyrophosphate content and varying Na_2WO_4 (0.05–0.15 M) and NH_4VO_3 (0.1–0.15 M) concentrations. Electrolytes were prepared by dissolving tungsten and vanadium salts in distilled water, mixing them, and gradually adding the mixture to the base pyrophosphate solution under stirring. The pH was monitored with a pH-meter pH-150M and glass electrode ESL-6307. Due to vanadate's low solubility, dissolution was performed at 40–50 °C. At pH 8–10, sodium tungstate and ammonium metavanadate are fully hydrolyzed, with the $[HVO_4]^{2-}$ anion in equilibrium with the pervanadate ion $[V_2O_7]^{4-}$. Under PEO conditions, high temperatures induce transformations of these anions into V_2O_5 and WO_3, which are incorporated into the coating surface layers [15].

Oxidation was performed in a single stage at current densities of 10–40 A/dm² and a maximum voltage U_{phase} = 80–140 V for 10–20 min, with continuous stirring and electrolyte cooling. A B5-50 DC power supply was used for polarization. After anodizing, samples were rinsed with distilled water and dried at room temperature.

The chemical composition of the coatings was determined by X-ray fluorescence using a portable "SPRUT" spectrometer, with a relative standard deviation of 10^{-3}–10^{-2}. Measurements were taken at a minimum of three points per sample and averaged, with an error of ±1 wt.%. For verification, energy-dispersive X-ray spectroscopy was performed using an Oxford INCA Energy 350 electron probe microanalyzer (15 keV electron beam). Surface morphology was examined using a ZEISS EVO 40XVP scanning electron microscope (G.V. Karpenko Institute of Physics, NASU). Secondary electron imaging allowed high-resolution and high-contrast visualization at 100–5000× magnification. Images were processed with SmartSEM software [16].

Photocatalytic activity was tested via the model oxidation of methyl orange (MO) in a 50 mL thermostatic glass photoreactor with magnetic stirring (100 rpm) at room temperature under air. Initial MO concentrations ranged from (0.02–2.0) ×

10^{-4} mol/dm³. Samples coated with hetero-oxide films were irradiated with a UV lamp DRT-125-1 (230–400 nm, 125 W) placed 5 cm above the solution. Solutions were pre-equilibrated in the dark for 60 min to establish adsorption equilibrium, then irradiated for 80 min. MO concentration was measured every 10 min using a KFK-2 spectrophotometer at λ = 490 nm. The degree of MO decomposition was calculated as $(C_o–C_t)/C_o$, where C_t is the current concentration and C_o is the initial concentration.

Electrocatalytic properties were studied by linear voltammetry in a neutral model medium (1 M Na_2SO_4, pH 7) using a MTech PGP-550S potentiostat–galvanostat in a thermostated three-electrode cell. A platinum mesh was used as the auxiliary electrode, and a saturated Ag/AgCl electrode (EVL-1M1) as the reference. All potentials were converted to the standard hydrogen electrode (SHE) scale. Electrocatalytic activity in hydrogen evolution was characterized by the exchange current density $j_o(H_2)$, determined from linearized Tafel plots.

3. Results and discussion

Previous studies have demonstrated that the incorporation of d-block elements into metal oxide matrices significantly enhances the catalytic performance of hetero-oxide coatings [17–19]. In the present work, the observed synergistic interaction between tungsten and vanadium oxides in improving the photo- and electrocatalytic activity of oxide films motivated a detailed investigation into the influence of electrolysis conditions, electrolyte composition, and substrate material on these properties.

The formation mechanisms of the composite oxides can be rationalized by considering the atomic radii of the constituent elements: titanium (0.068 nm), aluminum (0.143 nm), vanadium (0.052 nm), and tungsten (0.135 nm). Owing to its relatively small atomic radius, vanadium can readily incorporate into the TiO_2 lattice, partially substituting titanium ions within the oxide structure [20–23]. In contrast, the larger atomic radius of tungsten restricts its incorporation into the bulk oxide lattice, leading to its preferential localization in the near-surface region of the coating.

The presence of tungsten oxides in the surface layer, which are intrinsically less catalytically active, facilitates the formation of vanadium-rich oligomeric domains and intermediate oligomeric structures. These species enhance catalytic performance primarily through structural rather than electronic effects. As a result, tungsten oxides are stabilized in the surface layer in the form of W_xO_y, enabling the formation of multicomponent heterostructured systems such as WO_3–V_2O_5–TiO_2/Ti and WO_3–V_2O_5–Al_2O_3/Al. Previous investigations [24–27] have shown that the emergence of highly reactive surface sites arises from the combined effect of tungsten and vanadium oxides, leading to the generation of surface centers with enhanced catalytic activity.

During PEO of aluminum, high-temperature regions form at breakdown sites, where γ-Al_2O_3 transforms into α-Al_2O_3 (corundum) with a stable cubic lattice, increasing the spark-discharge voltage. Electrolyte penetration into the aluminum matrix at these sites is slower than in titanium, yet the resulting coatings still contain vanadium and tungsten oxides [28, 29].

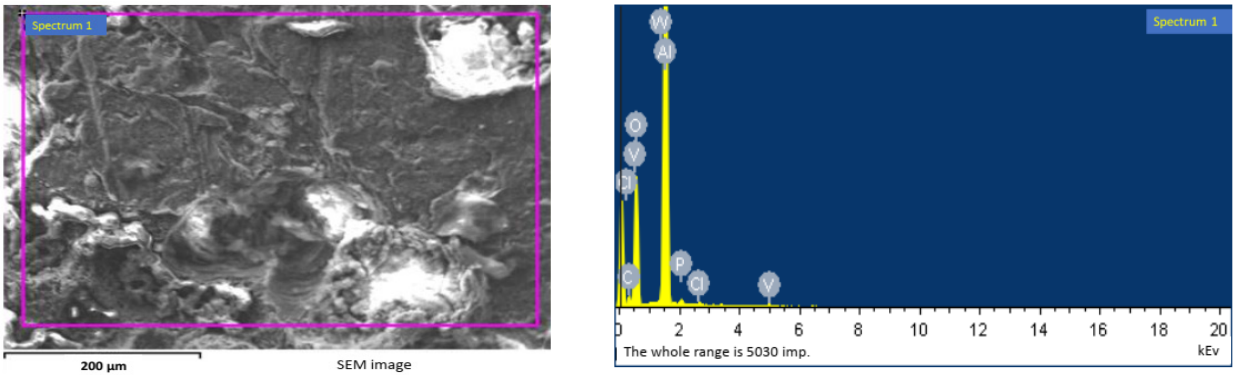
The formation of complex oxides differs between the two metals, likely due to the differing electrical resistivities of the oxide layers: Al_2O_3 films have resistivity in the range 10^{12}–10^{18} Ω·cm, while titanium films are 10^{10}–10^{12} Ω·cm. At temperatures above 400 °C, Al_2O_3 resistivity decreases by several orders of magnitude [30-38]. PEO monitoring shows that discharge intensity is lower on aluminum samples than on titanium. For titanium, sparking begins at U_{spark} = 60–70 V within 30 s, and the transition to the microarc regime occurs faster at lower voltages (105–120 V) than for aluminum, where U_{spark} = 80–100 V after 60–90 s.

The presence of α-Al_2O_3 complicates the incorporation of electrolyte components into the oxide film, resulting in a lower amount of incorporated elements (Table 1) and influencing the surface morphology of the coatings (Figures 1 and 2).

Table 1 – Composition of hetero-oxide coatings on aluminum and titanium substrates.

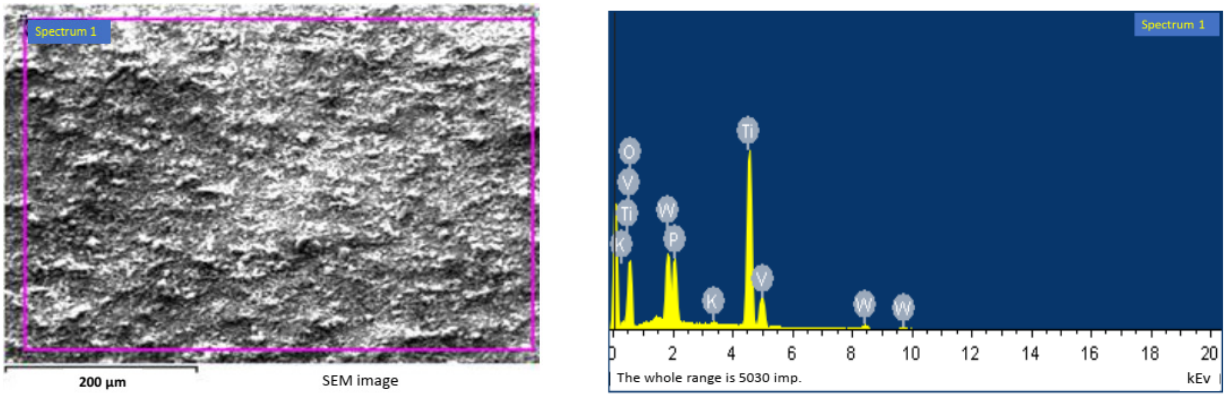
Composition of the oxide coating	Elemental mass fraction, %						
	V	W	Al	Ti	O	P	K
$WO_3 – V_2O_5 / Al_2O_3$	0,29	0,12,	46,35	-	52,65	0,59	-
$WO_3 – V_2O_5 / TiO_2$	1,51	2,83	-	27,59	60,99	6,76	0,32

Figure 1 shows that the surface of the WO_3 – V_2O_5 – Al_2O_3 / Al composite is uneven, with crater-like inclusions. In contrast, increasing the tungsten content in the WO_3 – V_2O_5 – TiO_2 / Ti coating produces a uniform, fine-grained structure without large agglomerates (Figure 2).



a) b)

Figure 1 – Morphology (a) and X-ray spectrum (b) of the composite surface on an aluminum substrate.



a) b)

Figure 2 – Morphology (*a*) and X-ray spectrum (*b*) of the composite surface on a titanium substrate.

The photocatalytic performance of the hetero-oxide coatings was assessed by tracking the temporal degradation of methyl orange (MO) in aqueous solutions. The results of these photocatalytic activity tests are presented as histograms in Figure 3.

The results indicate that the ratio of dopant metals has a significant impact on the photocatalytic activity of hetero-oxide coatings on aluminum substrates. Increasing the vanadium content in the electrolyte, however, reduces the photocatalytic activity of the hetero-oxide coatings on both aluminum and titanium. This effect can be explained by the sequence of oxide layer formation on the metal surfaces. V_2O_5 forms much more rapidly than WO_3 during oxidation reactions [22]. At high VO_3^- concentrations in the electrolyte, the accelerated formation of V_2O_5 hinders the uniform deposition of WO_3 on the coating surface, while WO_3 predominantly forms inside pores, reducing the exposed catalytically active surface area. Therefore, the optimal dopant ratio is 1:1.

The time-dependent degradation profiles of MO for mono-oxide coatings and hetero-oxide coatings prepared from electrolytes with a V:W ratio of 1:1 are shown in Figure 4.

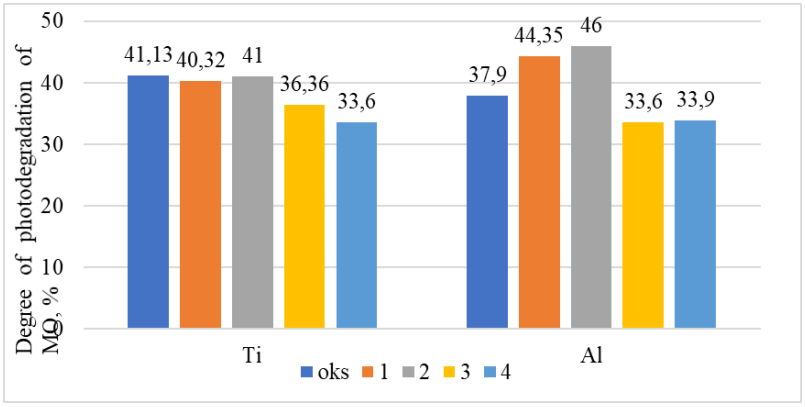


Figure 3 – Photocatalytic properties of coatings on aluminum and titanium substrates: mono-oxide coatings (ox) and hetero-oxide coatings obtained by PEO in electrolytes with V/W ratios of 1:3 (1), 1:1 (2), 2:1 (3), and 3:1 (4).

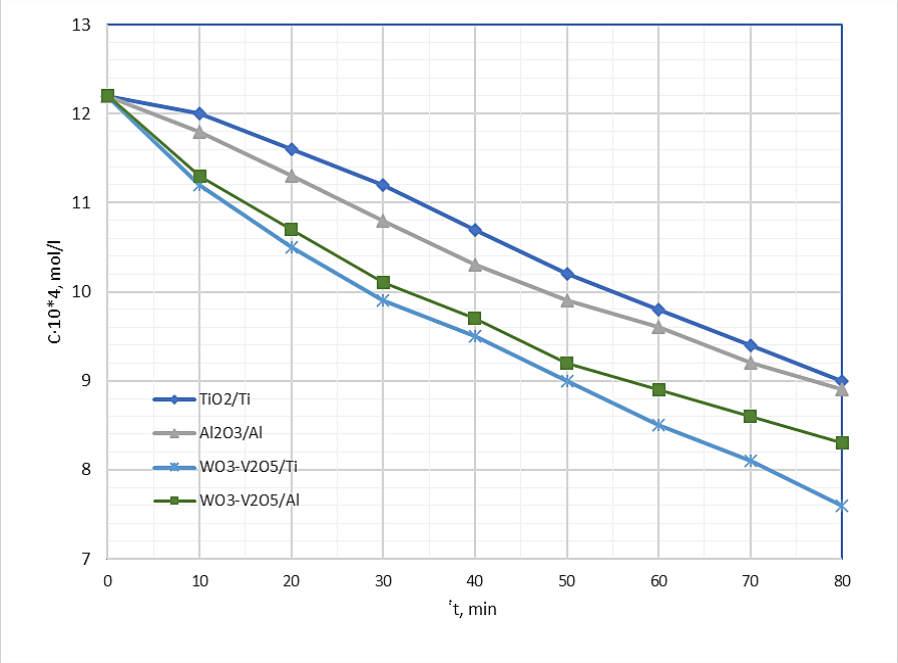
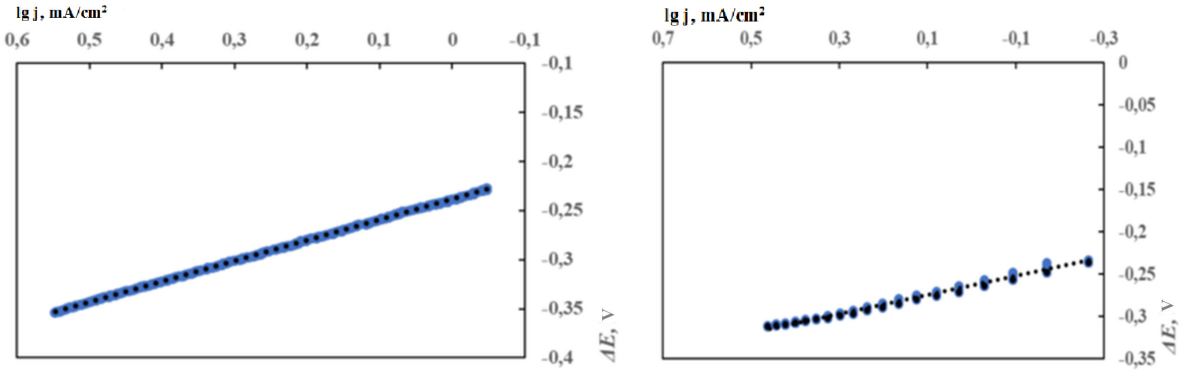


Figure 4 – Time-dependent profiles of photocatalytic degradation of MO in contact with mono- and hetero-oxide coatings (V:W ratio = 1:1).

Comparison of the coatings in the MO degradation reaction shows that doped hetero-oxide coatings exhibit significantly higher photocatalytic activity than mono-oxide coatings, demonstrating their potential for eco-technological applications.

The electrocatalytic activity of the hetero-oxide coatings was assessed using kinetic parameters from a model hydrogen evolution reaction. The hydrogen reduction potential and polarization behavior were found to depend on the coating composition, the nature of the substrate metal, and the pH of the medium. The presence of non-stoichiometric oxides, compositional variability, surface morphology, and the degree of surface development result in electrocatalytic properties of the hetero-oxide coatings that differ markedly from those of the pure metals (Figure 5).In a neutral medium, hydrogen evolution begins at –1.15 V on aluminum coatings and at –0.95 V on titanium coatings, indicating a reduction in hydrogen overpotential. The electrocatalytic activity of the coatings is characterized by the Tafel slope (b), determined from the linear portion of the Tafel plot (Figure 5, Table 2).

Lower b values indicate faster reaction kinetics. In this study, the observed b values differ from classical trends relating hydrogen evolution overpotential to current density and electrode material, reflecting the unique electrocatalytic behavior of the hetero-oxide coatings.



a) b)

Figure 5 – Linear regions of the polarization curves for the hydrogen evolution reaction in Tafel coordinates on $WO_3 – V_2O_5 – TiO_2$ / Ti (a) and $WO_3 – V_2O_5 – Al_2O_3$ / Al (b) coatings in a neutral 1 M Na_2SO_4 solution. Scan rate: 2 mV/s.

Table 2 – Electrocatalytic parameters of the coatings for hydrogen evolution.

Electrode material	–*a*, B	–*b*, B
Pt	0,31	0,10
Ti	0,82	0,14
Al	0,64	0,14
$WO_3 – V_2O_5 – Al_2O_3$ / Al	0,26	0,11
$WO_3 – V_2O_5 – TiO_2$ / Ti	0,23	0,20

In multicomponent oxide systems, unlike pure metals, the Tafel slope (b) can exceed 0.12 V. In this study, b for the $WO_3 – V_2O_5 – TiO_2$ / Ti composites was –0.20 V. For many metals, b is higher in alkaline solutions than in acidic media during hydrogen evolution; to avoid this effect, a neutral electrolyte was used.

The variation in b is influenced by several factors: the compositional diversity of non-stoichiometric oxides, differences in hydrogen adsorption on the oxide matrix (which can slow electrochemical desorption), and the formation of active centers from dopants (vanadium and tungsten). These factors complicate the hydrogen evolution mechanism on hetero-oxide surfaces and merit further investigation.

The Tafel constant a for $WO_3 – V_2O_5 – Al_2O_3$ / Al was –0.26 V (Table 2), close to that of $WO_3 – V_2O_5 – TiO_2$ / Ti (–0.23 V), and both values fall within the range typical for catalytically active materials. The slight difference in a arises from variations in the hetero-oxide matrix and the tungsten and vanadium oxide content. A higher proportion of non-stoichiometric tungsten and vanadium oxides in titanium-based coatings further lowers a. Overall, these results indicate the exceptionally high electrocatalytic activity of the hetero-oxide composites in hydrogen evolution, confirming their strong potential for practical applications.

4. Conclusion

Highly active hetero-oxide photocatalytic coatings were successfully synthesized on aluminum- and titanium-based substrates via plasma electrolytic oxidation incorporating vanadium and tungsten spe-

cies. The resulting materials demonstrated excellent functional performance across multiple application domains.

Evaluation of photocatalytic activity using methyl orange degradation revealed significantly enhanced reaction rates, confirming the strong potential of these coatings for environmentally oriented and eco-technological applications.

Electrochemical studies of hydrogen evolution reactions showed that the synthesized hetero-oxide composites exhibit exceptionally high electrocatalytic activity, underscoring their promise as efficient electrode materials for electrolytic hydrogen production.

The functional properties of the coatings exhibited a strong dependence on the dopant content, the characteristics of the metallic matrix, and the surface morphology.

(iv) Analysis of the Tafel parameters further confirmed the superior electrocatalytic characteristics of the coatings, supporting their applicability in practical hydrogen generation systems.

References

1. Friedemann A.E.R., Gesing Th.M., Plagemann P. Electrochemical rutile and anatase formation on PEO surfaces // Surface and Coatings Technology. – 2017. – Vol. 315. – P. 139-149. https://doi.org/10.1016/j.surfcoat.2017.01.042

2. Chakravorty A., Roy S. A review of photocatalysis, basic principles, processes, and materials // Sustainable Chemistry for the Environment. – 2024. – Vol. 8. – Art. 100155. https://doi.org/10.1016/j.scenv.2024.100155

3. Wu K.-R., Hung Ch.-H.J., Yeh Ch.-W., Wu J.-K. Microporous TiO_2-WO_3/TiO_2 films with visible-light photocatalytic activity synthesized by micro arc oxidation and DC magnetron sputtering // Applied Surface Science. – 2012. – Vol. 263. – Pp. 688-695. https://doi.org/10.1016/j.apsusc.2012.09.142

4. Lukiyanchuk I.V., Vasilyeva M.S., Yarovaya T.P., Nedozorov P.M., Tkachev V.V., Ustinov A.Yu., Budnikova Yu.B., Parotkina Yu.A. Photoactive TiO_2-V_2O_5-WO_3 film composites immobilized in titanium phosphate matrix by plasma electrolytic oxidation // Journal of Photochemistry and Photobiology A: Chemistry. – 2023, – Vol. 445. – Art. 11504. https://doi.org/10.1016/j.jphotochem.2023.115047

5. Lukiyanchuk I.V., Vasilyeva M.S., Ustinov A.Yu., Bryzhin A.A., Tarkhanova I.G. Ti/TiO_2/$NiWO_4$ + WO_3 composites for oxidative desulfurization and denitrogenation // Surface and Coatings Technology. – 2022. – Vol. 434. – Art. 128200. https://doi.org/10.1016/j.surfcoat.2022.128200

6. Hatel R., Baitoul M. Nanostructured Tungsten Trioxide (WO_3): synthesis, structural and morphological investigations // IOP Conf. Series: Journal of Physics: Conf. Series. – 2019. – Vol. 1292. – Art. 012014. https://doi.org/10.1088/1742-6596/1292/1/012014

7. He J., Luo Q., Cai Q.Z., Li X.W., Zhang D.Q. Microstructure and photocatalytic properties of WO_3/TiO_2 composite films by plasma electrolytic oxidation // Materials Chemistry and Physics. – 2011. – Vol. 129. – Pp. 242-248. https://doi.org/10.1016/j.matchemphys.2011.04.011

8. Javidi M., Fadaee H. Plasma electrolytic oxidation of 2024-T3 aluminum alloy and investigation on microstructure and wear behavior // Applied Surface Science. – 2013. – Vol. 286. – Pp. 212-219. https://doi.org/10.1016/j.apsusc.2013.09.049

9. Bairachnyi V., Rudenko N., Zhelavska Yu., Pilipenko A. Using aluminum alloys in the electrochemical hydrogen production // Materials Today: Proceedings. – 2019. – Vol. 6. – Pp. 299-304. https://doi.org/10.1016/j.matpr.2018.10.108

10. Ved M.V., Sakhnenko N.D., Karakurkchi A.V., Myrna T.Yu. Functional mixed cobalt and aluminum oxide coatings for environmental safety // Functional materials. – 2017. – Vol. 24. – Pp. 303–310. https://doi.org/10.15407/fm24.02.303

11. Curran J.A., Clyne T.W. Porosity in plasma electrolytic oxide coatings // Acta Materialia, – 2006. – Vol. 54. – Pp. 1985-1993. https://doi.org/10.1016/j.actamat.2005.12.029

12. Paiu M., Lutic D., Favier L., Gavrilescu M. Heterogeneous photocatalysis for advanced water treatment: Materials, mechanisms, reactor configurations, and emerging applications // Applied Science. – 2025. – Vol. 15. – P. 5681. https://doi.org/10.3390/app15105681

13. Bozheyev F., Nemkayeva R., Yerlanuly Y., Gabdullin M., Markhabayeva A. Performance of transition metal oxides for solar hydrogen conversion // ACS Catalysis. -2025. -Vol.15, -No.18. -Pp. 16449-16162. https://doi.org/10.1021/acscatal.5c03869

14. Karakurkchi A., Sakhnenko M., Korogodskaya A., Zyubanova S. Development of an approach to improvement the protection of the population in protective buildings of civil protection in the conditions of air pollution by toxic chemical agents // Technology Audit and Production Reserves. – 2022. – Vol. 1. – Pp. 6–11. http://doi.org/10.15587/2706-5448.2022.253650

15. Tseng Ch.-Ch., Lee J.-L., Kuo Tz.-Hs., Kuo Sh.-N., Tseng K.-H. The influence of sodium tungstate concentration and anodizing conditions on microarc oxidation (MAO) coatings for aluminum alloy // Surface and Coatings Technology. – 2012. – Vol. 206. – Pp. 3437-3443. https://doi.org/10.1016/j.surfcoat.2012.02.002

16. Sakhnenko N.D., Ved M.V. & Karakurkchi A.V. Nanoscale oxide PEO coatings forming from diphosphate electrolytes // In: Springer proceedings in physics. – 2017. – Pp. 507–531. https://doi.org/10.1007/978-3-319-56422-7_38

17. Sakhnenko M., Stepanova I., Korogodskaya A., Karakurkchi A., Skrypnyk O., Dzheniuk A. & Halak O. Patterns in the electrochemical synthesis of thin-film photocatalytic materials based on titanium heterooxide compounds // Eastern-European Journal of Enterprise Technologies. – 2022. – Vol. 6. – Pp. 30-39. https://doi.org/10.15587/1729-4061.2022.269942

18. Pizzini S. Physical chemistry of semiconductor materials and processes. Wiley. – 2015. 416 p.

19. Jaegers N.R., Lai J.-K., He Y., Walter E., Dixon D.A., Vasiliu M., Chen Y., Wang C., Hu M.Y., Mueller K.T., Wachs I.E., Wang Y., Hu J.Z. Mechanism by which tungsten oxide promotes the activity of supported V_2O_5/TiO_2 catalysts for NO_X abatement: Structural effects revealed by ^{51}V MAS NMR spectroscopy // Angewandte Chemie. – 2019. – Vol. 58. – Art. 12609. https://doi.org/10.1002/anie.201904503

20. Bayati M.R., Zargar H.R., Molaei R., Golestani-Fard F., Zanganeh N., Kajbafvala A. MAO-synthesized Al_2O_3-supported V_2O_5 nano-porous catalysts: Growth, characterization, and photoactivity // Applied Surface Science. – 2010. – Vol. 256 – Pp. 3806-3811. https://doi.org/10.1016/j.apsusc.2010.01.030

21. Abyzov A.M. Aluminum Oxide and Alumina Ceramics (review). Part 1. Properties of Al_2O_3 and commercial production of dispersed Al_2O_3 // Refractories and Industrial Ceramics. – 2019. – Vol. 60. – Pp. 24–32. https://doi.org/10.1007/s11148-019-00304-2

22. Karbasi M., Nikoomanzari E., Hosseini R., Bahramian H., Chaharmahali R., Giannakis S., Kaseem M., Fattah-Alhosseini A. A review on plasma electrolytic oxidation coatings for organic pollutant degradation: How to prepare them and what to expect of them? // Journal of Environmental Chemical Engineering. – 2023. – Vol. 11. – P. 110027. https://doi.org/10.1016/j.jece.2023.110027

23. Narivs'kyi O., Atchibayev R., Kemelzhanova A., Yar-Mukhamedova G., Snizhnoi G., Subbotin S., & Beisebayeva A. Mathematical modeling of the corrosion behavior of austenitic steels in chloride-containing media during the operation of plate-like heat exchangers // Eurasian Chemico-Technological Journal. – 2002. – Vol. 24(4). – P. 295-302. https://doi.org/10.18321/ectj1473

24. Sagyndykov A.B., Kalkozova Z.K., Yar-Mukhamedova G.S., Abdullin K.A. Fabrication of nanostructured silicon surface using selective chemical etching // Technical Physics. – 2017. – Vol. 62(11). – Pp. 1675-8. https://doi.org/10.1134/S106378421711024X

25. Mussabek G., Lysenko V., Yermukhamed D., Sivakov V., Timoshenko V. Yu. Thermally induced evolution of the structure and optical properties of silicon nanowires // Results in Physics. -2020. –Vol.18, -Art. 103258. https://doi.org/10.1016/j.rinp.2020.103258

26. Aldabergenova T.M., Kislitsin S.B., Larionov A.S., Yar-Mukhamedova G.S. Effect of low-energy alpha-particles irradiation on surface structure and physical-mechanical properties of high-purity tungsten // In AIP Conference Proceedings. – 2016. – Vol. 1783. – Art. 020003. https://doi.org/10.1063/1.4966296

27. Kemelzhanova A, Atchibayev R, Mukasev K, Myrzakul T, Yar-Mukhamedov Y. Nano-coatings protective properties in aminum environments // International Multidisciplinary Scientific GeoConference: SGEM. – 2019. – Vol. 19. – Pp. 297-303. https://doi.org/10.5593/sgem2019/6.1/S24.039

28. 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. 1128. – P. 1569. https://doi.org/10.30919/mm1569

29. Dzhus A., Subbotin S., Pulina T., Snizhnoi G. Modeling the resistance of plate-like heat exchangers made of 06khn28mdt alloy (analogous to aisi904l steel) to crevice corrosion in recycled water enterprises // Physical Sciences and Technology. – 2024. – Vol. 11(3-4). – Pp. 58–66. https://doi.org/10.26577/phst2024v11i2b07

30. Greshta V., Narivskyi O., Dzhus A., Vynar V., Yar-Mukhamedova G., Mukashev K., Beissen N., Mussabek G., Imanbayeva A., Zelele, D., Atchibayev R., & Kemelzhanova A. Corrosion behavior of magnesium alloys NZ30K and NZ30K alloyed with silver in the model solution of the osteosynthesis process // Eurasian Physical Technical Journal. – 2024. – Vol. 21(3(49). – P. 29–36. https://doi.org/10.31489/2024No3/29-36

31. Kemelzhanova A., Zhamanbayeva G., Zakhidov A., Kurmangaliyeva V., Temirgaliyeva E. Nanostructural perostrovskite for photovoltaics // International Multidisciplinary Scientific GeoConference: SGEM. – 2020. – Vol. 20. – Pp. 113-9. https://doi.org/10.5593/sgem2020/4.1/s17.015

32. Mussabek G.K., Yermukhamed D., Dikhanbayev K.K., Mathur S., Sivakov V.A. Self-organization growth of Ge-nanocolums // Materials Research Express, – 2017, – Vol. 4, – Art. 035003. https://doi.org/10.1088/2053-1591/aa5ed6

33. Greshta V. Effect of copper in silver coatings on the corrosion behavior of NZ30K–0.1 wt.% Ag alloy in Ringer–Locke solution // Physical Sciences and Technology. – 2025. – Vol. 12(1-2). – Pp. 95–102. https://doi.org/10.26577/phst20251219

34. Sakhnenko N., Ved M., Koziar M. Ternary cobalt-molybdenum-zirconium coatings: electrolytic deposition and functional properties // Physical Sciences and Technology. – 2018. – Vol. 3(2). – Pp. 65–75. https://doi.org/10.26577/phst-2016-2-108

35. Zellele, D. M., Yar-Mukhamedova, G. S., 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 // Materials. – 2024. – Vol. 17(23). – Art. 5715. https://doi.org/10.3390/ma17235715

36. 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). – Pp. 155-160. https://doi.org/10.18321/ectj1638

37. Dzhus A., Snizhnoi G. Prediction the durability of heat exchangers made of 06KhN28MDT alloy (analogous to AISI904L steel) to crevice corrosion during their operation in recycled water // Physical Sciences and Technology. – 2023. – Vol. 10(3-4). – Pp. 57–67. https://doi.org/10.26577/phst.2023.v10.i2.07

38. Zhilkashinova A., Skakov M., Zhilkashinova A., Abilev, M., Prokhorenkova N. Features of structural-phase states of Co-Cr-Al-Y composite coatings after heat treatment // Physical Sciences and Technology. – 2022. – Vol. 9 (1-2). – Pp. 45–54. https://doi.org/10.26577/phst.2022.v9.i1.06

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