

2 The application of X-rays for an electrodeposition of composite 3 coatings with modified structure and properties

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12 Abstract: Experimental studies of X-rays effect on the process of electrochemical deposition of
13 composite coatings are reviewed in the paper emphasizing the X-rays application for modification
14 of microstructural characteristics and mechanical performances of protective coatings. Research is
15 covered the Co/SiO₂ coatings electrodeposited from aqueous solutions under the effect of X-ray.
16 The results of elaborate investigations of dispersing ability of electrolytes with SiO₂- nanoparticles
17 and mass rate of composite coatings Co/SiO₂ point to the fact that the method of the electrochemical
18 deposition under the effect of X-rays during electrodeposition is considered as the method which
19 intensifies diffusion in the electrolyte volume and allows to obtain dense, morphology uniform
20 coatings with increased hardness and improved adhesion. It is shown that exposure of electro-
21 chemical system with X-rays during the Co/SiO₂ coatings electrodepositing occurs the orienting
22 effect on the growth of crystal grains.

23 Keywords: composite coatings; X-rays irradiation; radiolysis; nanoparticles; structure; properties

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1. Introduction

Electrochemical deposited composite coatings with included nanoparticles occupy an important place among various types of protective coatings and thin nanocomposite films. The method of an electrochemical deposition is widely used in different fields of industry for objects of various sizes and it greatly cheaper compare with different methods of covering such as plasma-assisted chemical vapor deposition [1–5], the ion implantation [6,7], the ion-beam [8,9] and magnetron sputtering [10,11], or another plasma techniques and chemical methods [12,13,14] which can be used primarily for covering small objects.

Formation of composite coatings with included nanoparticles with required surface morphology, microstructure and excellent properties in different cases depends on the composition of a reaction medium, electrodeposition conditions and modes and in most instances, it depends on the sedimentation stability of nanoparticles in an electrolyte. The most common employed method for supporting the sedimentation stability of nanoparticles is using different additives prevented coagulation of nanoparticles. The most visible disadvantage of employing additives is a change in the chemical composition of electrolytes leading to narrowing a range of working current densities of electrodeposition. Hence, factors have been described earlier contribute to form composite coatings with deterioration of qualities and properties [15–17].

Alongside with multipurpose procedures of deposition by electrochemical

reduction on conductivity substrates from electrolytes with insoluble suspended nanoparticles the effect of external factors on the formation of coatings with required properties are widely applied [18, 19].

The well-known method of deposition composite coatings with included nanoparticles by electrochemical reduction from suspended aqueous solution under ultrasonic vibrations. The application of ultrasonic field for suspending liquid and manufacturing of new material has a long history and has revealed broad prospects in the microstructure control and performance improvement for composite metals and alloys electrochemically deposited. Despite abundant researches on the sedimentation stability of electrolytes with nanoparticles with help of the ultrasonic technologies, the refinement mechanism of ultrasonic treatment during the electrodeposition process is still controversial. Particularly noteworthy is the surprising laboriousness and increasing energy consumption with the implementation of ultrasound into the technological process. This implementation is associated with the need to prevent a formation of standing sound waves caused by reflecting ultrasonic waves transferring back and forth from the surface of a cathode. The formation of standing waves also causes a decrease in diffusion to the cathode surface and promotes the accumulation of nanoparticles under the source of ultrasonic vibrations. It is obvious that accumulation of nanoparticles near the ultrasonic vibrations source leads to coagulation of insoluble particles and promotes to reduction of dispersing ability and to concomitant deterioration of coatings operational properties and subsequently to decrease in the economic efficiency of the technological process [20].

In order to overcome indicated limitations, the present research work focuses on considering the method of the electrodeposition of composite coatings with nanoparticles under the effect of X-rays [21–23]. The main mechanisms of X-ray irradiation of suspended electrolytes based on formation of active and mobile radiolysis products in volume of an irradiated electrolyte which contribute to natural mixing of electrolyte, lead to increase its dispersing ability and to intensification of the electrodeposition. This makes it possible to form dense, uniform in thickness, fine-grained coatings with improved operational properties [24].

Of particular interest are Co-coatings electroplated that use in the manufacture of reflectors, mirrors, jewelry, due to its high abrasion resistance and the lower cost enables use it in more applications.

The main aim of this study is the experimental investigation of X-rays effect on the process of electrochemical deposition of composite coatings Co/SiO₂ underlining X-rays application for modification of microstructural characteristics and mechanical performances of protective electrodeposited coatings.

2. Experimental

Co/SiO₂ composite coatings have been electrodeposited from the additive-free sulfate electrolyte with following composition: CoSO₄·7H₂O – 200 g/dm³, H₃BO₃ – 15 g/dm³ and NaCl – 10 g/dm³. The concentration of SiO₂ nanoparticles was 0.5 g/dm³ and 1 g/dm³. Deposition was performed with a preliminary reverse during 5 minutes. The low-carbon steel with a carbon content of 0.05–0.12% was used as substrates. Before plating all substrates were polished with help of polishing machine BAINPOL VT Auto for preparing samples with average roughness 0,05 μm. Coatings have been electrodeposited for 1h in the X-ray field (P_{eks} = 100 R/h) at controlled temperature of 23 °C [25].

Electrodeposition has been carried out in the thermostatic bath with two cells of 100 ml (figure 1). One cell was used for depositing coating under the effect of X-rays, exposing the electrolyte directly. Another cell was used for depositing reference coatings.

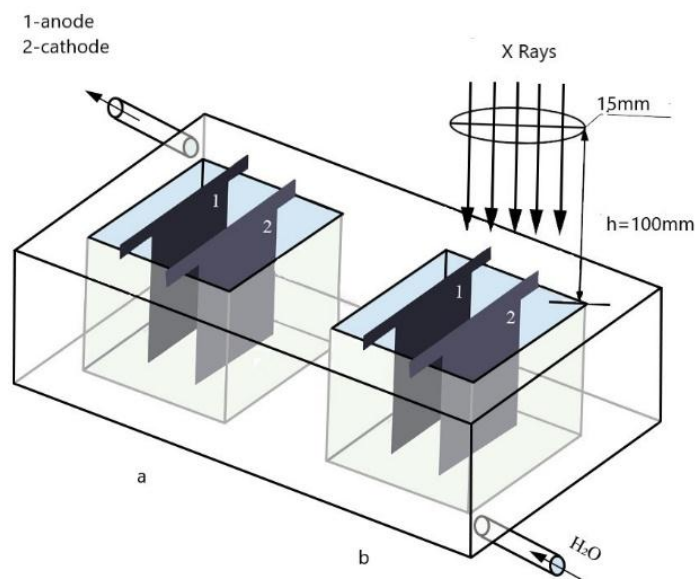


Figure 1. Schematic illustration of plating bath under effect of X-ray (a) cell for deposition of reference sample; (b) cell for deposition of irradiated sample

Current densities were chosen in the range from 1 to 3 A/dm². The coatings formed in the X-ray field, irradiated samples (Irr), and coatings formed without exposing with X-rays, reference samples (Ref) were compared to estimate its structural variations. The thickness was measured with a MTTs-3 meter (Minsk, Belarus). The mass gain and thickness of Co/SiO₂ coating were determined as the average of 10 measurements (10 samples). The surface morphology and elemental composition were studied using JSM-5610 LV scanning electron microscope equipped with the EDX JED-2201 chemical analysis system (JEOL, Akishima, Japan). Accelerating voltage was 20 keV. The estimated depth range of electrons does not exceed 0.98 μm. The energy resolution of the detector is about 0.137 keV. The phase Co/SiO₂ composition was studied by X-ray diffraction (XRD) with help of DRON-3M diffractometer in the CuKα radiation (Burevestnik, St. Petersburg, Russia). Microhardness of the coating surface was measured with a CASON-59 HV microhardness tester (Jinan Kason Testing Equipment Co, Jinan City, Shandong Province, China). The adhesion of Co/SiO₂ coatings was investigated by the scratch method based on applying of a scratch grid on the surface of testing coatings. The adhesion tests were carried out in accordance with the Interstate standard [26]. The dispersing ability of electrolytes was studied with help of a Moler's cell [27]. The Moler's cell has a rectangular shape with a collapsible cathode block. The cathode block consists of 10 indifferent aluminum cathodes. The main characteristic of the Moler's cell is that the cathode space is separated from the anode space with a non-conductive partition. Between the partition and one of the side bath walls must be a space of 1 or 2 mm. In this case, the slight gap is a non-polarizable anode that does not cause concentration changes in the solution. The advantage of the

Moler's cell is that the cathodic current distribution in it does not depend on the shape and does not depend on the anode location.

Value of dispersing ability is computed by measuring of mass distribution on all Al-cathodes according the Unified System of corrosion and ageing protection. Galvanic coating. Designation of dispersing ability of electrolytes during the creation of coverings [27]. The relative error of the method did not exceed 5 %.

3. Results

The Figure 1 shows the SEM images of surface morphology and cross sections of Co/SiO₂ composite coatings formed under the effect of X-rays and references sample formed from electrolytes with SiO₂ concentration of 0.5 g/dm³. As shown in Figure 1a, the reference sample formed without irradiation are characterized by needle-shaped crystallites normal oriented to the substrate plane and by coarse and inhomogeneous grains oriented lengthwise (parallel) to the substrate plane. This structure is typical for a cobalt microstructure [24]. By contrast, as can be seen from the Figure 1b, the irradiated samples differ from geometry surface with crystalline grains only parallel directed to the substrate. The observed differences in the surface morphology of exposed and reference samples caused by destruction of primary structure of the irradiated electrolyte and radiolysis transformations under the effect of X-rays.

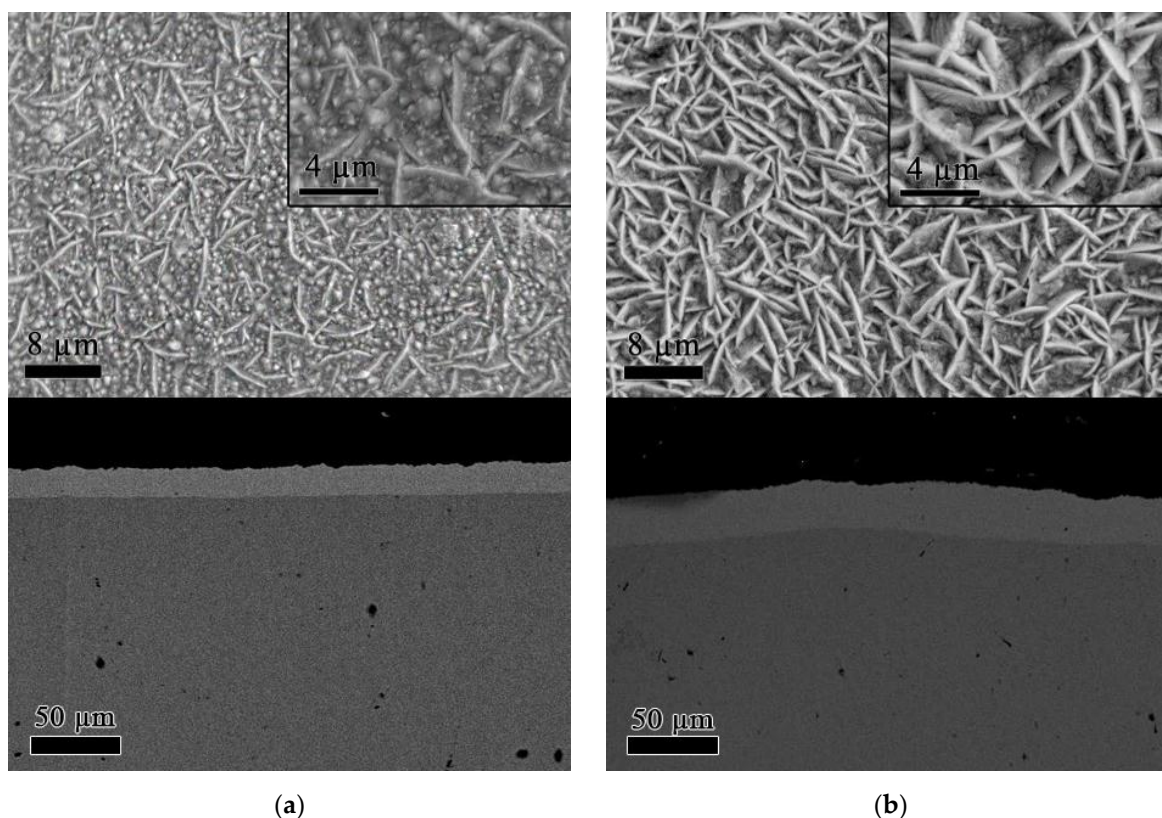
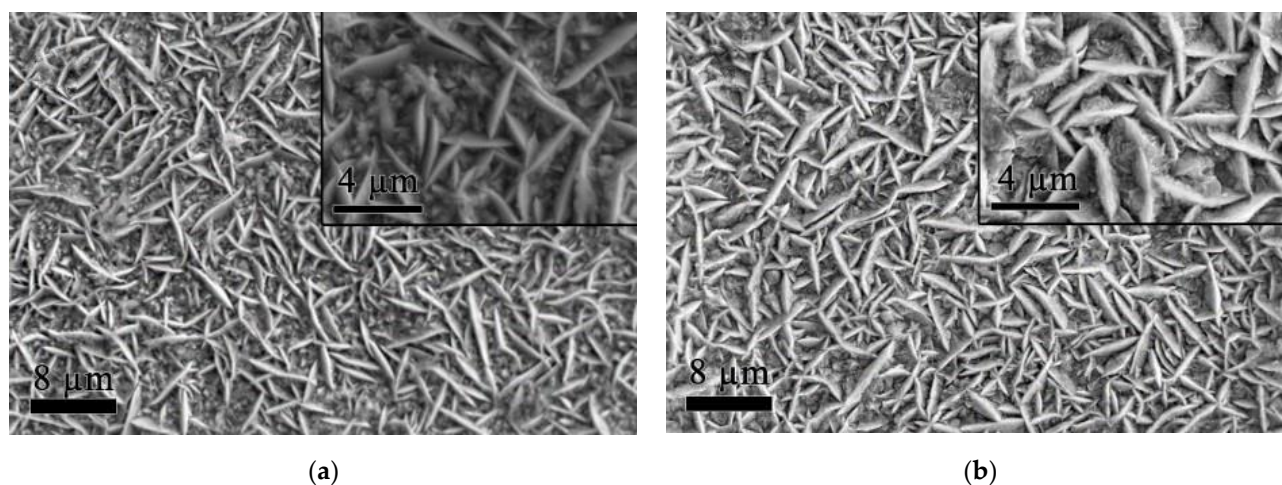


Figure 2. SEM images of surface and cross sections of Co/SiO₂ formed at 2 A/dm² current density from electrolyte with SiO₂ nanoparticles of 0.5 g/dm³ (a) reference sample; (b) irradiated sample.

Compare the Figure 2 and the Figure 3, it is obvious that well visible normal oriented grains on the references samples gradually become smaller (fig.3.a) and almost entirely eliminate on the surface of irradiated Co/SiO₂ coatings (Fig.3.b). It should be noted that coatings demonstrated on the figure 2 were formed from electrolyte with concentration of SiO₂ nanoparticles equaled 1 g/dm³.



144 **Figure 3.** SEM images of surface of Co/SiO₂ formed at 2 A/dm² current density from electrolyte with SiO₂ nanoparticles of
 145 1 g/dm³ (a) reference sample; (b) irradiated sample.

146 It should be noted that Co/SiO₂ coatings deposited from electrolyte with SiO₂
 147 nanoparticles of 1 g/dm³ characterize with more developed surface geometry in
 148 comparison with coatings which are deposited from the electrolyte with SiO₂
 149 nanoparticles of 0.5 g/dm³. So, it can be suggested that morphology and structure of
 150 Co/SiO₂ coatings affected by SiO₂ concentration. However it is clearly, that reference
 151 samples contain two types of crystalline grains, normal and parallel oriented to the
 152 substrate plane.

153 Comparative analysis of irradiated and reference cross sections of composite
 154 coatings Co/SiO₂ (Figure 2) allows to conclude that the rate of deposition under the effect
 155 of X-radiation is significantly higher. Moreover nonporous dense coatings are formed in
 156 X-rays field.

157 So, unlike the traditional electrodeposition process, the interfusion of the electrolyte
 158 with radical particles in X-ray irradiated electrolyte prevents the formation of cohesive
 159 contacts between SiO₂ nanoparticles and reduces the likelihood of coagulation and
 160 sedimentation. Due to this, the SiO₂ nanoparticles are transferred to the cathode, where
 161 they are overgrown with the reduced metal, forming their own finely dispersed
 162 agglomerate with an increased content of nanoparticles and with improved operational
 163 properties [21].

164 The tendencies to change the geometry surface of irradiated coatings Co/SiO₂
 165 positively correlate with data of study mass rate per unit area and thickness per time.
 166 Comparative relationships between the results of mass rate study at different current
 167 densities of composite coatings Co/SiO₂ from electrolytes with different concentrations of
 168 nanoparticles are presented in the Figure 4.

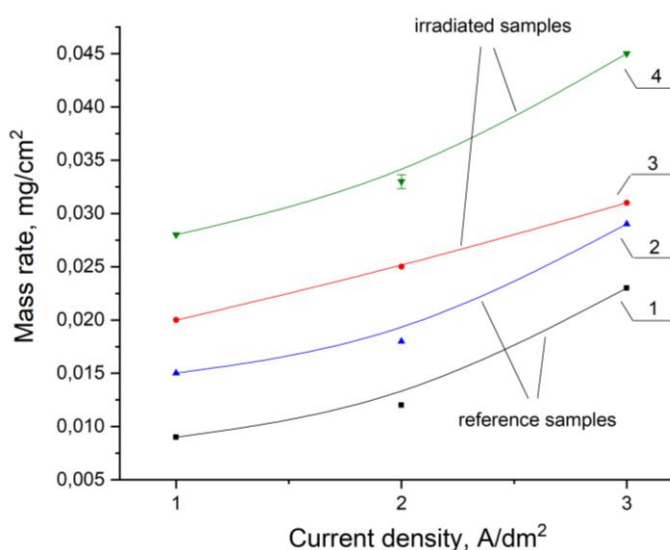


Figure 4. Mass rate in a unit area of the Co/SiO₂ coatings formed at different current densities of 1–3 A/dm²: 1 – reference sample, formed from electrolytes with 0.5 g/dm³; 2 – reference sample, formed from electrolytes with 1 g/dm³; 3 – irradiated sample, formed from electrolytes with 0.5 g/dm³; 4 – irradiated sample, formed from electrolytes with 1 g/dm³.

As well seen, the mass rate per unit area increases with increasing of current density corresponding to Faraday's laws. It is evident, the mass rate of irradiated samples is higher than references samples. Dependencies of thickness over current densities are presented on the Figure 5. The analysis shows the correlation with investigation of mass gain. On one side, increasing in mass rate per unit area of samples deposited in X-rays is caused by increasing in number of ions transferred to a cathode surface through the diffusion layer due to solution radiolysis. On the other hand is caused by change of pH of electrolyte [27]. In particular, the pH reduction prevents formation of coagulants of hydroxide compounds. Hence lack of their absorption on the cathode surface promotes to formation of more perfect, compact and non-porous coatings than reference coatings [24]. From another side, an increase in mass rate of Co/SiO₂ coatings indicates the increment of number of nanoparticles included into the base metal matrix due to increasing the dispersing ability of electrolytes.

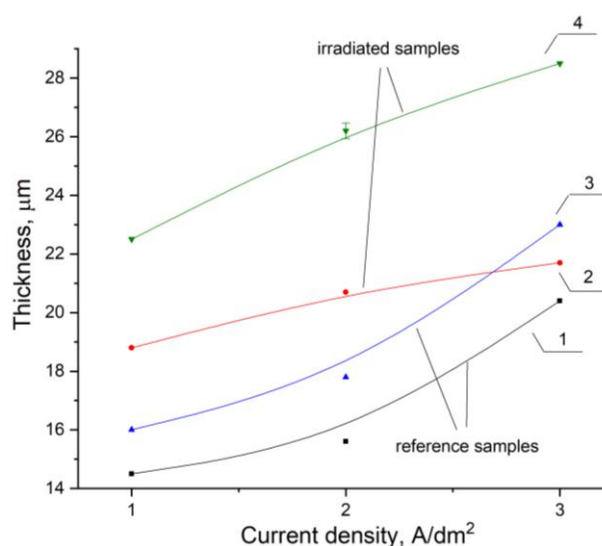
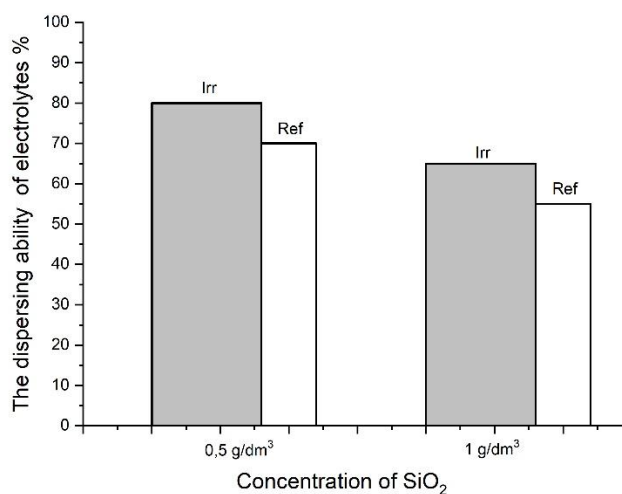


Figure 5. Thickness of Co/SiO₂ formed at different current densities: 1 – reference sample formed from electrolytes with 0.5 g/dm³; 2 – irradiated sample formed from electrolytes with 0.5 g/dm³;

190 3 – reference sample formed from electrolytes with 1 g/dm³; 4 – irradiated sample formed from
 191 electrolytes with 1 g/dm³.

192 Figure 6 illustrates the dispersing ability of electrolytes used for deposition Co/SiO₂
 193 coatings with concentration of SiO₂ nanoparticles in the electrolytes equaled 0.5 g/dm³
 194 and 1 g/dm³. It is well visible in the Figure 6 that X-ray irradiation of electrolytes leads to
 195 the increase in the dispersing ability of electrolytes with suspended nanoparticles. As
 196 well known that the dispersing ability of electrolytes shows the uniform current
 197 distribution over the cathode surface causing the formation of homogeneous coatings.
 198 Thus, X-rays irradiation of electrolytes promotes to the formation compact Co/SiO₂
 199 coatings.



200
 201 **Figure 6.** The dispersing ability of irradiated and nonirradiated electrolytes with different
 202 concentration of SiO₂ nanoparticles.

203 As can be seen in the Figure 6 the addition in concentration of nanoparticles in
 204 electrolytes reduces its dispersing ability. Hence, obtained data are allowed to suggest
 205 that since SiO₂ nanoparticles have a high ability to aggregate in aqueous solutions, X-ray
 206 irradiation degrade nanoparticles clusters due to an increase in the dispersing ability of
 207 electrolytes and contributes to the formation of composite coatings with even distributed
 208 nanoparticles with improved structure and properties.

209 Figure 7 presents the results of elemental analysis of composite Co/SiO₂ coatings. It
 210 shows that the effect of X-ray on the electrochemical cell during electrodeposition from
 211 electrolyte with nanoparticles of SiO₂ promotes to formation of composite coatings with a
 212 bit more SiO₂ concentration compare with reference samples. It should be mentioned that
 213 difference in SiO₂ content is less than 0.1 % that why we can consider the data only as
 214 qualitative characteristic.
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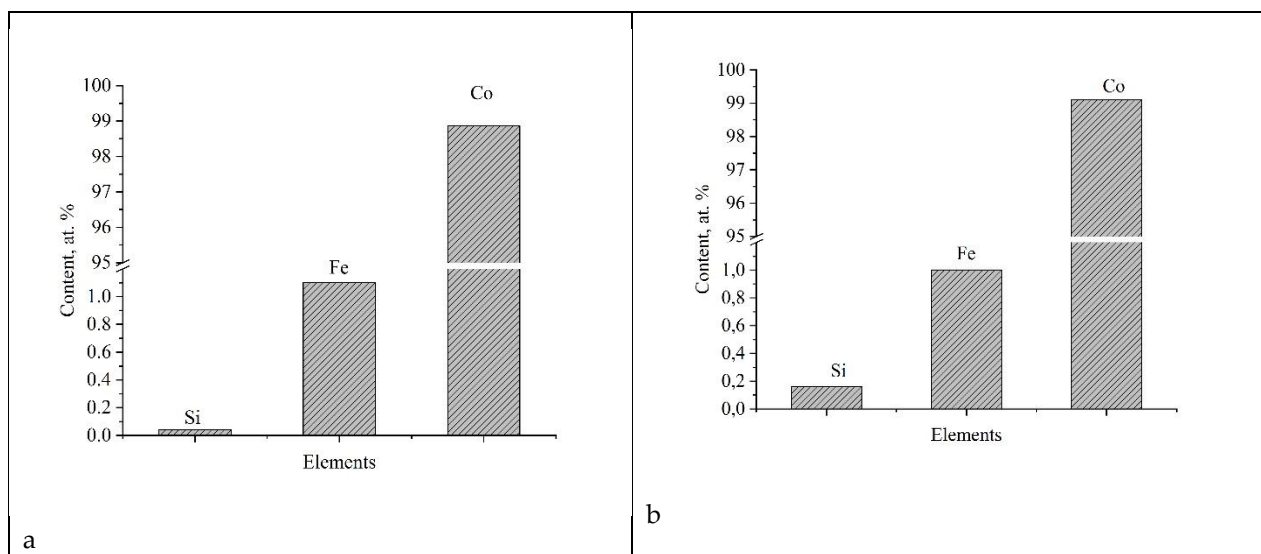


Figure 7 – Elemental composition of Co/SiO_2 , formed from the bath containing $0,5 \text{ g/dm}^3$ of nanoparticles SiO_2 under current density of 0.5 A/dm^2 (a) reference sample; (b) irradiated sample

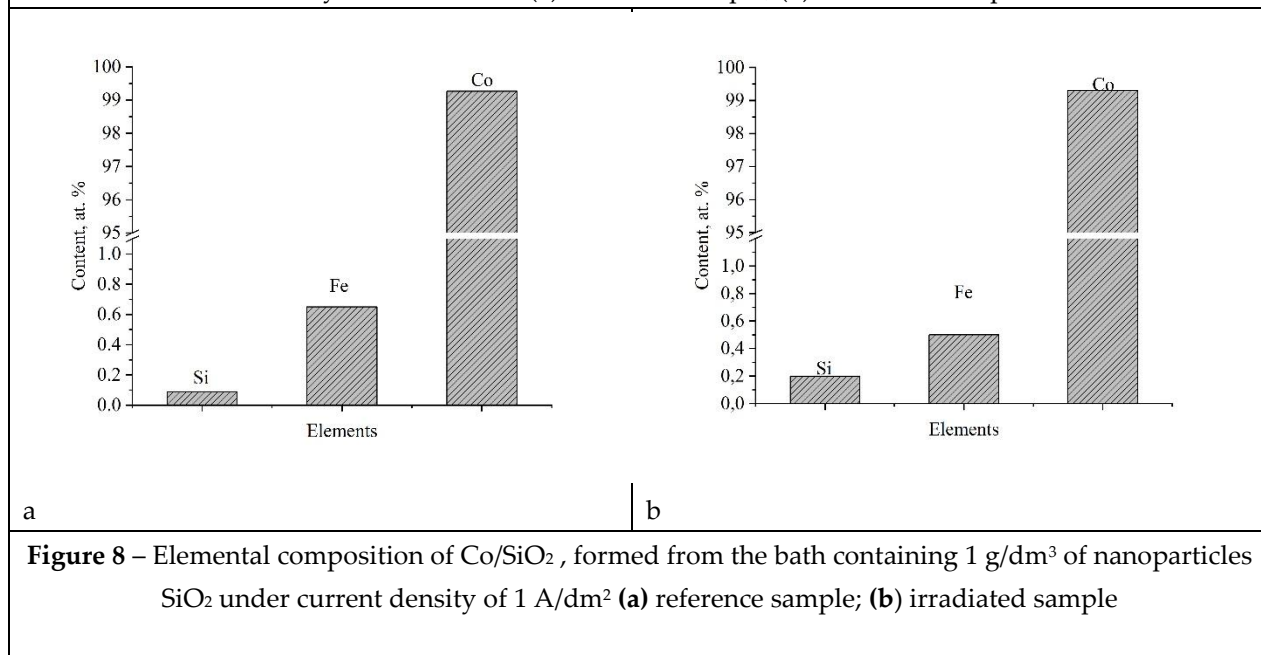


Figure 8 – Elemental composition of Co/SiO_2 , formed from the bath containing 1 g/dm^3 of nanoparticles SiO_2 under current density of 1 A/dm^2 (a) reference sample; (b) irradiated sample

Obtained data can be explained by the suggestion that X-ray acting on the solution with nanoparticles destroys nanoparticles clusters due to increasing in the dispersing ability of electrolytes. Obtained data correlates with investigation of mass gain, thickness and dispersing ability. Worth paying attention to the point of Fe content in the Co/SiO_2 . The Fe content in the coatings formed from electrolyte with concentration of SiO_2 of 1 g/dm^3 is less than in the coatings formed from electrolyte with concentration of SiO_2 of $0,5 \text{ g/dm}^3$. The reducing of Fe content can be caused by rising of the thickness and mass gain of irradiated coatings. As for Fe content in the coatings it can appear due to the preliminary reverse of current during 5 minutes before the electrodeposition and some amount of Fe ions transferred to the solution after reverse.

Figure 9 demonstrates the XRD patterns of reference Co-coatings, Co-coatings obtained in X-rays, Co/SiO_2 obtained from electrolytes with $0,5$ and 1 g/dm^2 under irradiation and without it. It is seen, that all investigated samples have simple phase composition,

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containing only Co-phase and oxide phase CoFe_2O_4 . The last has appeared due to the preliminary reverse of current. According to a little amount of SiO_2 there are no any peaks from SiO_2 . But it is well visible that addition of some SiO_2 into an electrolyte leads to formation of CoSiO_2 coatings with modified structured characterizing with crystalline orientation (110). It should be noted that intensity of the main peaks of irradiated coatings is higher than intensity of reference samples. This proves the suggestion that X-rays irradiation of electrolytes during electrodeposition promotes to orienting effect on the formation of crystal grains of the Co/SiO_2 coatings due radiation transformation in irradiated electrolyte.

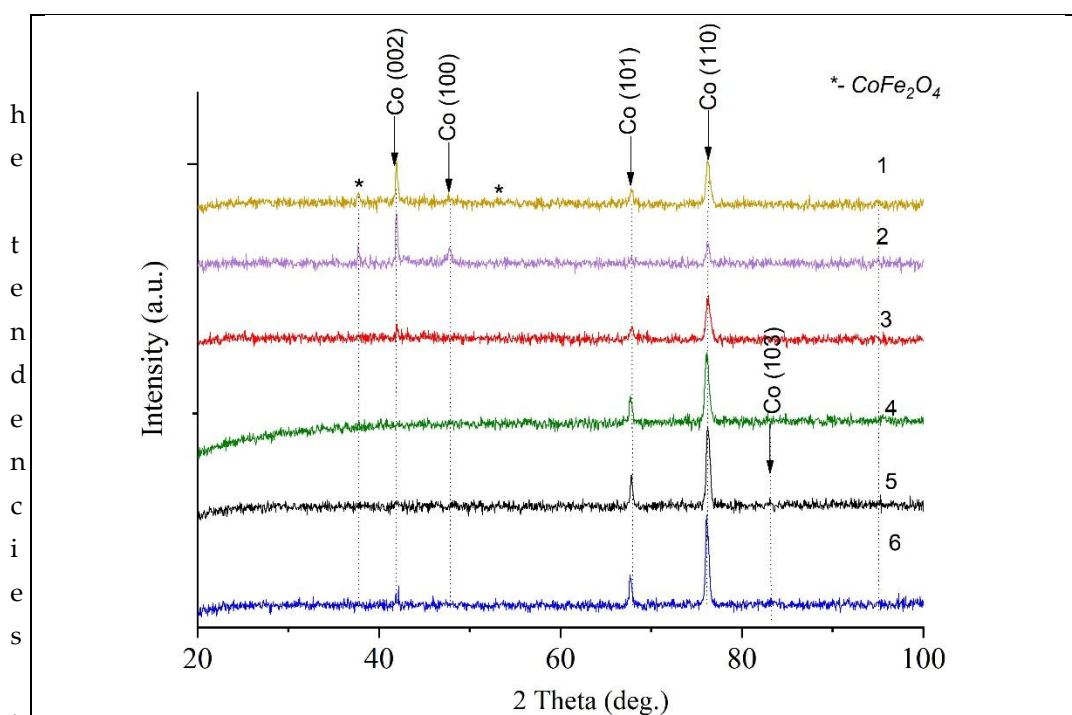


Figure 9—XRD patterns of CoSiO_2 coatings obtained in X-rays

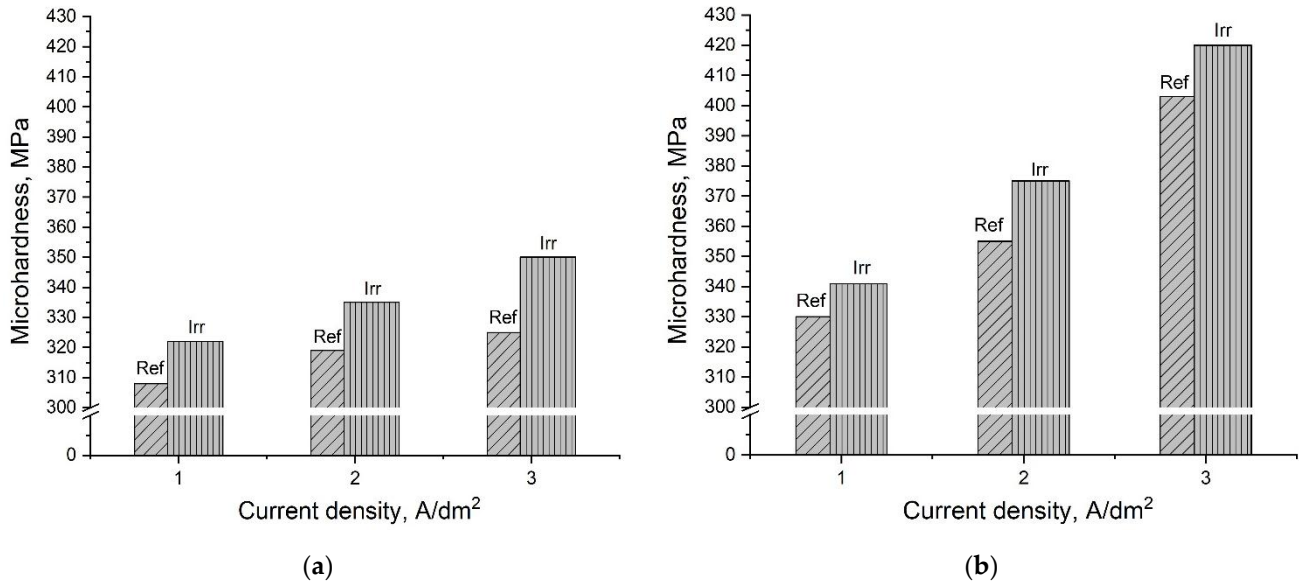
Reference Co-coating without SiO_2 , 2— Co-coating, formed under irradiation; 3— CoSiO_2 deposited from the bath with SiO_2 concentration of 0.5g/dm^3 , 4— CoSiO_2 deposited from the bath with SiO_2 concentration of 0.5g/dm^3 in the X-ray, 5— CoSiO_2 deposited from the bath with SiO_2 concentration of 1g/dm^3 , 6— CoSiO_2 deposited from the bath with SiO_2 concentration of 1g/dm^3 in the X-ray.

in the structure of composite coatings Co/SiO_2 generated the interest to investigate any operational properties.

As seen in Figure 10 microhardness of irradiated samples markedly increased in comparison with reference samples. In particular the difference in microhardness of reference and irradiated Co/SiO_2 coatings, formed from the electrolyte with SiO_2 of 0,5 % is around 7% .

Finally, the adhesion of Co/SiO_2 coatings was investigated by the scratch method based on applying of a scratch grid on the surface of testing coatings. It was found that all irradiated composite coatings Co/SiO_2 have excellent adhesion, equaled 1, according to the scale of scratch method (1 on a 4 scale, where 1 is the best rating). Unlike, reference

273 samples have adhesion only 2. The structural changes in matter can occur via primary
 274 radiolysis effects, which occur as a result of the adsorption radiation by aqueous
 275 electrolyte. Hence, these experimental results can be explained from the point of view of
 276 radiation chemistry and radiolysis of aqueous electrolytes have been admitted early.



277 **Figure 6.** Microhardness of irradiated (Irr) and non-irradiated (Ref) Co/SiO₂ formed at current densities of 1–3 A/dm² from
 278 electrolyte with SiO₂ nanoparticles of 0.5 g/dm³ (a) and 1 g/dm³ (b).

279 4. Conclusions

280 The results of elaborate investigations of the effect of X-rays on electrodeposition of
 281 composite coatings Co/SiO₂ from aqueous solution demonstrate increase in dispersing
 282 ability of electrolytes with SiO₂ nanoparticles, mass gain and thickness per time under
 283 irradiation due to the intensification of diffusion in the electrolyte by products of radiol-
 284 ysis.

285 It is shown that exposure of electrochemical system with X-rays during the Co/SiO₂
 286 coatings electrodeposition occurs the orienting effect on the growth of crystal grains and
 287 allows to obtain dense, morphology uniform coatings with increased hardness and im-
 288 proved adhesion.

289 So, the authors have found enough evidence to support that the method of the elec-
 290 trodeposition of composite coatings under the effect of X-rays makes it possible to
 291 achieve the technical result that consists of increasing the dispersing ability of electrolytes
 292 containing nanoparticles, reducing aggregation, and increasing the sedimentation stabil-
 293 ity of nanoparticles, which leads to modification of the microstructure and enhancement
 294 of performances of properties composite coatings with included nanoparticles SiO₂.

295
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 298 W.E., V.B. and P.O.; validation, N.V. and V.A.; formal analysis, N.V., V.A. and T.N.K.; investiga-
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 300 writing— original draft preparation, N.V.; writing—review and editing, T.N.K.; visualization,
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References

1. Milaniak, N.; Laroche, G.; Massines, F. Atmospheric-pressure plasma-enhanced chemical vapor deposition of nanocomposite thin films from ethyl lactate and silica nanoparticles. *Plasma Processes and Polymers* **2020**, e2000153.
2. Liu, X.,C.; Fecko, P.; Fohlerova, Z.; Karasek, T.; Pekarek, J.; Neuzil, P. Parylene micropillars coated with thermally grown SiO₂. *Journal of Vacuum Science & Technology B* **2020**, *38*(6), 063001.
3. Koltunowicz T. N. Inductive type properties of FeCoZr–CaF₂ and FeCoZr–PZT nanocomposites. *Journal of Materials Science: Materials in Electronics* **2015**, *26*(9), 6450–6457.
4. Svito, I.; Fedotova, J.,A.; Milosavljević, M.; Zhukowski, P.; Koltunowicz, T. N.; Saad, A.; Kierczynski, K.; Fedotov, A.K. Influence of sputtering atmosphere on hopping conductance in granular nanocomposite (FeCoZr)_x(Al₂O₃)_{1-x} films. *Journal of Alloys and Compounds* **2015**, *615*(SUPPL.1), S344–S347.
5. Zhukowski, P.; Koltunowicz, T. N.; Fedotova, J. A.; Larkin, A. V. An effect of annealing on electric properties of nanocomposites (CoFeZr)_x(Al₂O₃)_{1-x} produced by magnetron sputtering in the atmosphere of argon and oxygen beyond the percolation threshold. *Przegląd Elektrotechniczny* **2010**, *86*(7), 157–159.
6. Shang, H.; Fu, J.; Xie, C.; Li, Z.; Chen, D. Improving stress stability in low-pressure chemical vapor deposited silicon dioxide films by ion implantation. *Thin Solid Films* **2016**, *598*, 103–108.
7. Sourani, F.; Enayati, M. H.; Ashrafizadeh, F.; Sayyedani, F. S.; Chu, P. K. Enhancing surface properties of (Fe,Cr)Al – Al₂O₃ nanocomposite by oxygen ion implantation. *Journal of Alloys and Compounds* **2021**, *853*, 156892.
8. Koltunowicz, T. N.; Zukowski, P.; Bondariev, V.; Fedotov, A. K.; Svito, I.; Fedotova, J.; Saad A. Voltage and current resonance in nanocomposite (FeCoZr)_x(CaF₂)_(100-x) produced by ion-beam sputtering in pure argon atmosphere. *Acta Phys. Pol. A* **2015**, *128*(5), 897–900.
9. Becker, M.; Benz, S. L.; Chen, L.; Polity, A.; Klar, P. J.; Chatterjee, S. Controlled thin-film deposition of alpha or beta Ga₂O₃ by ion-beam sputtering. *Journal of Vacuum Science & Technology A* **2020**, *38*(6), 063412.
10. Sun, K. X.; Zhang, S. Y.; Wasa, K.; Shui, X. J. Characterization of La-doped xBiInO₃(1-x)PbTiO₃ piezoelectric films deposited by the radio-frequency magnetron sputtering method. *Chin. Phys. Lett.* **2016**, *33*, 064301.
11. Guo, L.; Zhao, M.; Zhuang, D.; Gong, Q.; Tan, H.; Cao, M.; Ouyang, L. A study on phase transformation of SnO_x thin films prepared by reactive magnetron sputtering. *Mater. Sci. Semicond. Process.* **2016**, *46*, 35–38.
12. Hoppe, C.; Mitschker, F.; Butterling, M.; Liedke, M. O.; de los Arcos, T.; Awakowicz, P.; Wagner, A.; Grundmeier, G. Characterisation of micropores in plasma deposited SiO(x) films by means of positron annihilation lifetime spectroscopy. *Journal of Physics-Applied Physics* **2020**, *53*(47), 475205.
13. Singh, J.; Chatha, S. S.; Singh, H. Characterization and corrosion behavior of plasma sprayed calcium silicate reinforced hydroxyapatite composite coatings for medical implant applications. *Ceramics International* **2021**, *47*(1), 782–792.
14. Ali, G. A. M.; Yusoff, M. M.; Ng, Y. H.; Lim, H. N.; Chong, K. F. Potentiostatic and galvanostatic electrodeposition of manganese oxide for supercapacitor application: a comparison study. *Curr. Appl. Phys.* **2015**, *15*, 1143–1147.
15. Aghazadeh, M. Cathodic Electrochemical Deposition of Nanostructured Metal Oxides/Hydroxides and their Composites for Supercapacitor Applications: A Review. *Anal. Bioanal. Electrochem* **2019**, *11*, 211–266.
16. Ilyin, V.; Semyonichev, V.; Salakhova, R.; Naletov, B.; Tikhoobraz, A. Nickel-plating electrolyte. RU Patent 2, 449, 063 filed 5 April 2011, and issued 27 April 1998.
17. Pogrebnjak, A.D.; Bagdasaryan, A.A.; Pshyk, A.; Dyadyura, K. Adaptive multicomponent nanocomposite coatings in surface engineering. *Physica-Usppekhi* **2017**, *60* (6), 586–607.
18. Müller, T.; Grimwood, J.; Bachmaier, A.; Pippan, R. Electrodeposition of Fe-C Alloys from Citrate Baths: Structure, Mechanical Properties, and Thermal Stability. *Metals* **2018**, *8*, 363.
19. Misaelides, P.; Hatzidimitriou, A.; Noli, F.; Pogrebnjak, A.D.; Tyurin, Y.N.; Kosionidis, S. Preparation, characterization, and corrosion behavior of protective coatings on stainless steel samples deposited by plasma detonation techniques, *Surface & Coatings Technology* **2004**, *180*, 290–296.
20. Jar-Mukhamedov, S. Method for electrodeposition of composite coatings and plant for its embodiment. RU Patent 2, 109, 855 filed 8 July 1991, and issued 27 April 1998.
21. Pikayev, A. Modern radiation chemistry. Radiolysis of gases and liquids. *Nauka* **1986**, 439.
22. Valko, N.; Moroz, N. Modification of a structure of the CoNiFe alloys by the X-ray irradiation. *Proceedings of 9th International Conference New Electrical and Electronic Technologies and their Industrial Implementation*, Zakopane, Poland, 23-26 June, **2015**, 11–13.
23. Koltunowicz, T.N.; Zhukowski, P.; Fedotova, J.A.; Bayev, V.G.; Streltsov, E.A.; Baran, L.V. Electrochemically Deposited Cobalt Nanoarrays in SiO₂/n-Si Templates Produced by Swift Heavy Ion-Induced Modification Technology, *Acta Physica Polonica A* **2013**, *123* (5), 929–931.
24. Valko, N.; Kasperovich, A.; Koltunowicz, T.N. Forming a structure of the CoNiFe alloys by X-ray irradiation. *Functional Materials Letters* **2019**, *11*, 1850044.

-
- 363 25. Kucera, M.; Gutten, M.; Simko, M.; Sebok, M.; Korenciak, D.; Jarina, R. and Pitonak, M. Electromagnetic Compatibility and
364 Radiation Analysis in Control Room. *Measurement Science Review* **2019**, *19*, 126–131.
- 365 26. GOST 9.302-88 Unified system of protection against corrosion and aging. Metal and non-metal coatings. Inorganic. Control
366 methods.
- 367 27. GOST 9.309-86 Galvanic coatings. Determination of the ability of electrolytes in a dispersive coating.