Техническая информация

http://doi.org/10.32864/polymmattech-2023-9-4-97-104

УДК 541.64.052+539.23+621.315

ПЕРСПЕКТИВЫ СИНТЕЗА ФУНКЦИОНАЛЬНЫХ БИОМАТЕРИАЛОВ ИЗ АКТИВНОЙ ГАЗОВОЙ ФАЗЫ

А. В. РОГАЧЕВ[1+], М. А. ЯРМОЛЕНКО[1], А. А. РОГАЧЕВ[2], ЦЗЯН СЯО ХУН[3]

[1]Гомельский государственный университет имени Ф. Скорины, Международная китайско-белорусская научная лаборатория по вакуумно-плазменным технологиям, ул. Советская, 104, 246019, г. Гомель, Беларусь
[2]Институт химии новых материалов НАН Беларуси, ул. Ф. Скорины, 36, 220141, г. Минск, Беларусь
[3]Нанкинский университет науки и технологии, Международная китайско-белорусская научная лаборатория по вакуумно-плазменным технологиям, ул. Сяолинвэй, 200, 210094, Нанкин, Китайская Народная Республика

Цель работы — анализ основных технологических направлений синтеза биологических материалов; определение эффективности применения методов нанесения из активной газовой фазы, генерируемой электронно-лучевым диспергированием полимеров и испарением низкомолекулярных соединений, для формирования многокомпонентных биопокрытий.

Дана краткая характеристика методов, применяющихся при синтезе биологических материалов, и приведены основные преимущества, реализуемые при их осаждении из активной газовой фазы и определяющие в значительной степени высокую эффективность формирования покрытий с заданными, не достигаемыми другими методами свойствами. В числе особенностей метода отмечается возможность нанесения в едином технологическом цикле нано- и микрокомпозиционных слоев с заданным распределением в его объеме наноразмерных частиц функционального наполнителя, многослойных функциональных покрытий.

В качестве наиболее перспективных направлений, учитывающих преимущества реализации плазмохимического синтеза, определены методы нанесении антибактериальных, противогрибковых нанокомпозиционных полимерных покрытий с пролонгированным высвобождением лекарственного соединения. Представлены данные о достижении высоких свойств при использовании осаждения из газовой фазы при формировании многослойных покрытий на основе кальцийфосфатных соединений, целлюлозной матрицы и лекарственных компонентов, характеризующихся высокой эффективностью при лечении костных повреждений.

Ключевые слова: биологические материалы, электронно-лучевое нанесение, биопокрытия, полимеры, регенерация костных тканей.

PROSPECTS FOR THE SYNTHESIS OF FUNCTIONAL BIOMATERIALS FROM THE ACTIVE GAS PHASE

A. V. ROGACHEV[1+], V. A. YARMOLENKO[1], A. A. ROGACHEV[2], JIANG XIAO HONG[3]

[1]Francisk Skorina Gomel State University, International Chinese-Belorussian Scientific Laboratory on Vacuum-Plasma Technology, Sovetskaya St., 104, 246019, Gomel, Belarus
[2]Institute of Chemistry of New Materials, National Academy of Sciences of Belarus, F. Skorini St., 36, 220141, Minsk, Belarus
[3]Nanjing University of Science and Technology, International Chinese-Belorussian Scientific Laboratory on Vacuum-Plasma Technology, Xiaolingwei St., 200, 210094, Nanjing, Republic of China

The purpose of this work is to analyze the main technological directions for the synthesis of biological materials and to determine the effectiveness of applying deposition methods from the active gas phase generated by electron beam dispersion of polymers and the evaporation of low molecular weight compounds for

[+]Автор, с которым следует вести переписку. E-mail: rogachevav@mail.ru

the formation of multicomponent biocoatings.

A brief description of the biological materials synthesis methods is presented. The main advantages of the deposition method from the active gas phase are given. It is noted that it is impossible to obtain coatings with such properties by other application methods. The method of deposition from the active gas phase allows the application of nano- and micro composition layers in a single technological cycle. Coatings with a given distribution of nanoscale particles and filler in the volume of a thin layer can be obtained.

Methods for applying antibacterial, antifungal nanocomposite polymer coatings with a prolonged release of a drug compound have been identified as the most promising areas, taking into account the advantages of implementing plasma-chemical synthesis. Data are presented on the achievement of high properties when using deposition from the gas phase in the deposition of multilayer coatings based on calcium phosphate compounds, a cellulose matrix, and drug components that are highly effective in the treatment of bone injuries.

Keywords: biological materials, electron beam deposition, biocoatings, polymers, bone regeneration.

Поступила в редакцию 27.06.2023

Образец цитирования:

Рогачев А. В., Ярмоленко М. А., Рогачев А. А., Цзян Сяо Хун. Перспективы синтеза функциональных биоматериалов из активной газовой фазы // Полимерные материалы и технологии. 2023. Т. 9, № 4. С. 97–104. http://doi.org/10.32864/polymmattech-2023-9-4-97-104

Citation sample:

Rogachev A. V., Yarmolenko M. A., Rogachev A. A., Tszyan Syao Khun. Perspektivy sinteza funktsional'nykh biomaterialov iz aktivnoy gazovoy fazy [Prospects for the synthesis of functional biomaterials from the active gas phase]. *Polimernye materialy i tekhnologii* [Polymer Materials and Technologies], 2023, vol. 9, no. 4, pp. 97–104. http://doi.org/10.32864/polymmattech-2023-9-4-97-104

Литература

1. Xu H., Cai Y., Chu X., Chu H., Li J., Zhang D. A mussel-bioinspired multi-functional hyperbranched polymeric coating with the integrating antibacterial and antifouling activities for implant interface modification // Polymer Chemistry, 2021, vol. 12, no. 23, pp. 3413–3426. doi: 10.1039/D1PY00246E
2. Ishihama H., Ishii K., Nagai S., Kakinuma H., Sasaki, A., Yoshioka K., Kuramoto T., Shiono Y., Funao H., Isogai N., Tsuji T., Okada Y., Koyasu S., Toyama Y., Nakamura M., Aizawa M., Matsumoto M. An antibacterial coated polymer prevents biofilm formation and implant-associated infection // Sci Rep, 2021, vol. 11. doi: 10.1038/s41598-021-82992-w
3. Liu J., Liu J., Attarilar S., Wang C., Tamaddon M., Yang C., Xie K., Yao J., Wang L., Liu C., Tang Y. Nano-Modified Titanium Implant Materials: A Way Toward Improved Antibacterial Properties // Front Bioeng Biotechnol, 2020, vol. 8. doi: 10.3389/fbioe.2020.576969
4. Yi L.-J., Li J.-F., Ma M.-G., Zhu Y.-J. Nanostructured Calcium-based Biomaterials and their Application in Drug Delivery // Current Medicinal Chemistry, 2020, vol. 27, pp. 5189–5212. doi: 10.2174/0929867326666190222193357
5. Singhvi M. S., Zinjarde S. S., Gokhale D. V. Polylactic acid: synthesis and biomedical applications // Journal of Applied Microbiology, 2019, vol. 127, pp. 1612–1626. doi: 10.1111/jam.14290
6. Ogay V., Mun E. A., Kudaibergen G., Baidarbekov M., Kassymbek K., Zharkinbekov Z., Saparov A. Progress and Prospects of Polymer-Based Drug Delivery Systems for Bone Tissue Regeneration // Polymers, 2020, vol. 12, no. 12. doi: 10.3390/polym12122881
7. Manzini B. M., Machado L. M. R., Noritomi P. Y., Lopes da Silva J. V. Advances in Bone tissue engineering: A fundamental review // J Biosci, 2021, vol. 46, no. 17. doi: 10.1007/s12038-020-00122-6
8. Deng C., Chang J., Wu C. Bioactive scaffolds for osteochondral regeneration // J. Orthop. Transl., 2019, vol. 17, pp. 15–25.

doi: 10.1016/j.jot.2018.11.006
9. Liu Y., Rogachev A. V., Yarmolenko V. A., Rogachev A. A., Xiaohong Jiang, Sun D., Xiao J., Yarmolenko M. A. The structure and properties of bioactive multilayer coatings applied by a low-energy electron beam on the implant surface // Surface & Coatings Technology, 2019, vol. 378. doi: 10.1016/j.surfcoat.2019.124969
10. Maharjan B., Park J., Kaliannagounder V. K., Awasthi G. P., Joshi M. K., Park C. H., Kim C. S. Regenerated cellulose nanofiber reinforced chitosan hydrogel scaffolds for bone tissue engineering // Carbohydrate Polymers, 2021, vol. 251. doi: 10.1016/j.carbpol.2020.117023
11. Kim S. E., Tiwari A. P. Three dimensional polycaprolactone/cellulose scaffold containing calcium-based particles: a new platform for bone regeneration // Carbohydrate Polymers, 2020, vol. 250. doi: 10.1016/j.carbpol.2020.116880
12. Liu Y., Qin X., Rogachev A. V., Rogachev A. A., Kontsevaya I. I., Pyzh A. E., Xiaohong Jiang, Yarmolenko V. A., Rudenkov A. S., Yarmolenko M. A. Structure and properties of microcellulose-based coatings deposited via a low-energy electron beam and their effect on the properties of wound dressings // Carbohydrate Polymer Technologies and Applications, 2021, vol. 2. doi: 10.1016/j.carpta.2021.100146
13. Li B., Liu Y., Rogachev A. V., Yarmolenko V. A., Rogachev A. A., Pyzh A. E., Xiaohong Jiang, Yarmolenko M. A. Features of electron beam deposition of polymer coatings with the prolonged release of the drug component // Materials Science & Engineering C, 2020, vol. 110. doi: 10.1016/j.msec.2020.110730
14. Xu Q., Xu Z., Xiaohong Jiang, Yarmolenko M. A., Rogachev A. A., Rogachev A. V. Antibacterial coatings based on polycaprolactone and polyurethane with prolonged release of ciprofloxacin // Surface & Coatings Technology, 2020, vol. 405. doi: 10.1016/j.surfcoat.2020.126584
15. Рогачев А. А. Физико-химия полимерных покрытий, осаждаемых из активной газовой фазы. М. : Научный мир, 2014. 287 с.
16. Ярмоленко М. А., Рогачев А. А., Лучников П. А., Рогачев А. В., Джанг Сянь Хун. Микро- и нанокомпозиционные полимерные покрытия, осаждаемые из активной газовой фазы. М. : Радиотехника, 2016. 424 с.
17. Cheng T., Cao J., Xiaohong Jiang, Yarmolenko M. A., Rogachev A. A., Rogachev A. V. Study of Icaritin Films by Low-Energy Electron Beam Deposition // Eurasian Chemico-Technological Journal, 2021, vol. 23, pp. 77–87. doi: 10.18321/ectj1077
18. Cheng T., Cao J., Wu T., Xiaohong Jiang, Yarmolenko M. A., Rogachev A. A., Rogachev A. V. Study on osteoinductive activity of biotin film by low-energy electron beam deposition // Biomaterials Advances, 2022, vol. 135. doi: 10.1016/j.bioadv.2022.212730
19. He C., Rogachev A. V., Li B., Yarmolenko V. A., Rogachev A. A., Tapal'skii D. V., Xiaohong Jiang, Sun D., Yarmolenko M. A. Synthesis and structure of antibacterial coatings formed by electron-beam dispersion of polyvinyl chloride in vacuum // Surface & Coatings Technology, 2018, vol. 354, pp. 38–45. doi: 10.1016/j.surfcoat.2018.09.013
20. Rahachou A. V., Rogachev A. A., Yarmolenko M. A., Jiang Xiaohong, Liu Z. Molecular structure and optical properties of PTFE-based nanocomposite polymer–metal coatings // Applied Surface Science, 2012, vol. 258, no. 6, pp. 1976–1980. doi: 10.1016/j.apsusc.2011.05.084
21. Rogachev A. A., Yarmolenko M. A., Rogachou A. V, Tapalski D. V., Xiaoheng Liu, Gorbachev D. L. Morphology and structure of antibacterial nanocomposite organic polymer and metal-polymer coatings deposited from active gas phase // RSC Adv., 2013, vol. 3, no. 28, pp. 11226–11233. doi: 10.1039/C3RA23284K
22. Sun J., Rogachev A. V., Yarmolenko M. A., Rogachev A. A., Xiaohong Jiang, Tapal'skii D. V., Gorbachev D. L., Bespal'ko A. A. Nanocomposite coatings based on copper and the products of polyethylene destruction, features of their formation, structure and antibacterial properties // RSC Adv., 2016, vol. 6, no. 35, pp. 29220–29228. doi: 10.1039/C6RA02933G
23. Xiao J., Rogachev A. V., Yarmolenko V. A., Rogachev A. A., Liu Y., Xiaohong Jiang, Sun D., Yarmolenko M. A. Formation features, structure and properties of bioactive coatings based on phosphate-calcium layers, deposited by a low energy electron beam // Surface & Coatings Technology, 2019, vol. 359, pp. 6–15. doi: 10.1016/j.surfcoat.2018.12.051
24. Liu Y., Rogachev A. V., Tan X., Rogachev A. A., Xiaohong Jiang, Pyzh A. E., Yarmolenko V. A., Yarmolenko M. A., Rudenkov A. S. Low-energy electron beam deposition of metal-containing organic-inorganic coatings with selective activity against microorganisms // Vacuum, 2023, vol. 209. doi: 10.1016/j.vacuum.2022.111803
25. Xu Q., Xu Z., Xiaohong Jiang, Yarmolenko M. A., Rogachev A. A., Rogachev A. V. Antibacterial coatings based on polycaprolactone and polyurethane with prolonged release of ciprofloxacin // Surface & Coatings Technology, 2021, vol. 405. doi: 10.1016/j.surfcoat.2020.126584
26. Xu Q., Li B., Xu Z., Xiaohong Jiang, Yarmolenko M. A., Rogachev A. A., Rogachev A. V. PCL Based CIP-Loaded Double-Layer Films Deposited by Low-Electron Beam Dispersion Method and its Antibacterial Properties // Eurasian Chem.-Technol. J., 2020, vol. 22, no. 4, pp. 255–262. doi: 10.18321/ectj997
27. Lian R., Cao J., Xiaohong Jiang, Rogachev A. V. Physicochemical, antibacterial properties and cytocompatibility of starch / chitosan films incorporated with zinc oxide nanoparticles // Materials Today Communications, 2021, vol. 27. doi: 10.1016/j.mtcomm.2021.102265
28. Cao J., Liu X., Xiaohong Jiang, Lian R., Du B., Rogachev A. V. Studies of magnesium - hydroxyapatite micro/nano film for drug sustained release // Applied Surface Science, 2021, vol. 565. doi: 10.1016/j.apsusc.2021.150598
29. Cao J., Yang B., Yarmolenka M. A., Ruizhe Lian, Xiaohong Jiang, Jiangning Zhao, Rogachev A. V. Osteogenic potential evaluation of biotin combined with magnesium-doped hydroxyapatite sustained-release film // Materials Science & Engineering C, 2022, vol. 135. doi: 10.1016/ j.msec.2022.112679
30. Liu Y., Cao J., Rogachev A. V., Rogachev A. A., Kontsevaya I. I., Xiaohong Jiang, Yarmolenko V. A., Rudenkov A. S., Yarmolenko M. A., Gorbachev D. L., Pyzh A. E. Low-energy electron beam deposition of coatings based on lignin and quercetin, their structure and properties // Vacuum, 2022, vol. 205. doi: 10.1016/j.vacuum.2022.111416
31. Руденков А. С., Ярмоленко М. А., Фролов С. А. Влияние термообработки на морфологию и структуру нанокомпозиционных покрытий на основе крахмала и ацетата меди // Проблемы физики, математики и техники. 2023. № 1 (54). С. 54–59. doi: 10.54341/20778708_2023_1_54_54
32. Рогачев А. В., Ярмоленко М. А., Рогачев А. А., Саркисов О. А. Физико-химические закономерности плазмохимического синтеза, структура и свойства нанокомпозиционных полимерных покрытий // Наноструктурные материалы: технология, свойства, применение : сб. науч. ст. / редкол.: П. А. Витязь (гл. ред.) [и др.]. Минск : Белорусская наука, 2017. С. 162–171.

References

1. Xu H., Cai Y., Chu X., Chu H., Li J., Zhang D. A mussel-bioinspired multi-functional hyperbranched polymeric coating with the integrating antibacterial and antifouling activities for implant interface modification. *Polymer Chemistry*, 2021, vol. 12, no. 23, pp. 3413–3426. doi: 10.1039/D1PY00246E
2. Ishihama H., Ishii K., Nagai S., Kakinuma H., Sasaki, A., Yoshioka K., Kuramoto T., Shiono Y., Funao H., Isogai N., Tsuji T., Okada Y., Koyasu S., Toyama Y., Nakamura M., Aizawa M., Matsumoto M. An antibacterial coated polymer prevents biofilm formation and implant-associated infection. *Sci Rep*, 2021, vol. 1. doi: 10.1038/s41598-021-82992-w
3. Liu J., Liu J., Attarilar S., Wang C., Tamaddon M., Yang C., Xie K., Yao J., Wang L., Liu C., Tang Y. Nano-Modified Titanium Implant Materials: A Way Toward Improved Antibacterial Properties. *Front Bioeng Biotechnol*, 2020, vol. 8. doi: 10.3389/fbioe.2020.576969
4. Yi L.-J., Li J.-F., Ma M.-G., Zhu Y.-J. Nanostructured Calcium-based Biomaterials and their Application in Drug Delivery. *Current*

Medicinal Chemistry, 2020, vol. 27, pp. 5189–5212. doi: 10.2174/0929867326666190222193357
5. Singhvi M. S., Zinjarde S. S., Gokhale D. V. Polylactic acid: synthesis and biomedical applications. *Journal of Applied Microbiology*, 2019, vol. 127, pp. 1612–1626. doi: 10.1111/jam.14290
6. Ogay V., Mun E. A., Kudaibergen G., Baidarbekov M., Kassymbek K., Zharkinbekov Z., Saparov A. Progress and Prospects of Polymer-Based Drug Delivery Systems for Bone Tissue Regeneration. *Polymers*, 2020, vol. 12, no. 12. doi: 10.3390/polym12122881
7. Manzini B. M., Machado L. M. R., Noritomi P. Y., Lopes da Silva J. V. Advances in Bone tissue engineering: A fundamental review. J Biosci, 2021, vol. 46, no. 17. doi: 10.1007/s12038-020-00122-6
8. Deng C., Chang J., Wu C. Bioactive scaffolds for osteochondral regeneration. *J. Orthop. Transl*., 2019, vol. 17, pp. 15–25. doi: 10.1016/j.jot.2018.11.006
9. Liu Y., Rogachev A. V., Yarmolenko V. A., Rogachev A. A., Xiaohong Jiang, Sun D., Xiao J., Yarmolenko M. A. The structure and properties of bioactive multilayer coatings applied by a low-energy electron beam on the implant surface. *Surface & Coatings Technology*, 2019, vol. 378. doi: 10.1016/j.surfcoat.2019.124969
10. Maharjan B., Park J., Kaliannagounder V. K., Awasthi G. P., Joshi M. K., Park C. H., Kim C. S. Regenerated cellulose nanofiber reinforced chitosan hydrogel scaffolds for bone tissue engineering. *Carbohydrate Polymers*, 2021, vol. 251. doi: 10.1016/j.carbpol.2020.117023
11. Kim S. E., Tiwari A. P. Three dimensional polycaprolactone/cellulose scaffold containing calcium-based particles: a new platform for bone regeneration. *Carbohydrate Polymers*, 2020, vol. 250. doi: 10.1016/j.carbpol.2020.116880
12. Liu Y., Qin X., Rogachev A. V., Rogachev A. A., Kontsevaya I. I., Pyzh A. E., Xiaohong Jiang, Yarmolenko V. A., Rudenkov A. S., Yarmolenko M. A. Structure and properties of microcellulose-based coatings deposited via a low-energy electron beam and their effect on the properties of wound dressings. *Carbohydrate Polymer Technologies and Applications*, 2021, vol. 2. doi: 10.1016/j.carpta.2021.100146
13. Li B., Liu Y., Rogachev A. V., Yarmolenko V. A., Rogachev A. A., Pyzh A. E., Xiaohong Jiang, Yarmolenko M. A. Features of electron beam deposition of polymer coatings with the prolonged release of the drug component. *Materials Science & Engineering C*, 2020, vol. 110. doi: 10.1016/j.msec.2020.110730
14. Xu Q., Xu Z., Xiaohong Jiang, Yarmolenko M. A., Rogachev A. A., Rogachev A. V. Antibacterial coatings based on polycaprolactone and polyurethane with prolonged release of ciprofloxacin. *Surface & Coatings Technology*, 2020, vol. 405. doi: 10.1016/j.surfcoat.2020.126584
15. Rogachev A. A. *Fiziko-khimiya polimernykh pokrytiy, osazhdaemykh iz aktivnoy gazovoy fazy* [Physical chemistry of polymer coatings deposited from the active gas phase]. Moscow : Nauchnyy mir Publ., 2014. 287 p.
16. Yarmolenko M. A., Rogachev A. A., Luchnikov P. A., Rogachev A. V., Dzhang Syan' Khun. *Mikro- i nanokompozitsionnye polimernye pokrytiya, osazhdaemye iz aktivnoy gazovoy* [Micro- and nanocomposite polymer coatings deposited from the active gas phase]. Moscow : Radiotekhnika Publ., 2016. 424 p.
17. Cheng T., Cao J., Xiaohong Jiang, Yarmolenko M. A., Rogachev A. A., Rogachev A. V. Study of Icaritin Films by Low-Energy Electron Beam Deposition. *Eurasian Chemico-Technological Journal*, 2021, vol. 23, pp. 77–87. doi: 10.18321/ectj1077
18. Cheng T., Cao J., Wu T., Xiaohong Jiang, Yarmolenko M. A., Rogachev A. A., Rogachev A. V. Study on osteoinductive activity of biotin film by low-energy electron beam deposition. *Biomaterials Advances*, 2022, vol. 135. doi: 10.1016/j.bioadv.2022.212730
19. He C., Rogachev A. V., Li B., Yarmolenko V. A., Rogachev A. A., Tapal'skii D. V., Xiaohong Jiang, Sun D., Yarmolenko M. A. Synthesis and structure of antibacterial coatings formed by electron-beam dispersion of polyvinyl chloride in vacuum. *Surface & Coatings Technology*, 2018, vol. 354, pp. 38–45. doi: 10.1016/j.surfcoat.2018.09.013
20. Rahachou A. V., Rogachev A. A., Yarmolenko M. A., Jiang Xiaohong, Liu Z. Molecular structure and optical properties of PTFE-based nanocomposite polymer–metal coatings. *Applied Surface Science*, 2012, vol. 258, no. 6, pp. 1976–1980. doi: 10.1016/j.apsusc.2011.05.084
21. Rogachev A. A., Yarmolenko M. A., Rogachou A. V, Tapalski D. V., Xiaoheng Liu, Gorbachev D. L. Morphology and structure of antibacterial nanocomposite organic polymer and metal-polymer coatings deposited from active gas phase. *RSC Adv.*, 2013, vol. 3, no. 28, pp. 11226–11233. doi: 10.1039/C3RA23284K
22. Sun J., Rogachev A. V., Yarmolenko M. A., Rogachev A. A., Xiaohong Jiang, Tapal'skii D. V., Gorbachev D. L., Bespal'ko A. A. Nanocomposite coatings based on copper and the products of polyethylene destruction, features of their formation, structure and antibacterial properties. *RSC Adv*., 2016, vol. 6, no. 35, pp. 29220–29228. doi: 10.1039/C6RA02933G
23. Xiao J., Rogachev A. V., Yarmolenko V. A., Rogachev A. A., Liu Y., Xiaohong Jiang, Sun D., Yarmolenko M. A. Formation features, structure and properties of bioactive coatings based on phosphate-calcium layers, deposited by a low energy electron beam. *Surface & Coatings Technology*, 2019, vol. 359, pp. 6–15. doi: 10.1016/j.surfcoat.2018.12.051
24. Liu Y., Rogachev A. V., Tan X., Rogachev A. A., Xiaohong Jiang, Pyzh A. E., Yarmolenko V. A., Yarmolenko M. A., Rudenkov A. S. Low-energy electron beam deposition of metal-containing organic-inorganic coatings with selective activity against microorganisms. *Vacuum*, 2023, vol. 209. doi: 10.1016/j.vacuum.2022.111803
25. Xu Q., Xu Z., Xiaohong Jiang, Yarmolenko M. A., Rogachev A. A., Rogachev A. V. Antibacterial coatings based on polycaprolactone and polyurethane with prolonged release of ciprofloxacin. *Surface & Coatings Technology*, 2021, vol. 405. doi: 10.1016/j.surfcoat.2020.126584
26. Xu Q., Li B., Xu Z., Xiaohong Jiang, Yarmolenko M. A., Rogachev A. A., Rogachev A. V. PCL Based CIP-Loaded Double-Layer Films Deposited by Low-Electron Beam Dispersion Method and its Antibacterial Properties. *Eurasian Chem.-Technol. J*., 2020, vol. 22, no. 4, pp. 255–262. doi: 10.18321/ectj997
27. Lian R., Cao J., Xiaohong Jiang, Rogachev A. V. Physicochemical, antibacterial properties and cytocompatibility of starch / chitosan films incorporated with zinc oxide nanoparticles. *Materials Today Communications*, 2021, vol. 27. doi: 10.1016/j.mtcomm.2021.102265
28. Cao J., Liu X., Xiaohong Jiang, Lian R., Du B., Rogachev A. V. Studies of magnesium - hydroxyapatite micro/nano film for drug sustained release. *Applied Surface Science*, 2021, vol. 565. doi: 10.1016/j.apsusc.2021.150598
29. Cao J., Yang B., Yarmolenka M. A., Ruizhe Lian, Xiaohong Jiang, Jiangning Zhao, Rogachev A. V. Osteogenic potential evaluation of biotin combined with magnesium-doped hydroxyapatite sustained-release film. *Materials Science & Engineering* C, 2022, vol. 135. doi: 10.1016/j.msec.2022.112679
30. Liu Y., Cao J., Rogachev A. V., Rogachev A. A., Kontsevaya I. I., Xiaohong Jiang, Yarmolenko V. A., Rudenkov A. S., Yarmolenko M. A., Gorbachev D. L., Pyzh A. E. Low-energy electron beam deposition of coatings based on lignin and quercetin, their structure and properties. *Vacuum*, 2022, vol. 205. doi: 10.1016/j.vacuum.2022.111416
31. Rudenkov A. S., Yarmolenko M. A., Frolov S. A. Vliyanie termoobrabotki na morfologiyu i strukturu nanokompozitsionnykh pokrytiy na osnove krakhmala i atsetata medi [Effect of Heat Treatment on the Morphology and Structure of Nanocomposite Coatings Based on Starch and Copper Acetate]. *Problemy fiziki, matematiki i tekhniki* [Problems of Mathematics, Physics and Technics], 2023, no. 1 (54), pp. 54–59. doi: 10.54341/20778708_2023_1_54_54
32. Rogachev A. V., Yarmolenko M. A., Rogachev A. A., Sarkisov O. A. Fiziko-khimicheskie zakonomernosti plazmokhimicheskogo sinteza, struktura i svoystva nanokompozitsionnykh polimernykh pokrytiy [Physical and chemical regularities of plasma-chemical synthesis, structure and properties of nanocomposite polymer coatings]. *Nanostrukturnye materialy: tekhnologiya, svoystva, primenenie* [Nanostructured materials: technology, properties, application]. Minsk : Belorusskaya nauka Publ., 2017. C. 162–171.