ABSTRACT AND REFERENCES

MATERIALS SCIENCE

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DEVELOPMENT OF THE CHEMICAL VAPOR DEPOSITION PROCESS FOR APPLYING MOLYBDENUM COATINGS ON THE COMPONENTS IN ASSEMBLY AND ENGINE CONSTRUCTION (p. 6–15)

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The process of chemical vapor deposition of Mo and Mo-C coatings was studied by means of thermal decomposition of molybdenum hexacarbonyl. The kinetics of the coating growth in the range of 480 °C–540 °C and the pressure in the reaction volume from 9 Pa to 16 Pa were explored. The dependences of coating growth rate, the magnitudes of their microhardness on the parameters of their obtaining, as well as the changes in the morphology of the coating surface, roughness, and structure, were established. The tribological properties of the obtained coatings coupled with bronze Br.Su3H3S20F0.2 were explored at the friction machine 2070 SMT-1 according to the "cube–roller" scheme in a load interval of 0.2–1.4 kN. The lubrication during determining the friction coefficients was carried out by immersion of the movable counter body into a bath with fuel TC-1, GOST 10227-86. It was necessary to conduct such research because there is insufficient information when it comes to the specific equipment and peculiarities of the object onto which a coating is applied.

When developing the process of coating application on specific components, techniques, and means to ensure the uniformity of parts heating and precursor feeding to their surface were tested. As a result of the conducted studies, we obtained the regions of parameters of obtaining coatings with different structure, rate, hardness, as well as the patterns of changes in these characteristics at the change of the basic parameters of the process of obtaining such coatings. Depending on application conditions, coatings may have hardness from ~11,000 MPa to 18,000 MPa at a growth rate from 50 μm/h to 170 μm/h. The mean values of the friction coefficient of coatings with different microstructure and microhardness were 0.101 at the load of 0.2 kN and 0.077 at the load of 1.4 kN.

Based on the conducted research, it was possible to develop the process of applying the metal and metal-carbide molybdenum-based CVD coatings in regards to the components of the assembly and engine construction, which can serve as the basis for the development of industrial technologies.

Keywords: CVD processes, molybdenum, molybdenum-carbide coating, properties of coatings, tribological characteristics, development of technologies.

References

1. Pauell, K., Oksli, Dzh., Blocher Ml., Dzh. (Eds.) (1970). Osazhdenie iz gazovoy fazy. Moscow: Atomizdat, 472.
2. Pierson, H. O. (1997). Handbook of Chemical Vapor Deposition. William Andrew Publishing.
3. Syrkin, V. G., Babin, V. N. (2000). Gaz vyrashchivaet metally. Moscow: Nauka, 190.
4. Choy, K. (2003). Chemical vapour deposition of coatings. Progress in Materials Science, 48 (2), 57–170. doi: https://doi.org/10.1016/s0079-6425(01)00009-3
5. Yerokhin, M. N., Kazantsev, S. P., Chupyatov, N. N. (2018). Technological equipment for obtaining metal coatings by decomposing metalorganic compounds with CVD method. Vestnik of Moscow Goryachkin Agroengineering University, 6 (88), 40–44.
6. Martinho, R. P., Silva, F. J. G., Martins, C., Lopes, H. (2019). Comparative study of PVD and CVD cutting tools performance in milling of duplex stainless steel. The International Journal of Advanced Manufacturing Technology, 102 (5-8), 2423–2439. doi: https://doi.org/10.1007/s00170-019-03351-8
7. Reale, F., Sharda, K., Mattevi, C. (2016). From bulk crystals to atomically thin layers of group VI-transition metal dichalcogenides vapour phase synthesis. Applied Materials Today, 3, 11–22. doi: https://doi.org/10.1016/j.apmt.2015.12.003
8. Konakov, S. (2017). Localized microreactor deposition of thin films and nanostructures as new approach to investigation of chemical vapor deposition. Nanoindustry Russia, 75 (4), 76–82. doi: https://doi.org/10.22184/1993-8578.2017.75.4.76.82
9. Santos, M., Bilek, M. M. M., Wise, S. G. (2015). Plasma-synthesised carbon-based coatings for cardiovascular applications. Biosurface and Biotribology, 1 (3), 146–160. doi: https://doi.org/10.1016/j.bsbt.2015.08.001
10. Drosos, C., Vernardou, D. (2015). Perspectives of energy materials grown by APCVD. Solar Energy Materials and Solar Cells, 140, 1–8. doi: https://doi.org/10.1016/j.solmat.2015.03.019
11. Beaux, M. F., Vodnik, D. R., Peterson, R. J., Bennett, B. L., Salazar, J. J., Holesinger, T. G. et. al. (2018). Chemical vapor deposition of Mo tubes for fuel cladding applications. Surface and Coatings Technology, 337, 510–515. doi: https://doi.org/10.1016/j.surfcoat.2018.01.063
12. Drieux, P., Chollon, G., Jacques, S., Allemand, A., Cavagnat, D., Buffeteau, T. (2013). Experimental study of the chemical vapor deposition from CH3SiHCl2/H2: Applica-

tion to the synthesis of monolithic SiC tubes. Surface and Coatings Technology, 230, 137–144. doi: https://doi.org/10.1016/j.surfcoat.2013.06.046

13. Song, W., Yan, J., Ji, H. (2019). Fabrication of GNS/MoS2 composite with different morphology and its tribological performance as a lubricant additive. Applied Surface Science, 469, 226–235. doi: https://doi.org/10.1016/j.apsusc.2018.10.266
14. Singh, A., Moun, M., Singh, R. (2019). Effect of different precursors on CVD growth of molybdenum disulfide. Journal of Alloys and Compounds, 782, 772–779. doi: https://doi.org/10.1016/j.jallcom.2018.12.230
15. Zhuk, Y. N. (2011). Advanced CVD coatings: Protect critical parts in harsh environments. Advanced Materials and Processes, 169 (8), 21–24.
16. Erokhin, M. N., Kazantsev, S. P., Chupyatov, N. N. (2017). Wear-resistance of carbide-containing chrome coatings obtained from gas phase. Vestnik FGOU VPO "Moskovskiy Gosudarstvenniy Agroinzhenerniy Universitet Imeni V.P. Goryachkina", 5, 48–53. doi: https://doi.org/10.26897/1728-7936-2017-5-48-53
17. Erohin, M. N., Chupyatov, N. N. (2013). The use of chemical vapor depositionto improve the wear resistance of precision hydraulic componentssystems of machines and equipment in the livestock. Vestnik VNIIMZH, 4 (12), 61–64.
18. Iliyn, V. A., Panarin, A. V. (2011). Pyrolytic chromium carbide coating (technology, equipment, properties). Izvestiya Samarskogo nauchnogo tsentra Rossiyskoy akademii nauk, 13 (4 (2)), 357–360.
19. Vasin, V. A., Krit, B. L., Nevrovskiy, V. A., Somov, O. V., Morozova, N. V. (2016). O primenenii piroliticheskih karbidohromovyh pokrytiy v uzlah treniya mashin. Elektronnaya obrabotka materialov, 52 (5), 21–25.
20. Sagalovich, A. V., Grigor'ev, A. V., Kononyhin, A. V., Popov, V. V., Sagalovich, V. V. (2011). Nanesenie pokrytiy na slozhnoprofil'nye pretsizionnye poverhnosti gazofaznym metodom (CVD). Fizicheskaya inzheneriya poverhnosti, 9 (3), 229–236.
21. Sagalovych, A., Sagalovych, V. (2013). Mo-C multilayered CVD coetings. Tribology in Industry, 35 (4), 261–269.
22. Syrkin, V. G. (1985). Gazofaznaya metallizatsiya cherez karbonily. Moscow: Metallurgiya, 248.
23. Syrkin, V. G. (2000). CVD-metod. Himicheskaya parofaznaya metallizatsiya. Moscow: Nauka, 496.
24. Directive 2011/65/EU of the European parliament and of the council of 8 June 2011on the restriction of the use of certain hazardous substances in electrical and electronic equipment (recast). Official Journal of the European Union.

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DETERMINATION OF REGULARITIES OF THE INFLUENCE OF THE ELEMENTAL COMPOSITION OF NIOBIUM-BASED ALLOYS ON THEIR STRUCTURE AND PROPERTIES (p. 16–23)

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The method of x-ray diffractometry was used to study the effect of the composition of two, three, four and five elemental niobium-based alloys on their phase-structural state, average crystallite size, and thermal expansion coefficient in the temperature range of +20 °C...–170 °C. As elements of filling, vanadium, tantalum, hafnium, molybdenum, zirconium, tungsten and titanium were used. These elements either in equilibrium – at room temperature (R_T=+20 °C), or in high-temperature states have a bcc crystal lattice similar to Nb.

It is found that in alloys based on two, three, four and five elements, for the compositions used in the work, the formation of a single-phase state with a bcc crystal lattice of a solid solution occurs. At the structural level, the alloy composition affects the ratio of the intensity of the diffraction peaks from different planes. For two diffraction orders from the most closely packed {110} plane in the bcc lattice, a change in the intensity value for the second diffraction order is revealed. The greatest decrease in relative intensity occurs in binary alloys with a large discrepancy in the size of the atomic radii of the components. In multi-element alloys, a smaller drop in intensity is observed. This may be associated with a reduction in the distortion of the crystal lattice due to the ordering of the elements that make up the alloys.

At the substructural level, the alloy composition affects the average crystallite size. For binary alloy compositions, the greatest effect is associated with Zr and Hf filling elements having a significantly larger atomic radius. This leads to a decrease in the average crystallite size of the alloy solid solution to the smallest value of 11 nm (NbZr alloy) and the release of the second phase (NbHf alloy).

It is found that the coefficient of linear thermal expansion determined by the X-ray diffraction method at 2 temperatures (R_T=+20 °C and T=–170 °C) in multi-element alloys exceeds the values for the starting elements. The largest increase in CTE is observed in alloys containing 17–26 at. % V and W, which have the smallest atomic radius.

Keywords: multi-element alloy, niobium, high-entropy alloy, distortion, phase composition, coefficient of thermal expansion.

References

1. Mayrhofer, P. H., Mitterer, C., Hultman, L., Clemens, H. (2006). Microstructural design of hard coatings. Progress in

Materials Science, 51 (8), 1032–1114. doi: https://doi.org/10.1016/j.pmatsci.2006.02.002
2. Sobol, O. V., Postelnyk, A. A., Meylekhov, A. A., Andreev, A. A., Stolbovoy, V. A. (2017). Structural Engineering of the Multilayer Vacuum Arc Nitride Coatings Based on Ti, Cr, Mo and Zr. Journal of Nano- and Electronic Physics, 9 (3), 03003-1–03003-6. doi: https://doi.org/10.21272/jnep.9(3).03003
3. Azarenkov, N. A., Sobol', O. V., Beresnev, V. M., Pogrebnyak, A. D., Kolesnikov, D. A., Turbin, P. V., Toryanik, I. N. (2013). Vacuum-plasma coatings based on the multielement nitrides. Metallofizika i noveishie tekhnologii, 35 (8), 1061–1084. Available at: http://dspace.nbuv.gov.ua/bitstream/handle/123456789/104178/07-Azarenkov.pdf?sequence=1
4. Cherepova, T., Dmitrieva, G., Tisov, O., Dukhota, O., Kindrachuk, M. (2019). Research on the Properties of Co-Tic and Ni-Tic Hip-Sintered Alloys. Acta Mechanica et Automatica, 13 (1), 57–67. doi: https://doi.org/10.2478/ama-2019-0009
5. Sobol', O. V., Andreev, A. A., Stolbovoi, V. A., Fil'chikov, V. E. (2012). Structural-phase and stressed state of vacuum-arc-deposited nanostructural Mo-N coatings controlled by substrate bias during deposition. Technical Physics Letters, 38 (2), 168–171. doi: https://doi.org/10.1134/s1063785012020307
6. Sobol', O. V., Andreev, A. A., Gorban', V. F., Krapivka, N. A., Stolbovoi, V. A., Serdyuk, I. V., Fil'chikov, V. E. (2012). Reproducibility of the single-phase structural state of the multielement high-entropy Ti-V-Zr-Nb-Hf system and related superhard nitrides formed by the vacuum-arc method. Technical Physics Letters, 38 (7), 616–619. doi: https://doi.org/10.1134/s1063785012070127
7. Sobol', O. V., Andreev, A. A., Gorban', V. F., Meylekhov, A. A., Postelnyk, H. O. (2016). Structural Engineering of the Vacuum Arc ZrN/CrN Multilayer Coatings. Journal of Nano- and Electronic Physics, 8 (1), 01042-1–01042-5. doi: https://doi.org/10.21272/jnep.8(1).01042
8. Sobol', O. V., Andreev, A. A., Gorban', V. F., Stolbovoy, V. A., Melekhov, A. A., Postelnyk, A. A. (2016). Possibilities of structural engineering in multilayer vacuum-arc ZrN/CrN coatings by varying the nanolayer thickness and application of a bias potential. Technical Physics, 61 (7), 1060–1063. doi: https://doi.org/10.1134/s1063784216070252
9. Sobol', O. V., Meilekhov, A. A. (2018). Conditions of Attaining a Superhard State at a Critical Thickness of Nanolayers in Multiperiodic Vacuum-Arc Plasma Deposited Nitride Coatings. Technical Physics Letters, 44 (1), 63–66. doi: https://doi.org/10.1134/s1063785018010224
10. Sobol', O. V., Andreev, A. A., Gorban', V. F. (2016). Structural Engineering of Vacuum-ARC Multiperiod Coatings. Metal Science and Heat Treatment, 58 (1-2), 37–39. doi: https://doi.org/10.1007/s11041-016-9961-3
11. Raghavan, R., Hari Kumar, K. C., Murty, B. S. (2012). Analysis of phase formation in multi-component alloys. Journal of Alloys and Compounds, 544, 152–158. doi: https://doi.org/10.1016/j.jallcom.2012.07.105
12. Senkov, O. N., Wilks, G. B., Scott, J. M., Miracle, D. B. (2011). Mechanical properties of Nb25Mo25Ta25W25 and V20Nb20Mo20Ta20W20 refractory high entropy alloys. Intermetallics, 19 (5), 698–706. doi: https://doi.org/10.1016/j.intermet.2011.01.004
13. Ranganathan, S. (2003). Alloyed pleasures: multimetallic cocktails. Current science, 85 (10), 1404–1406. Available at: https://pdfs.semanticscholar.org/e4d2/1223b04a774d2ac1b134bb46cfc0ba810f43.pdf
14. Li, C., Li, J. C., Zhao, M., Jiang, Q. (2009). Effect of alloying elements on microstructure and properties of multiprincipal elements high-entropy alloys. Journal of Alloys and Compounds, 475 (1-2), 752–757. doi: https://doi.org/10.1016/j.jallcom.2008.07.124
15. Sobol', O. V., Yakushchenko, I. V. (2015). Influence of ion implantation on the structural and stressed state and mechanical properties of nitrides of high-entropy (TiZrAlYNb)N and (TiZrHfVNbTa)N alloys. Journal of nano- and electronic physics, 7 (3), 03044-1-03044-6. Available at: http://jnep.sumdu.edu.ua/download/numbers/2015/3/articles/jnep_2015_V7_03044.pdf
16. Yeh, J.-W., Chen, S.-K., Lin, S.-J., Gan, J.-Y., Chin, T.-S., Shun, T.-T. et. al. (2004). Nanostructured High-Entropy Alloys with Multiple Principal Elements: Novel Alloy Design Concepts and Outcomes. Advanced Engineering Materials, 6 (5), 299–303. doi: https://doi.org/10.1002/adem.200300567
17. Sobol', O. V., Andreev, A. A., Gorban', V. F., Postelnyk, H. O., Stolbovoy, V. A., Zvyagolsky, A. V. et. al. (2019). The use of negative bias potential for structural engineering of vacuum-arc nitride coatings based on high-entropy alloys. Problems of atomic science and technology, 120 (2), 127–135. Available at: https://vant.kipt.kharkov.ua/ARTICLE/VANT_2019_2/article_2019_2_127.pdf
18. Guo, S., Liu, C. T. (2011). Phase stability in high entropy alloys: Formation of solid-solution phase or amorphous phase. Progress in Natural Science: Materials International, 21 (6), 433–446. doi: https://doi.org/10.1016/s1002-0071(12)60080-x
19. Zhang, Y., Zhou, Y. J., Lin, J. P., Chen, G. L., Liaw, P. K. (2008). Solid-Solution Phase Formation Rules for Multi-component Alloys. Advanced Engineering Materials, 10 (6), 534–538. doi: https://doi.org/10.1002/adem.200700240
20. Pickering, E. J., Jones, N. G. (2016). High-entropy alloys: a critical assessment of their founding principles and future prospects. International Materials Reviews, 61 (3), 183–202. doi: https://doi.org/10.1080/09506608.2016.1180020
21. Cantor, B., Chang, I. T. H., Knight, P., Vincent, A. J. B. (2004). Microstructural development in equiatomic multicomponent alloys. Materials Science and Engineering: A, 375-377, 213–218. doi: https://doi.org/10.1016/j.msea.2003.10.257
22. Chen, J., Zhou, X., Wang, W., Liu, B., Lv, Y., Yang, W. et. al. (2018). A review on fundamental of high entropy alloys with

promising high–temperature properties. Journal of Alloys and Compounds, 760, 15–30. doi: https://doi.org/10.1016/j.jallcom.2018.05.067

23. Cheng, C.-Y., Yang, Y.-C., Zhong, Y.-Z., Chen, Y.-Y., Hsu, T., Yeh, J.-W. (2017). Physical metallurgy of concentrated solid solutions from low-entropy to high-entropy alloys. Current Opinion in Solid State and Materials Science, 21 (6), 299–311. doi: https://doi.org/10.1016/j.cossms.2017.09.002
24. Miracle, D. B., Senkov, O. N. (2017). A critical review of high entropy alloys and related concepts. Acta Materialia, 122, 448–511. doi: https://doi.org/10.1016/j.actamat.2016.08.081
25. Zhang, Y., Yang, X., Liaw, P. K. (2012). Alloy Design and Properties Optimization of High-Entropy Alloys. JOM, 64 (7), 830–838. doi: https://doi.org/10.1007/s11837-012-0366-5
26. Florea, I., Florea, R. M., Baltatescu, O., Soare, V., Chelariu, R., Carcea, I. (2013). High entropy alloys. Journal of Optoelectronics and Advanced Materials, 15 (7-8), 761–767. Available at: https://www.researchgate.net/publication/274640494_High_entropy_alloys
27. Tang, W.-Y., Yeh, J.-W. (2009). Effect of Aluminum Content on Plasma-Nitrided Al x CoCrCuFeNi High-Entropy Alloys. Metallurgical and Materials Transactions A, 40 (6), 1479–1486. doi: https://doi.org/10.1007/s11661-009-9821-5
28. Chen, M.-R., Lin, S.-J., Yeh, J.-W., Chen, S.-K., Huang, Y.-S., Tu, C.-P. (2006). Microstructure and Properties of Al0.5CoCrCuFeNiTix (x=0–2.0) High-Entropy Alloys. Materials Transactions, 47 (5), 1395–1401. doi: https://doi.org/10.2320/matertrans.47.1395
29. Wu, J.-M., Lin, S.-J., Yeh, J.-W., Chen, S.-K., Huang, Y.-S., Chen, H.-C. (2006). Adhesive wear behavior of AlxCoCrCuFeNi high-entropy alloys as a function of aluminum content. Wear, 261 (5-6), 513–519. doi: https://doi.org/10.1016/j.wear.2005.12.008
30. Chen, Y. Y., Hong, U. T., Shih, H. C., Yeh, J. W., Duval, T. (2005). Electrochemical kinetics of the high entropy alloys in aqueous environments – a comparison with type 304 stainless steel. Corrosion Science, 47 (11), 2679–2699. doi: https://doi.org/10.1016/j.corsci.2004.09.026
31. Chen, Y. Y., Duval, T., Hung, U. D., Yeh, J. W., Shih, H. C. (2005). Microstructure and electrochemical properties of high entropy alloys – a comparison with type-304 stainless steel. Corrosion Science, 47 (9), 2257–2279. doi: https://doi.org/10.1016/j.corsci.2004.11.008
32. Wang, Z., Fang, Q., Li, J., Liu, B., Liu, Y. (2018). Effect of lattice distortion on solid solution strengthening of BCC high-entropy alloys. Journal of Materials Science & Technology, 34 (2), 349–354. doi: https://doi.org/10.1016/j.jmst.2017.07.013
33. Tong, C.-J., Chen, Y.-L., Yeh, J.-W., Lin, S.-J., Chen, S.-K., Shun, T.-T. et. al. (2005). Microstructure characterization of Al x CoCrCuFeNi high-entropy alloy system with multiprincipal elements. Metallurgical and Materials Transactions A, 36 (4), 881–893. doi: https://doi.org/10.1007/s11661-005-0283-0
34. Andreev, A. A., Voyevodin, V. N., Sobol', O. V., Gorban', V. F., Kartmazov, G. N., Stolbovoy, V. A. et. al. (2013). Regularities in the effect of model ion irradiation on the structure and properties of vacuum-arc nitride coatings. Problems of atomic science and technology, 5 (87), 142–146. Available at: https://vant.kipt.kharkov.ua/ARTICLE/VANT_2013_5/article_2013_5_142.pdf
35. Sobol', O. V., Dur, O., Postelnyk, A. A., Kraievska, Z. V. (2019). Structural engineering and functional properties of vacuum-arc coatings of high-entropy (TiZrNbVHf)N and (TiZrNbVHfTa)N alloys nitrides. Functional materials, 26 (2), 310–318. doi: https://doi.org/10.15407/fm26.02.310
36. Yeh, J.-W. (2013). Alloy Design Strategies and Future Trends in High-Entropy Alloys. JOM, 65 (12), 1759–1771. doi: https://doi.org/10.1007/s11837-013-0761-6
37. Stepanov, N. D., Shaysultanov, D. G., Ozerov, M. S., Zherebtsov, S. V., Salishchev, G. A. (2016). Second phase formation in the CoCrFeNiMn high entropy alloy after recrystallization annealing. Materials Letters, 185, 1–4. doi: https://doi.org/10.1016/j.matlet.2016.08.088
38. Stepanov, N. D., Yurchenko, N. Y., Zherebtsov, S. V., Tikhonovsky, M. A., Salishchev, G. A. (2018). Aging behavior of the HfNbTaTiZr high entropy alloy. Materials Letters, 211, 87–90. doi: https://doi.org/10.1016/j.matlet.2017.09.094
39. Firstov, S. A., Gorban', V. F., Krapivka, N. A., Pechkovskiy, E. P. (2012). Raspredelenie elementov v lityh mnogokomponentnyh vysokoentropiynyh odnofaznyh splavah s OTSK kristallicheskoy reshetkoy. Kompozity i nanomaterialy, 3, 48–65.
40. Sobol', O. V., Shovkoplyas, O. A. (2013). On advantages of X-ray schemes with orthogonal diffraction vectors for studying the structural state of ion-plasma coatings. Technical Physics Letters, 39 (6), 536–539. doi: https://doi.org/10.1134/s1063785013060126
41. Jenkins, R., Snyder, R. L. (1996). Introduction to X-ray Powder Diffractometry. John Wiley & Sons Inc. doi: https://doi.org/10.1002/9781118520994
42. Mikhailov, I. F., Baturin, A. A., Mikhailov, A. I., Borisova, S. S. (2012). Increasing the sensitivity of X-ray fluorescent scheme with secondary radiator using the initial spectrum filtration. Functional materials, 19 (1), 126–129. Available at: http://dspace.nbuv.gov.ua/bitstream/handle/123456789/135279/21-Mikhailov.pdf?sequence=1
43. Heyrovska, R. (2013). Atomic, ionic and bohr radii linked via the golden ratio for elements of groups 1 - 8 including lanthanides and actinides. International journal of sciences, 2, 63–68. Available at: https://www.ijsciences.com/pub/pdf/V2-201304-18.pdf
44. Finkel', V. A. (1971). Nizkotemperaturnaya rentgenografiya metallov. Moscow: Metallurgiya, 256.
45. Chirkin, V. S. (1967). Teplofizicheskie svoystva materialov yadernoy tehniki. Moscow: Atomizdat, 474.

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THE EFFECT OF LFG PLASMA SPUTTERING POWER ON HARDNESS OF CARBON THIN FILMS ON SKD11 STEEL USING TARGET MATERIAL FROM BATTERY CARBON RODS (p. 24–29)

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Battery waste is one of waste that can damage the environment and there has not been much good processing in Indonesia. Even though, battery waste contains carbon which can be used as a target material for deposition of carbon films using plasma sputtering. The focus of this research is to determine the effect and optimum power value of plasma argon generation, so that the power generation value can produce the highest hardness value of SKD11 steel can be obtained. The method used as plasma is argon gas. Argon plasma is generated by using a 40 kHz LGF. Thin film of carbon synthesize on SKD11 steel was tested to determine the value of hardness using micro hardness Vickers. Based on the experimental result, the optimum power treatment obtained at 340 Watt with the highest average hardness value is 316.7 HV. Based on SEM-EDX observation, it can be described that comparison of atomic carbon from carbon rods without treatment (1.5 %) and carbon thin films on SKD11 with optimum power treatment (13.36 %) show different value. Number of atomic carbon of thin films on SKD11 with power treatment more higher than atomic carbon of carbon rods without treatment, it causes higher hardness value of thin films on SKD11 steel after plasma sputtering treatment on optimum power parameters than SKD11 steel without treatment. SKD11 steel that has a high hardness value used as dies, forming, and cutting that requires high hardness performance.

Keywords: SKD11 Steel, plasma sputtering, battery rods, power, LGF, hardness, argon, deposition, thin films, carbon.

References

1. Purkuncoro, A. E., Santjojo, D. J. D. H., Irawan, Y. S., Soenoko, R. (2019). Deposition of Carbon Thin Film by Means of a Low-Frequency Plasma Sputtering Using Battery Carbon Rods as a Target. IOP Conference Series: Materials Science and Engineering, 515, 012041. doi: https://doi.org/10.1088/1757-899x/515/1/012041
2. Klotz, K., Weistenhöfer, W., Neff, F., Hartwig, A., van Thriel, C., Drexler, H. (2017). The Health Effects of Aluminum Exposure. Deutsches Aerzteblatt Online, 114 (39), 653–659. doi: https://doi.org/10.3238/arztebl.2017.0653
3. Tanong, K., Blais, J.-F., Mercier, G. (2014). Metal Recycling Technologies for Battery Waste. Recent Patents on Engineering, 8 (1), 13–23. doi: https://doi.org/10.2174/1872212108666140204004041
4. Nindhia, T. G. T., Surata, I. W., Atmika, I. K. A., Negara, D. N. K. P., Artana, I. P. G. (2015). Processing Carbon Rod from Waste of Zing-Carbon Battery for Biogas Desulfurizer. Journal of Clean Energy Technologies, 3 (2), 119–122. doi: https://doi.org/10.7763/jocet.2015.v3.179
5. Nindhia, T. G. T., Surata, I. W., Atmika, I. K. A., Negara, D. N. K. P., Artana, I. P. G. (2015). Processing Carbon Rod from Waste of Zing-Carbon Battery for Biogas Desulfurizer. Journal of Clean Energy Technologies, 3 (2), 119–122. doi: https://doi.org/10.7763/jocet.2015.v3.179
6. Erdemir, A., Donnet, C. (2006). Tribology of diamond-like carbon films: recent progress and future prospects. Journal of Physics D: Applied Physics, 39 (18), R311–R327. doi: https://doi.org/10.1088/0022-3727/39/18/r01
7. Chu, P. K., Li, L. (2006). Characterization of amorphous and nanocrystalline carbon films. Materials Chemistry and Physics, 96 (2-3), 253–277. doi: https://doi.org/10.1016/j.matchemphys.2005.07.048
8. Mori, T., Sakurai, T., Sato, T., Shirakura, A., Suzuki, T. (2016). Growth process of hydrogenated amorphous carbon films synthesized by atmospheric pressure plasma enhanced CVD using nitrogen and helium as a dilution gas. Japanese Journal of Applied Physics, 55 (4), 045503. doi: https://doi.org/10.7567/jjap.55.045503
9. Wen, F., Liu, J., Xue, J. (2017). The Studies of Diamond-Like Carbon Films as Biomaterials: Review. Colloid and Surface Science, 2 (3), 81–95.
10. Abdelrahman, M. M. (2015). Study of Plasma and Ion Beam Sputtering Processes. Journal of Physical Science and Application, 5 (2). doi: https://doi.org/10.17265/2159-5348/2015.02.007
11. Plasma Technology (2007). Available at: https://pdf.directindustry.com/pdf/diener-electronic/plasma-technology-diener-electronic/50802-410101.html
12. Hammadi, O. (2015). Fundamentals of Plasma Sputtering. Nanophotonics and Nanodevices Fabricated by Magnetron Sputtering Technique. doi: http://doi.org/10.13140/RG.2.1.3855.5605
13. General Catalog of YSS Tool Steels (2015). Available at: https://www.hitachi-metals.co.jp/e/products/auto/ml/pdf/yss_tool_steels_d.pdf
14. Yu, Z., Wang, Z. G., Yamazaki, K., Sano, S. (2006). Surface finishing of die and tool steels via plasma-based electron

beam irradiation. Journal of Materials Processing Technology, 180 (1-3), 246–252. doi: https://doi.org/10.1016/j.jmatprotec.2006.06.014
15. Kong, J. H., Sung, J. H., Kim, S. G., Kim, S. W. (2006). Microstructural Changes of SKD11 Steel during Carbide Dispersion Carburizing and Subzero Treatment. Solid State Phenomena, 118, 115–120. doi: https://doi.org/10.4028/www.scientific.net/ssp.118.115
16. De la Concepción, V. L., Lorusso, H. N., Svoboda, H. G. (2015). Effect of Carbon Content on Microstructure and Mechanical Properties of Dual Phase Steels. Procedia Materials Science, 8, 1047–1056. doi: https://doi.org/10.1016/j.mspro.2015.04.167
17. Calik, A., Duzgun, A., Sahin, O., Ucar, N. (2010). Effect of Carbon Content on the Mechanical Properties of Medium Carbon Steels. Zeitschrift Für Naturforschung A, 65 (5), 468–472. doi: https://doi.org/10.1515/zna-2010-0512
18. Jones, B. J., Anguilano, L., Ojeda, J. J. (2011). Argon plasma treatment techniques on steel and effects on diamond-like carbon structure and delamination. Diamond and Related Materials, 20 (7), 1030–1035. doi: https://doi.org/10.1016/j.diamond.2011.06.004
19. Mróz, W., Burdyńska, S., Prokopiuk, A., Jedyński, M., Budner, B., Korwin-Pawlowski, M. L. (2009). Characteristics of Carbon Films Deposited by Magnetron Sputtering. Acta Physica Polonica A, 116, S-120–S-122. doi: https://doi.org/10.12693/aphyspola.116.s-120
20. Miyamoto, K. (2000). Fundamentals of Plasma Physics and Controlled Fusion. Available at: http://people.physics.anu.edu.au/~jnh112/AIIM/c17/Miyamoto.pdf
21. González, J. M., Bertran, E. (2015). Mechanical and Surface Characterization of Diamond-Like Carbon Coatings onto Polymeric Substrate. Available at: https://arxiv.org/ftp/arxiv/papers/1509/1509.08512.pdf
22. Telasang, G., Dutta Majumdar, J., Wasekar, N., Padmanabham, G., Manna, I. (2015). Microstructure and Mechanical Properties of Laser Clad and Post-cladding Tempered AISI H13 Tool Steel. Metallurgical and Materials Transactions A, 46 (5), 2309–2321. doi: https://doi.org/10.1007/s11661-015-2757-z
23. Aizawa, T., Fukuda, T. (2013). Oxygen plasma etching of diamond-like carbon coated mold-die for micro-texturing. Surface and Coatings Technology, 215, 364–368. doi: https://doi.org/10.1016/j.surfcoat.2012.07.095
24. Jongwannasiri, C., Watanabe, S. (2014). Effects of RF Power and Treatment Time on Wettability of Oxygen Plasma-Treated Diamond-like Carbon Thin Films. International Journal of Chemical Engineering and Applications, 5 (1), 13–16. doi: https://doi.org/10.7763/ijcea.2014.v5.342
25. Björling, M., Larsson, R., Marklund, P. (2014). The Effect of DLC Coating Thickness on Elstohydrodynamic Friction. Tribology Letters, 55 (2), 353–362. doi: https://doi.org/10.1007/s11249-014-0364-6

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BIFUCTIONAL INDIGOCARMININTERCALATED Ni-Al LAYERED DOUBLE HYDROXIDE: INVESTIGATION OF CHARACTERISTICS FOR PIGMENT AND SUPERCAPACITOR APPLICATION (p. 30–39)

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In the modern world, one promising direction is the production and use of multifunction compounds. Ni-Al layered double hydroxide is widely used as the active material in supercapacitors. Nickel compounds are also colored and can be used as pigments. The characteristics of bifunctional indigo carmine intercalated Ni-Al (Ni:Al=4:1) hydroxides, synthesized at an equilibrium pH and pH=14 have been studied. The crystal structure of the prepared samples was studied by means of X-ray diffraction analysis and thermogravimetry, pigment characteristics – by measuring and calculating color characteristics in CIELab and XYZ systems, electrochemical characteristics – cyclic voltammetry and galvanostatic charge-discharge cycling. Comparative analysis of the electrochemical characteristics of Ni-Al-indigo carmine and Ni-Al-carbonate hydroxides has been conducted. Using XRD and thermogravimetry analysis methods, it was found that Ni-Al–indigo carmine hydroxide is a layered double hydroxide with the structure of α-$Ni(OH)_2$ with average (synthesis at pH=14 and low (synthesis at equilibrium pH) crystallinity. It was found that synthesized Ni-Al-indigo carmine LDH had color bordering between light and blue (color tone 483–485 nm) with the lightness of 40–50 % and average color purity. It was found that the specific capacity of indigo carmine intercalated Ni-Al LDH (synthesis at pH=14 exceeded that of carbonate intercalated: the maximum specific capacity at full discharge was 1,007 F/g hydroxide and 2,996 F/h Ni, at discharge to 0 B –946 F/g. First, for Ni-Al-indigo carmine LDH, two discharge plateaus were observed, which correspond to the discharge of Ni^{3+} and indigo carmine.

Keywords: Ni-Al layered double hydroxide, pigment, specific capacity, supercapacitor, discharge plateau.

References

1. Hall, D. S., Lockwood, D. J., Bock, C., MacDougall, B. R. (2015). Nickel hydroxides and related materials: a review of their structures, synthesis and properties. Proceedings of the Royal Society A: Mathematical, Physical and Engineer-

ing Sciences, 471 (2174), 20140792. doi: https://doi.org/10.1098/rspa.2014.0792
2. Vidotti, M., Torresi, R., Torresi, S. I. C. de. (2010). Nickel hydroxide modified electrodes: a review study concerning its structural and electrochemical properties aiming the application in electrocatalysis, electrochromism and secondary batteries. Química Nova, 33 (10), 2176–2186. doi: https://doi.org/10.1590/s0100-40422010001000030
3. Chen, J. (1999). Nickel Hydroxide as an Active Material for the Positive Electrode in Rechargeable Alkaline Batteries. Journal of The Electrochemical Society, 146 (10), 3606. doi: https://doi.org/10.1149/1.1392522
4. Chen, H., Wang, J. M., Pan, T., Zhao, Y. L., Zhang, J. Q., Cao, C. N. (2005). The structure and electrochemical performance of spherical Al-substituted α-$Ni(OH)_2$ for alkaline rechargeable batteries. Journal of Power Sources, 143 (1-2), 243–255. doi: https://doi.org/10.1016/j.jpowsour.2004.11.041
5. Kamath, P. V., Dixit, M., Indira, L., Shukla, A. K., Kumar, V. G., Munichandraiah, N. (1994). Stabilized α-$Ni(OH)_2$ as Electrode Material for Alkaline Secondary Cells. Journal of The Electrochemical Society, 141 (11), 2956. doi: https://doi.org/10.1149/1.2059264
6. Sun, Y.-K., Lee, D.-J., Lee, Y. J., Chen, Z., Myung, S.-T. (2013). Cobalt-Free Nickel Rich Layered Oxide Cathodes for Lithium-Ion Batteries. ACS Applied Materials & Interfaces, 5 (21), 11434–11440. doi: https://doi.org/10.1021/am403684z
7. Kovalenko, V., Kotok, V. (2018). Influence of ultrasound and template on the properties of nickel hydroxide as an active substance of supercapacitors. Eastern-European Journal of Enterprise Technologies, 3 (12 (93)), 32–39. doi: https://doi.org/10.15587/1729-4061.2018.133548
8. Kovalenko, V., Kotok, V. (2017). Study of the influence of the template concentration under homogeneous precepitation on the properties of $Ni(OH)_2$ for supercapacitors. Eastern-European Journal of Enterprise Technologies, 4 (6 (88)), 17–22. doi: https://doi.org/10.15587/1729-4061.2017.106813
9. Zheng, C., Liu, X., Chen, Z., Wu, Z., Fang, D. (2014). Excellent supercapacitive performance of a reduced graphene oxide/$Ni(OH)_2$ composite synthesized by a facile hydrothermal route. Journal of Central South University, 21 (7), 2596–2603. doi: https://doi.org/10.1007/s11771-014-2218-7
10. Kotok, V. A., Kovalenko, V. L., Solovov, V. A., Kovalenko, P. V., Ananchenko, B. A. (2018). Effect of deposition time on properties of electrochromic nickel hydroxide films prepared by cathodic template synthesis. ARPN Journal of Engineering and Applied Sciences, 13 (9), 3076–3086.
11. Solovov, V. A., Nikolenko, N. V., Kovalenko, V. L., Kotok, V. A., Burkov, A. A., Kondrat'ev, D. A. et. al. (2018). Synthesis of Ni(II)-Ti(IV) Layered Double Hydroxides Using Coprecipitation At High Supersaturation Method. ARPN Journal of Engineering and Applied Sciences, 13 (24), 9652–9656.
12. Solovov, V., Kovalenko, V., Nikolenko, N., Kotok, V., Vlasova, E. (2017). Influence of temperature on the characteristics of Ni(II), Ti(IV) layered double hydroxides synthesised by different methods. Eastern-European Journal of Enterprise Technologies, 1 (6 (85)), 16–22. doi: https://doi.org/10.15587/1729-4061.2017.90873
13. Wang, Y., Zhang, D., Peng, W., Liu, L., Li, M. (2011). Electrocatalytic oxidation of methanol at Ni–Al layered double hydroxide film modified electrode in alkaline medium. Electrochimica Acta, 56 (16), 5754–5758. doi: https://doi.org/10.1016/j.electacta.2011.04.049
14. Fan, Y., Yang, Z., Cao, X., Liu, P., Chen, S., Cao, Z. (2014). Hierarchical Macro-Mesoporous $Ni(OH)_2$ for Nonenzymatic Electrochemical Sensing of Glucose. Journal of The Electrochemical Society, 161 (10), B201–B206. doi: https://doi.org/10.1149/2.0251410jes
15. Ramesh, T. N., Kamath, P. V. (2006). Synthesis of nickel hydroxide: Effect of precipitation conditions on phase selectivity and structural disorder. Journal of Power Sources, 156 (2), 655–661. doi: https://doi.org/10.1016/j.jpowsour.2005.05.050
16. Rajamathi, M., Vishnu Kamath, P., Seshadri, R. (2000). Polymorphism in nickel hydroxide: role of interstratification. Journal of Materials Chemistry, 10 (2), 503–506. doi: https://doi.org/10.1039/a905651c
17. Kovalenko, V., Kotok, V. (2018). Comparative investigation of electrochemically synthesized (α+β) layered nickel hydroxide with mixture of α-$Ni(OH)_2$ and β-$Ni(OH)_2$. Eastern-European Journal of Enterprise Technologies, 2 (6 (92)), 16–22. doi: https://doi.org/10.15587/1729-4061.2018.125886
18. Kovalenko, V., Kotok, V. (2017). Definition of effectiveness of β-$Ni(OH)_2$ application in the alkaline secondary cells and hybrid supercapacitors. Eastern-European Journal of Enterprise Technologies, 5 (6 (89)), 17–22. doi: https://doi.org/10.15587/1729-4061.2017.110390
19. Li, J., Luo, F., Tian, X., Lei, Y., Yuan, H., Xiao, D. (2013). A facile approach to synthesis coral-like nanoporous β-Ni(OH) 2 and its supercapacitor application. Journal of Power Sources, 243, 721–727. doi: https://doi.org/10.1016/j.jpowsour.2013.05.172
20. Kovalenko, V. L., Kotok, V. A., Sykchin, A. A., Mudryi, I. A., Ananchenko, B. A., Burkov, A. A. et. al. (2016). Nickel hydroxide obtained by high-temperature two-step synthesis as an effective material for supercapacitor applications. Journal of Solid State Electrochemistry, 21 (3), 683–691. doi: https://doi.org/10.1007/s10008-016-3405-2
21. Jayashree, R. S., Vishnu Kamath, P. (2001). Suppression of the α→β-nickel hydroxide transformation in concentrated alkali: Role of dissolved cations. Journal of Applied Electrochemistry, 31, 1315–1320. doi: https://doi.org/10.1023/a:1013876006707
22. Hu, M., Yang, Z., Lei, L., Sun, Y. (2011). Structural transformation and its effects on the electrochemical performances of a layered double hydroxide. Journal of Power Sources, 196 (3), 1569–1577. doi: https://doi.org/10.1016/j.jpowsour.2010.08.041
23. Córdoba de Torresi, S. I., Provazi, K., Malta, M., Torresi, R. M. (2001). Effect of Additives in the Stabilization of the α Phase of $Ni(OH)_2$ Electrodes. Journal of The Electrochemical Society, 148 (10), A1179. doi: https://doi.org/10.1149/1.1403731

24. Nalawade, P., Aware, B., Kadam, V. J., Hirlekar, R. S. (2009). Layered double hydroxides: A review. Journal of Scientific & Industrial Research, 68, 267–272
25. Liu, B., Wang, X. Y., Yuan, H. T. et. al. (1999). Physical and electrochemical characteristics of aluminium-substituted nickel hydroxide. Journal of Applied Electrochemistry, 29, 853–858. doi: http://doi.org/10.1023/A:1003537900947
26. Lei, L., Hu, M., Gao, X., Sun, Y. (2008). The effect of the interlayer anions on the electrochemical performance of layered double hydroxide electrode materials. Electrochimica Acta, 54 (2), 671–676. doi: https://doi.org/10.1016/j.electacta.2008.07.004
27. Kotok, V., Kovalenko, V., Vlasov, S. (2018). Investigation of Ni–Al hydroxide with silver addition as an active substance of alkaline batteries. Eastern-European Journal of Enterprise Technologies, 3 (6 (93)), 6–11. doi: https://doi.org/10.15587/1729-4061.2018.133465
28. Kovalenko, V., Kotok, V. (2017). Obtaining of Ni–Al layered double hydroxide by slit diaphragm electrolyzer. Eastern-European Journal of Enterprise Technologies, 2 (6 (86)), 11–17. doi: https://doi.org/10.15587/1729-4061.2017.95699
29. Kovalenko, V., Kotok, V., Yeroshkina, A., Zaychuk, A. (2017). Synthesis and characterisation of dyeintercalated nickelaluminium layereddouble hydroxide as a cosmetic pigment. Eastern-European Journal of Enterprise Technologies, 5 (12 (89)), 27–33. doi: https://doi.org/10.15587/1729-4061.2017.109814
30. Kovalenko, V., Kotok, V. (2019). Influence of the carbonate ion on characteristics of electrochemically synthesized layered (α+β) nickel hydroxide. Eastern-European Journal of Enterprise Technologies, 1 (6 (97)), 40–46. doi: https://doi.org/10.15587/1729-4061.2019.155738
31. Kovalenko, V., Kotok, V. (2019). Anionic carbonate activation of layered (α+β) nickel hydroxide. Eastern-European Journal of Enterprise Technologies, 3 (6 (99)), 44–52. doi: https://doi.org/10.15587/1729-4061.2019.169461
32. Arizaga, G. G. C., Gardolinski, J. E. F. da C., Schreiner, W. H., Wypych, F. (2009). Intercalation of an oxalatooxoniobate complex into layered double hydroxide and layered zinc hydroxide nitrate. Journal of Colloid and Interface Science, 330 (2), 352–358. doi: https://doi.org/10.1016/j.jcis.2008.10.025
33. Andrade, K. N., Pérez, A. M. P., Arízaga, G. G. C. (2019). Passive and active targeting strategies in hybrid layered double hydroxides nanoparticles for tumor bioimaging and therapy. Applied Clay Science, 181, 105214. doi: https://doi.org/10.1016/j.clay.2019.105214
34. Cursino, A. C. T., Rives, V., Arizaga, G. G. C., Trujillano, R., Wypych, F. (2015). Rare earth and zinc layered hydroxide salts intercalated with the 2-aminobenzoate anion as organic luminescent sensitizer. Materials Research Bulletin, 70, 336–342. doi: https://doi.org/10.1016/j.materresbull.2015.04.055
35. Kovalenko, V., Kotok, V. (2019). "Smart" anticorrosion pigment based on layered double hydroxide: construction and characterization. Eastern-European Journal of Enterprise Technologies, 4 (12 (100)), 23–30. doi: https://doi.org/10.15587/1729-4061.2019.176690
36. Li, Y. W., Yao, J. H., Liu, C. J., Zhao, W. M., Deng, W. X., Zhong, S. K. (2010). Effect of interlayer anions on the electrochemical performance of Al-substituted α-type nickel hydroxide electrodes. International Journal of Hydrogen Energy, 35 (6), 2539–2545. doi: https://doi.org/10.1016/j.ijhydene.2010.01.015
37. Qi, J., Xu, P., Lv, Z., Liu, X., Wen, A. (2008). Effect of crystallinity on the electrochemical performance of nanometer Al-stabilized α-nickel hydroxide. Journal of Alloys and Compounds, 462 (1-2), 164–169. doi: https://doi.org/10.1016/j.jallcom.2007.07.102
38. Li, H., Chen, Z., Wang, Y., Zhang, J., Yan, X. (2016). Controlled synthesis and enhanced electrochemical performance of self-assembled rosette-type Ni-Al layered double hydroxide. Electrochimica Acta, 210, 15–22. doi: https://doi.org/10.1016/j.electacta.2016.05.132
39. Bao, J., Zhu, Y. J., Xu, Q. S., Zhuang, Y. H., Zhao, R. D., Zeng, Y. Y., Zhong, H. L. (2012). Structure and Electrochemical Performance of Cu and Al Codoped Nanometer α-Nickel Hydroxide. Advanced Materials Research, 479-481, 230–233. doi: https://doi.org/10.4028/www.scientific.net/amr.479-481.230
40. Huang, J., Lei, T., Wei, X., Liu, X., Liu, T., Cao, D. et. al. (2013). Effect of Al-doped β-$Ni(OH)_2$ nanosheets on electrochemical behaviors for high performance supercapacitor application. Journal of Power Sources, 232, 370–375. doi: https://doi.org/10.1016/j.jpowsour.2013.01.081
41. Kotok, V., Kovalenko, V., Malyshev, V. (2017). Comparison of oxygen evolution parameters on different types of nickel hydroxide. Eastern-European Journal of Enterprise Technologies, 5 (12 (89)), 12–19. doi: https://doi.org/10.15587/1729-4061.2017.109770
42. Hu, M., Gao, X., Lei, L., Sun, Y. (2009). Behavior of a Layered Double Hydroxide under High Current Density Charge and Discharge Cycles. The Journal of Physical Chemistry C, 113 (17), 7448–7455. doi: https://doi.org/10.1021/jp808715z
43. Memon, J., Sun, J., Meng, D., Ouyang, W., Memon, M. A., Huang, Y. et. al. (2014). Synthesis of graphene/Ni–Al layered double hydroxide nanowires and their application as an electrode material for supercapacitors. Journal of Materials Chemistry A, 2 (14), 5060. doi: https://doi.org/10.1039/c3ta14613h
44. Mignani, A., Ballarin, B., Giorgetti, M., Scavetta, E., Tonelli, D., Boanini, E. et. al. (2013). Heterostructure of Au Nanoparticles – NiAl Layered Double Hydroxide: Electrosynthesis, Characterization, and Electrocatalytic Properties. The Journal of Physical Chemistry C, 117 (31), 16221–16230. doi: https://doi.org/10.1021/jp4033782
45. Kovalenko, V., Kotok, V. (2019). Investigation of characteristics of double Ni–Co and ternary Ni–Co–Al layered hydroxides for supercapacitor application. Eastern-European Journal of Enterprise Technologies, 2 (6 (98)), 58–66. doi: https://doi.org/10.15587/1729-4061.2019.164792

46. Wang, Q., Feng, Y., Feng, J., Li, D. (2011). Enhanced thermal- and photo-stability of acid yellow 17 by incorporation into layered double hydroxides. Journal of Solid State Chemistry, 184 (6), 1551–1555. doi: https://doi.org/10.1016/j.jssc.2011.04.020
47. Liu, J. Q., Zhang, X. C., Hou, W. G., Dai, Y. Y., Xiao, H., Yan, S. S. (2009). Synthesis and Characterization of Methyl-Red/Layered Double Hydroxide (LDH) Nanocomposite. Advanced Materials Research, 79-82, 493–496. doi: https://doi.org/10.4028/www.scientific.net/amr.79-82.493
48. Tian, Y., Wang, G., Li, F., Evans, D. G. (2007). Synthesis and thermo-optical stability of o-methyl red-intercalated Ni–Fe layered double hydroxide material. Materials Letters, 61 (8-9), 1662–1666. doi: https://doi.org/10.1016/j.matlet.2006.07.094
49. Hwang, S.-H., Jung, S.-C., Yoon, S.-M., Kim, D.-K. (2008). Preparation and characterization of dye-intercalated Zn–Al-layered double hydroxide and its surface modification by silica coating. Journal of Physics and Chemistry of Solids, 69 (5-6), 1061–1065. doi: https://doi.org/10.1016/j.jpcs.2007.11.002
50. Tang, P., Deng, F., Feng, Y., Li, D. (2012). Mordant Yellow 3 Anions Intercalated Layered Double Hydroxides: Preparation, Thermo- and Photostability. Industrial & Engineering Chemistry Research, 51 (32), 10542–10545. doi: https://doi.org/10.1021/ie300645b
51. Tang, P., Feng, Y., Li, D. (2011). Fabrication and properties of Acid Yellow 49 dye-intercalated layered double hydroxides film on an alumina-coated aluminum substrate. Dyes and Pigments, 91 (2), 120–125. doi: https://doi.org/10.1016/j.dyepig.2011.03.012
52. Tang, P., Feng, Y., Li, D. (2011). Improved thermal and photostability of an anthraquinone dye by intercalation in a zinc–aluminum layered double hydroxides host. Dyes and Pigments, 90 (3), 253–258. doi: https://doi.org/10.1016/j.dyepig.2011.01.007
53. Shamim, M., Dana, K. (2017). Efficient removal of Evans blue dye by Zn–Al–NO_3 layered double hydroxide. International Journal of Environmental Science and Technology, 15 (6), 1275–1284. doi: https://doi.org/10.1007/s13762-017-1478-9
54. Mahjoubi, F. Z., Khalidi, A., Abdennouri, M., Barka, N. (2017). Zn–Al layered double hydroxides intercalated with carbonate, nitrate, chloride and sulphate ions: Synthesis, characterisation and dye removal properties. Journal of Taibah University for Science, 11 (1), 90–100. doi: https://doi.org/10.1016/j.jtusci.2015.10.007
55. Pahalagedara, M. N., Samaraweera, M., Dharmarathna, S., Kuo, C.-H., Pahalagedara, L. R., Gascón, J. A., Suib, S. L. (2014). Removal of Azo Dyes: Intercalation into Sonochemically Synthesized NiAl Layered Double Hydroxide. The Journal of Physical Chemistry C, 118 (31), 17801–17809. doi: https://doi.org/10.1021/jp505260a
56. Darmograi, G., Prelot, B., Layrac, G., Tichit, D., Martin-Gassin, G., Salles, F., Zajac, J. (2015). Study of Adsorption and Intercalation of Orange-Type Dyes into Mg–Al Layered Double Hydroxide. The Journal of Physical Chemistry C, 119 (41), 23388–23397. doi: https://doi.org/10.1021/acs.jpcc.5b05510
57. Marangoni, R., Bouhent, M., Taviot-Guého, C., Wypych, F., Leroux, F. (2009). Zn_2Al layered double hydroxides intercalated and adsorbed with anionic blue dyes: A physico-chemical characterization. Journal of Colloid and Interface Science, 333 (1), 120–127. doi: https://doi.org/10.1016/j.jcis.2009.02.001
58. El Hassani, K., Beakou, B. H., Kalnina, D., Oukani, E., Anouar, A. (2017). Effect of morphological properties of layered double hydroxides on adsorption of azo dye Methyl Orange: A comparative study. Applied Clay Science, 140, 124–131. doi: https://doi.org/10.1016/j.clay.2017.02.010
59. Abdellaoui, K., Pavlovic, I., Bouhent, M., Benhamou, A., Barriga, C. (2017). A comparative study of the amaranth azo dye adsorption/desorption from aqueous solutions by layered double hydroxides. Applied Clay Science, 143, 142–150. doi: https://doi.org/10.1016/j.clay.2017.03.019
60. Santos, R. M. M. dos, Gonçalves, R. G. L., Constantino, V. R. L., Santilli, C. V., Borges, P. D., Tronto, J., Pinto, F. G. (2017). Adsorption of Acid Yellow 42 dye on calcined layered double hydroxide: Effect of time, concentration, pH and temperature. Applied Clay Science, 140, 132–139. doi: https://doi.org/10.1016/j.clay.2017.02.005
61. Bharali, D., Deka, R. C. (2017). Adsorptive removal of congo red from aqueous solution by sonochemically synthesized NiAl layered double hydroxide. Journal of Environmental Chemical Engineering, 5 (2), 2056–2067. doi: https://doi.org/10.1016/j.jece.2017.04.012
62. Ahmed, M. A., Brick, A. A., Mohamed, A. A. (2017). An efficient adsorption of indigo carmine dye from aqueous solution on mesoporous Mg/Fe layered double hydroxide nanoparticles prepared by controlled sol-gel route. Chemosphere, 174, 280–288. doi: https://doi.org/10.1016/j.chemosphere.2017.01.147
63. Kotok, V., Kovalenko, V. (2018). Definition of the aging process parameters for nickel hydroxide in the alkaline medium. Eastern-European Journal of Enterprise Technologies, 2 (12 (92)), 54–60. doi: https://doi.org/10.15587/1729-4061.2018.127764
64. Burmistr, M. V., Boiko, V. S., Lipko, E. O., Gerasimenko, K. O., Gomza, Y. P., Vesnin, R. L. et. al (2014). Antifriction and Construction Materials Based on Modified Phenol-Formaldehyde Resins Reinforced with Mineral and Synthetic Fibrous Fillers. Mechanics of Composite Materials, 50 (2), 213–222. doi: https://doi.org/10.1007/s11029-014-9408-0
65. Kovalenko, V., Kotok, V. (2018). "The popcorn effect": obtaining of the highly active ultrafine nickel hydroxide by microwave treatment of wet precipitate. Eastern-European Journal of Enterprise Technologies, 5 (6 (95)), 12–20. doi: https://doi.org/10.15587/1729-4061.2018.143126
66. Kotok, V., Kovalenko, V. (2017). Optimization of nickel hydroxide electrode of the hybrid supercapacitor. Eastern-European Journal of Enterprise Technologies, 1 (6 (85)), 4–9. doi: https://doi.org/10.15587/1729-4061.2017.90810

67. Kovalenko, V., Kotok, V., Kovalenko, I. (2018). Activation of the nickel foam as a current collector for application in supercapacitors. Eastern-European Journal of Enterprise Technologies, 3 (12 (93)), 56–62. doi: https://doi.org/10.15587/1729-4061.2018.133472

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DEVELOPMENT AND STUDY OF PROTECTIVE PROPERTIES OF THE COMPOSITE MATERIALS FOR SHIELDING THE ELECTROMAGNETIC FIELDS OF A WIDE FREQUENCY RANGE (p. 40–47)

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Composites were shown to be the most promising materials for protection against electromagnetic fields. A technology of magnetic treatment of textile material with magnetic fluid and technology of ultrasonic treatment of a mixture of latex and iron ore concentrate has been developed. This has increased saturation of fibers of the textile material with magnetic fluid nanoparticles, dispersity of the iron ore concentrate, and isotropy of the liquid metal-polymer material. As a result of the use of this technology, the consumption of magnetic fluid for the treatment of the textile material decreased from 45–50 g/m^2 to 35 g/m^2 with an improvement of shielding properties. It has been experimentally established that one layer of metal-textile material reduces the magnetic field of industrial frequency by 6 times and the electric field of industrial frequency by 1.5 times. Corresponding figures for the metal-polymer material were 3 and 2. It was found that an electromagnetic field with a frequency of 2.45 GHz is reduced 3.6 times by the single-layer metal-textile material and 5.7 times by the metal-polymer material. It was shown that the metal-textile material with such properties is suitable for the manufacture of personal protective means for personnel operating electrical and radio transmission equipment. Metal-polymeric material is suitable for the manufacture of collective protective means. A calculated evaluation of the effectiveness of protective materials was proposed. It is based on determining the shielding factors of structures of standard shapes. This enables the determination of electrophysical and magnetic properties of the material and their use in the development of protective materials with required shielding factors. The necessity of optimization of shielding factors under conditions of simultaneous influence of electromagnetic fields of heterogeneous sources was substantiated.

Keywords: composite materials, electromagnetic field, electromagnetic shield, magnetic fluid, ultrasonic treatment, shielding factor.

References

1. Bandara, P., Carpenter, D. O. (2018). Planetary electromagnetic pollution: it is time to assess its impact. The Lancet Planetary Health, 2 (12), e512–e514. doi: https://doi.org/10.1016/s2542-5196(18)30221-3
2. Lynkou, L. M., Bogush, V. A., Borbot'ko, T. V., Nasonova, N. V., Belousova, E. S., Boiprav, O. V. (2019). New technologies for creation of electromagnetic radiation shields based on modified powder, nanostructured and film materials. Doklady BGUIR, 2, 85–99. Available at: https://doklady.bsuir.by/jour/article/view/1070/1070#
3. Sukach, S., Riznik, D., Zachepa, N., Chenchevoy, V. (2020). Normalization of the Magnetic Fields of Electrical Equipment in Case of Unauthorized Influence on Critical Information Infrastructure Facilities. Soft Target Protection, 337–349. doi: https://doi.org/10.1007/978-94-024-1755-5_28
4. Zhang, H., Zhang, Z., Mo, W., Hu, P., Ding, H., Liu, Y. et. al. (2017). Shielding of the geomagnetic field reduces hydrogen peroxide production in human neuroblastoma cell and inhibits the activity of CuZn superoxide dismutase. Protein & Cell, 8 (7), 527–537. doi: https://doi.org/10.1007/s13238-017-0403-9
5. Directive 2013/35/EU of the European Parliament and of the Council of 26 June 2013 on the minimum health and

safety requirements regarding the exposure of workers to the risks arising from physical agents (electromagnetic fields). Available at: https://eur-lex.europa.eu/eli/dir/2013/35/oj

6. Koppel, T., Ahonen, M., Carlberg, M., Hedendahl, L., Hardell, L. (2019). Radiofrequency radiation from nearby mobile phone base stations-a case comparison of one low and one high exposure apartment. Oncology Letters, 18 (5), 5383–5391. doi: https://doi.org/10.3892/ol.2019.10899
7. Ledent, M., Beauvois, V., Demaret, I., Ansseau, M., Scantamburlo, G. (2015). 50 Hz electric and magnetic fields and health: which message to the public? Rev Med Liege, 70 (4), 172–180. Available at: https://www.ncbi.nlm.nih.gov/pubmed/26054167
8. Patil, N., Velhal, N. B., Pawar, R., Puri, V. (2015). Electric, magnetic and high frequency properties of screen printed ferrite-ferroelectric composite thick films on alumina substrate. Microelectronics International, 32 (1), 25–31. doi: https://doi.org/10.1108/mi-12-2013-0080
9. Yahya Taha Abdo Al Ademi, Ahmed Abdulbaset Arabi Abulkasem, Pulko T. A., Nasonova N. V., Lynkov L. M. (2014). Wideband shields of electromagnetic radiation on the basis of liquid-containing cellulose. Trudy MAI, 77. Available at: http://trudymai.ru/upload/iblock/679/6790ee3847ae80d7e97a14321b89ba66.pdf?lang=ru&issue=77
10. Mondal, S., Ganguly, S., Das, P., Khastgir, D., Das, N. C. (2017). Low percolation threshold and electromagnetic shielding effectiveness of nano-structured carbon based ethylene methyl acrylate nanocomposites. Composites Part B: Engineering, 119, 41–56. doi: https://doi.org/10.1016/j.compositesb.2017.03.022
11. Yadav, R. S., Kuritka, I., Vilcakova, J., Machovsky, M., Skoda, D., Urbanek, P. et. al. (2019). Polypropylene Nanocomposite Filled with Spinel Ferrite $NiFe_2O_4$ Nanoparticles and In-Situ Thermally-Reduced Graphene Oxide for Electromagnetic Interference Shielding Application. Nanomaterials, 9 (4), 621. doi: https://doi.org/10.3390/nano9040621
12. Polevikov, V. K., Erofeenko, V. T. (2017). Numerical modeling the interaction of a magnetic field with a cylindrical magnetic fluid layer. Informatics, 2 (54), 5–13. Available at: https://inf.grid.by/jour/article/view/207/209
13. Li, J., Li, L., Wan, M., Yu, H., Liu, L. (2018). Innovation applications of electromagnetic forming and its fundamental problems. Procedia Manufacturing, 15, 14–30. doi: https://doi.org/10.1016/j.promfg.2018.07.165
14. Glyva, V., Barabash, O., Kasatkina, N., Katsman, M., Levchenko, L., Tykhenko, O. et. al. (2020). Studying the shielding of an electromagnetic field by a textile material containing ferromagnetic nanostructures. Eastern-European Journal of Enterprise Technologies, 1 (10 (103)), 26–31. doi: https://doi.org/10.15587/1729-4061.2020.195232
15. Glyva, V., Lyashok, J., Matvieieva, I., Frolov, V., Levchenko, L., Tykhenko, O. et. al. (2018). Development and investigation of protective properties of the electromagnetic and soundproofing screen. Eastern-European Journal of Enterprise Technologies, 6 (5 (96)), 54–61. doi: https://doi.org/10.15587/1729-4061.2018.150778
16. Grebennikov, M., Silichikhis, S., Stebelkov, I. (2013). Physical and technological aspects of parts strengthening in ultrasonic field. Vestnik dvigatelestroeniya, 1, 72–74. Available at: https://cyberleninka.ru/article/n/fizika-i-tehnologiya-uprochneniya-detaley-v-pole-ultrazvuka
17. Han, Q. (2015). Ultrasonic Processing of Materials. Metallurgical and Materials Transactions B, 46 (4), 1603–1614. doi: https://doi.org/10.1007/s11663-014-0266-x
18. Standard of Building Biology Testing Methods: SBM-2015. Institut für Baubiologie + Nachhaltigkeit IBN. Available at: https://buildingbiology.com/site/wp-content/uploads/standard-2015-englisch.pdf

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DETERMINING THE STRENGTH AND THERMAL, CHEMICAL RESISTANCE OF THE EPOXY POLYMERCOMPOSITE FILLED WITH BASALT MICRONANO FIBER IN THE AMOUNT OF 15–80 % BY WEIGHT (p. 48–55)

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The possibility to obtain composites containing the micronano basalt fiber (MNBF) in the amount of 15–80 % by weight has been experimentally demonstrated; it is distinguished by a series of improved properties such as strength, chemical and fire resistance. It has been shown that at average concentrations (up to 15 %) the properties of the composite differ slightly from the unfilled polymer (N-polymer). However, at 50 % by weight, and especially 80 % by weight, there are serious changes in the properties manifested by a profound change in the morphology, as confirmed by SEM-microscopy.

It has been established that the introduction of microbasalt could increase strength at compression to 10 % (with a measurement error less than 5 %), and only at a very high filling in the amount of 80 % by weight. Strengthening the effect of microbasalt is expressed in an increase in the compression load of a composite aged in water and its elastic modulus up to 6–12 %. It has been determined that the drop in bending strength (by about 2 times) after filling is a tendency that is characteristic of almost all epoxy fillers. Basalt fiber was no exception. The natural exception is only those samples with basalt roving, which increase their strength at bending. At the same time, the high content (but not at 15 % by weight) has revealed an almost two-fold growth in the module at bending: higher for the composite with roving, which is very important from a practical point of view. Microbasalt filling reduces the rate and degree of swelling in 35 % H_2O_2 – the more active the higher the percentage of filling. Visually, they demonstrate the signs of oxidation with peroxide (white); however, no significant destruction (as in acetone) has been detected. We have built the curves to estimate the degree of the polymer swelling. In addition, the swelling character of the composites with a high degree of filling, in the amount of 50 and 80 % by weight, has been investigated. The study results led to the conclusion of the degree of compaction of the structure of the composite and the increase in its resistance to aggressive environments through an increase in the share of the inorganic phase.

Keywords: epoxy polymer, micronanobasalt fiber, strength, adhesion, resistance to abrasion, acetone-ethyl acetate.

References

1. Gorelov, B., Gorb, A., Nadtochiy, A., Starokadomsky, D., Kuryliuk, V., Sigareva, N. et. al. (2019). Epoxy filled with bare and oxidized multi-layered graphene nanoplatelets: a comparative study of filler loading impact on thermal properties. Journal of Materials Science, 54 (12), 9247–9266. doi: https://doi.org/10.1007/s10853-019-03523-7
2. Starokadomsky, D. (2019). Epoxy Composites Reinforced with Bazaltfibre Filled for Osteo-, Paleo-Prostheses and External Implants. Biomedical Journal of Scientific & Technical Research, 18 (1). doi: https://doi.org/10.26717/bjstr.2019.18.003092
3. Danchenko, Y., Bykov, R., Kachomanova, M., Obizhenko, T., Belous, N., Antonov, A. (2013). Environmentally friendly epoxyamine filled compositions curing under the low temperatures. Eastern-European Journal of Enterprise Technologies, 6 (10 (66)), 9–12. doi: https://doi.org/10.15587/1729-4061.2013.19165
4. Starokadomskii, D. L., Solov'eva, T. N. (2002). Effect of silicon oxide fillers on photochemical curing of compounds based on acrylic monomers and oligomers. Russian Journal of Applied Chemistry, 75, 138–141. doi: https://doi.org/10.1023/A:1015597713736
5. Starokadomskii, D. L. (2008). Effect of nanodispersed silica (Aerosil) on the thermal and chemical resistance of photocurable polyacrylate compounds. Russian Journal of Applied Chemistry, 81 (12), 2155–2161. doi: https://doi.org/10.1134/s1070427208120227
6. Starokadomsky, D. L., Ischenko, A. A., Rassokhin, D. A., Reshetnyk, M. N. (2019). Epoxy composites for equipment repair with 50 wt% silicon carbide, titanium nitride, cement, gypsum: effects of heat strengthening, strength/durability, morphology, comparison with european commercial analogues. Kompozity i nanostruktury, 11 (2), 85–93. Available at: https://www.elibrary.ru/item.asp?id=40101991
7. Starokadomskii, D. L. (2017). Epoxy composites with 10 and 50 wt % micronanoiron: strength, microstructure, and chemical and thermal resistance. Russian Journal of Applied Chemistry, 90 (8), 1337–1345. doi: https://doi.org/10.1134/s1070427217080249
8. Brailo, M., Buketov, A., Yakushchenko, S., Sapronov, O., Vynar, V., Kobelnik, O. (2018). The Investigation of Tribological Properties of Epoxy-Polyether Composite Materials for Using in the Friction Units of Means of Sea Transport. Materials Performance and Characterization, 7 (1), 275–299. doi: https://doi.org/10.1520/mpc20170161
9. Staroadomskyk, D. L. (2019). Possibilities of creating fire-resistant, thermo-hardening and thermoplastic at 250 °C epoxy-composite plastics with micro dispersions of SiC, TiN and cement. Plasticheskie massy, 5-6, 40–43. doi: https://doi.org/10.35164/0554-2901-2019-5-6-40-43
10. Bulut, M. (2017). Mechanical characterization of Basalt/epoxy composite laminates containing graphene nanopellets. Composites Part B: Engineering, 122, 71–78. doi: https://doi.org/10.1016/j.compositesb.2017.04.013
11. Lapena, M. H., Marinucci, G. (2017). Mechanical Characterization of Basalt and Glass Fiber Epoxy Composite Tube. Materials Research, 21 (1). doi: https://doi.org/10.1590/1980-5373-mr-2017-0324
12. Ulegin, S. V., Kadykova, Y. A., Artemenko, S. E., Demidova, S. A. (2014). Basalt-Filled Epoxy Composite Materials. International Polymer Science and Technology, 41 (5), 57–60. doi: https://doi.org/10.1177/0307174x1404100513
13. Wu, G., Dong, Z.-Q., Wang, X., Zhu, Y., Wu, Z.-S. (2015). Prediction of Long-Term Performance and Durability of BFRP Bars under the Combined Effect of Sustained Load and Corrosive Solutions. Journal of Composites for Construction, 19 (3), 04014058. doi: https://doi.org/10.1061/(asce)cc.1943-5614.0000517
14. Danchenko, Y., Andronov, V., Barabash, E., Obigenko, T., Rybka, E., Meleshchenko, R., Romin, A. (2017). Research of the intramolecular interactions and structure in epoxyamine composites with dispersed oxides. Eastern-European Journal of Enterprise Technologies, 6 (12 (90)), 4–12. doi: https://doi.org/10.15587/1729-4061.2017.118565
15. Alexander, J., Augustine, B. S. M., Prudhuvi, S., Paudel, A. (2016). Hygrothermal effect on natural frequency and damping characteristics of basalt/epoxy composites. Materials Today: Proceedings, 3 (6), 1666–1671. doi: https://doi.org/10.1016/j.matpr.2016.04.057
16. Mahesha, C. R., Shivarudraiah, Mohan, N., Rajesh, M. (2017). Role of Nanofillers on Mechanical and Dry sliding

Wear Behavior of Basalt- Epoxy Nanocomposites. Materials Today: Proceedings, 4 (8), 8192–8199. doi: https://doi.org/10.1016/j.matpr.2017.07.161

17. Ricciardi, M. R., Papa, I., Lopresto, V., Langella, A., Antonucci, V. (2019). Effect of hybridization on the impact properties of flax/basalt epoxy composites: Influence of the stacking sequence. Composite Structures, 214, 476–485. doi: https://doi.org/10.1016/j.compstruct.2019.01.087
18. Ary Subagia, I. D. G., Tijing, L. D., Kim, Y., Kim, C. S., Vista IV, F. P., Shon, H. K. (2014). Mechanical performance of multiscale basalt fiber–epoxy laminates containing tourmaline micro/nano particles. Composites Part B: Engineering, 58, 611–617. doi: https://doi.org/10.1016/j.compositesb.2013.10.034
19. Kim, D., Mittal, G., Kim, M., Kim, S., Yop Rhee, K. (2019). Surface modification of MMT and its effect on fatigue and fracture behavior of basalt/epoxy based composites in a seawater environment. Applied Surface Science, 473, 55–58. doi: https://doi.org/10.1016/j.apsusc.2018.12.127
20. Lee, S.-O., Choi, S.-H., Kwon, S. H., Rhee, K.-Y., Park, S.-J. (2015). Modification of surface functionality of multi-walled carbon nanotubes on fracture toughness of basalt fiber-reinforced composites. Composites Part B: Engineering, 79, 47–52. doi: https://doi.org/10.1016/j.compositesb.2015.03.077
21. Lee, J. H., Rhee, K. Y., Park, S. J. (2010). The tensile and thermal properties of modified CNT-reinforced basalt/epoxy composites. Materials Science and Engineering: A, 527 (26), 6838–6843. doi: https://doi.org/10.1016/j.msea.2010.07.080
22. Mostovoy, A. S., Kadykova, Y. A., Bekeshev, A. Z., Tastanova, L. K. (2018). Epoxy composites modified with microfibers of potassium polytitanates. Journal of Applied Polymer Science, 135 (35), 46651. doi: https://doi.org/10.1002/app.46651
23. Mostovoy, A. S., Nurtazina, A. S., Burmistrov, I. N., Kadykova, Y. A. (2018). Effect of Finely Dispersed Chromite on the Physicochemical and Mechanical Properties of Modified Epoxy Composites. Russian Journal of Applied Chemistry, 91 (11), 1758–1766. doi: https://doi.org/10.1134/s1070427218110046
24. Biswas, S., Shahinur, S., Hasan, M., Ahsan, Q. (2015). Physical, Mechanical and Thermal Properties of Jute and Bamboo Fiber Reinforced Unidirectional Epoxy Composites. Procedia Engineering, 105, 933–939. doi: https://doi.org/10.1016/j.proeng.2015.05.118
25. Zuev, Yu. S. (1972). Razrushenie polimerov pod deystviem agressivnyh sred. Moscow: Himiya, 232. Available at: https://www.twirpx.com/file/279819/
26. Starokadomskii, D. L. (2008). Effect of the content of unmodified nanosilica with varied specific surface area on physicomechanical properties and swelling of epoxy composites. Russian Journal of Applied Chemistry, 81 (11), 1987–1991. doi: https://doi.org/10.1134/s1070427208110232
27. Starokadomsky, D. (2017). Filling with the Graphene Nanoplates as a Way to Improve Properties of Epoxy-Composites for Industrial and Geophysical Machinery. American Journal of Physics and Applications, 5 (6), 120. doi: https://doi.org/10.11648/j.ajpa.20170506.19
28. Ullegaddi, K., Shivarudraiah, Mahesha, C. R. (2019). Significance of Tungsten Carbide Filler Reinforcement on Ultimate Tensile Strength of Basalt Fiber Epoxy Composites. International Journal of Recent Technology and Engineering, 8 (3), 7913–7916. doi: https://doi.org/10.35940/ijrte.c6617.098319
29. Sharma, V., Meena, M. L., Kumar, M. (2020). Effect of filler percentage on physical and mechanical characteristics of basalt fiber reinforced epoxy based composites. Materials Today: Proceedings. doi: https://doi.org/10.1016/j.matpr.2020.02.533