ISSN 2712-8008
Volume / Том 23 №3 2023
Journal Homepage: http://vestnik.pstu.ru/geo/

Perm Journal of Petroleum
and Mining Engineering

UDC 622+544-971.2
Article / Статья

Material Structure Parameters Influence on Oil and Gas Field Equipment Corrosion Resistance

Raphael A. Apakashev. Mark. L. Khazin

Ural State Mining University (30 Kuybysheva st., Ekaterinburg, 620144, Russian Federation)

Влияние параметров структуры материала на коррозионную стойкость нефтегазопромыслового оборудования

Р.А. Апакашев. М.Л. Хазин

Уральский государственный горный университет (Россия, 620144, г. Екатеринбург, ул. Куйбышева, 30)

Received / Получена: 06.03.2023. Accepted / Принята: 28.08.2023. Published / Опубликована: 25.03.2024

Keywords:
aluminum. bronze. composite materials. copper. corrosion. nanomaterials. oil and gas equipment. steel.

To improve the reliability and durability of oil and gas equipment. it is promising to use micro- and nanostructured metals and alloys. as well as metal-matrix composites. Conventional and nanostructured samples of aluminum. copper. BrA9ZhZL bronze. AMg6 alloy. and alumina-matrix dispersion-reinforced composite containing 6.3 wt % titanium were studied. Structuring treatment of metal materials was carried out in the liquid phase. The aluminum matrix composite was synthesized by powder metallurgy. A model electrolyte solution without forced circulation containing 30 g/L NaCl and an addition of acetic acid to pH = 4.0 was used as a corrosive medium. The test base was 144 h. the temperature was +22 °C. the volume of the solution in the cell with three samples was 500 ml. The relative calculated error of the tests was 5 %. For all the studied samples. a continuous uniform distribution of corrosion damage to the metal surface is observed. At the same time. the corrosion rate (P. mm/year) of nanostructured samples of metals and alloys is approximately 11 % less than the corrosion rate of samples of the same metals and alloys that were not subjected to structuring treatment. For the aluminum matrix composite. it was noted that the dispersed reinforcement of aluminum with titanium provides an increase in the corrosion resistance of the matrix metal by 9.6 %. The results of the studies performed indicate an increased corrosion resistance of nanostructured metallic materials and an aluminum matrix composite. which is important when they are used as part of equipment operating in a corrosive environment.

Ключевые слова:
алюминий. бронза. медь. композиционные материалы. коррозия. наноматериалы. нефтегазопромысловое оборудование. сталь.

Для повышения надежности и долговечности работы нефтегазопромыслового оборудования является перспективным применение микро- и наноструктурированных металлов и сплавов. а также металломатричных композитов. Исследовали обычные и наноструктурированные образцы алюминия. меди. бронзы БрА9Ж3Л. сплава АМг6 и алюмоматричный дисперсно армированный композит. содержащий 6.3 % (мас.) титана. Структурирующую обработку металлических материалов проводили в жидкофазном состоянии. Алюмоматричный композит синтезировали методом порошковой металлургии. В качестве коррозионной среды использовали модельный раствор электролита без принудительной циркуляции. содержащий 30 г/л NaCl и добавку уксусной кислоты до pH = 4.0. База испытаний составила 144 ч. температура +22 °С. объем раствора в ячейке с тремя образцами – 500 мл. Относительная расчетная погрешность испытаний составила 5 %. Для всех изученных образцов наблюдается сплошное равномерное распределение коррозионного поражения металлической поверхности. При этом скорость коррозии (П. мм/год) наноструктурированных образцов металлов и сплавов примерно на 11 % меньше. чем скорость коррозии образцов тех же металлов и сплавов. не подвергавшихся структурирующей обработке. Для алюмоматричного композита отмечено. что дисперсное армирование алюминия титаном обеспечивает повышение коррозионной стойкости матричного металла на 9.6 %. Результаты проведенных исследований свидетельствуют о повышенной коррозионной стойкости наностуктурированных металлических материалов и алюмоматричного композита. что важно при их применении в составе оборудования. эксплуатируемого в коррозионно-активной среде.

© **Raphael A. Apakashev** (Author ID in Scopus: 6603092433. ORCID: 0000-0002-9006-3667) – Doctor of Chemical Sciences. Professor. Vice-Rector for Scientific Work (tel.: +007 (343) 257 45 25; e-mail: parknedra@yandex.com).
© **Mark L. Khazin** (Author ID in Scopus: 6506526940. ORCID: 0000-0002-6081-4474) – Doctor of Engineering. Professor (tel.: +007 (343) 283 09 57; e-mail: Khasin@ursmu.ru). The contact person for correspondence.

© **Апакашев Рафаил Абдрахманович** (ORCID: 0000-0002-9006-3667) – доктор химических наук. профессор. проректор по научной работе (тел.: +007 (343) 257 45 25; e-mail: parknedra@yandex.com).
© **Хазин Марк Леонтьевич** (ORCID: 0000-0002-6081-4474) – доктор технических наук. профессор (тел: +007 (343) 283 09 57; e-mail: Khasin@ursmu.ru). Контактное лицо для переписки.

Please cite this article in English as:
Apakashev R.A.. Khazin M.L. Material Structure Parameters Influence on Oil and Gas Field Equipment Corrosion Resistance. *Perm Journal of Petroleum and Mining Engineering*. 2023. vol.23. no.3. pp.133-140. DOI: 10.15593/2712-8008/2023.3.4

Просьба ссылаться на эту статью в русскоязычных источниках следующим образом:
Апакашев Р.А.. Хазин М.Л. Влияние параметров структуры материала на коррозионную стойкость нефтегазопромыслового оборудования // Недропользование. – 2023. – Т.23. №3. – С.133–140. DOI: 10.15593/2712-8008/2023.3.4

Introduction

The oil and gas industry plays a significant role in the Russian economy and accounts for 15-25 % of GDP (in 2022, 20 %) (Fig. 1). In other countries, the share of the oil and gas sector in GDP is, for example, 50 % in Saudi Arabia, 30 % in the UAE, 14 % in Norway, 13.3 % in Kazakhstan, less than 10 % in Canada, and 8 % in the USA (RBC:тhttps://www.rbc.ru/economics/13/07/21/60ec40d39a7947f74aeb2aae).

Metallic equipment and structures in the oil and gas industry come into contact with crude oil, natural gas, petroleum products, solvents, water, soil, and the atmosphere. Oil and petroleum products contain a significant amount of aggressive components (chlorides, hydrogen sulfide, carbon dioxide, bacteria, etc.), which complicates the operation of oil extraction and transportation [1–4].

Equipment corrosion during oil and gas extraction is inevitable and is caused by water, carbon dioxide (CO_2), and hydrogen sulfide (H_2S). This process can be exacerbated in wells where high temperatures combined with H_2S create additional corrosion issues and lead to the formation of iron sulfide (FeS) deposits [4, 5]. Therefore, corrosion of petrochemical equipment is one of the factors affecting the safety processes and the sustainability of the petrochemical industry [3, 6–8].

Acids and gases, sulfur oxides and organic vapors corrode materials and cause damage. The removal of various gases from the flow can be achieved through absorption, electrostatic separators, and adsorption [9–11]. The wastewater contains various chemicals, which needs treatment to protect the environment. Organic and inorganic impurities (such as phenol, acetic acid, and organic compounds) can be removed using various chemical and biological methods [2, 5, 10]. The removal of impurities helps reduce corrosion, and some of these chemicals can be reused after water separation from [5, 7, 8]. The combination of numerous factors makes petrochemical equipment vulnerable to various corrosion phenomena, which can lead to significant losses and accidents.

Large losses due to corrosion are typical for all countries with petrochemical and oil refining industries (Table 1).

Almost 80 % of accidents and equipment failures at oil extraction and refining enterprises in Russia result from corrosive damage. For example, the specific failure rate of pipelines (units/km/year) due to corrosion for oil companies such as PJSC Gazprom Neft, OJSC Dagneft, PJSC LUKOIL, PJSC OC Rosneft, LLC RN-Yuganskneftegaz, JSC Samaraneftegaz, LLC RN-Sakhalinmorneftegaz, and LLC RN-Stavropolneftegaz significantly exceeds the allowable reliability standards for field pipeline systems. At the wells operated by LLC "LUKOIL-Komi," LLC "RNS Stavropolneftegaz," OJSC "Tomskneft" EOC, and others, the service life of the pump-compressor pipes suspension does not exceed 4-6 months [1, 2, 9, 10].

Corrosion-related accidents increase the costs of both scheduled and unscheduled repairs of oil field equipment and reduce its depreciation periods. In Russia, metal losses due to corrosion account for up to 12 % of the total mass of metal assets, which is equivalent to a loss of almost 30 % of the metal produced by the metallurgical industry in a year. However, the main damage from corrosion is not the loss of metal as a material, but rather significant costs for repairing corrosion-damaged equipment as well as losses due to plant downtime during oil and gas extraction. In many countries, the total losses from corrosion amount to 30 % of the oil and gas production costs or 4-6 % of national income [1, 4, 5, 12].

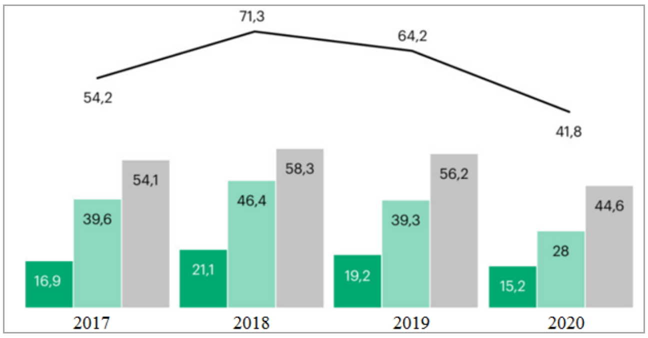


Fig. 1. Oil and gas sector in the Russian economy (Rosstat, Ministry of Finance, Federal Customs Service, Bank of Russia, BP company: https://www.rbc.ru/economics/13/07/2021/60ec40d39a7947f74aeb2aae):

- ● – the share of the oil and gas sector in Russia's GDP, %
- ● – share of oil and gas revenues in the federal budget, %
- ● – the share of oil and gas in commodity exports of Russia's GDP, %
- – average prices for Brent oil, USD per barrel

Table 1

Corrosion losses [3–7, 9, 10]

Country	Total losses from corrosion, million USD/year	Corrosion protection costs, million USD/year
England	440	
USA	500	
Japan	575	340
Russia	390	370

Corrosion protection

Corrosion is one of the most serious problems faced by oil production companies and refineries. The annual costs for corrosion protection are estimated in the billions of dollars, which lead to development of new corrosion-resistant materials and protective measures [2–4, 14–17]. The importance of the issue is confirmed by 1,887 studies published from 2000 to 2020 on search resourses as WOS SCIE, SSCI, A & HCI, and CPCI-S [2–4, 7, 13].

To protect equipment from corrosion, various methods are used: corrosion inhibitors and modern materials, cathodic protection and the application of protective coatings. Each method has its own features, advantages and disadvantages.

Corrosion inhibitors are commonly used to reduce the corrosive effects of metals [14–17]. However, most inhibitor compounds have harmful effects on the environment, and are also expensive and toxic.

Therefore, there is a growing need to replace petroleum inhibitors with environmentally friendly ones [17–20].

Steel and aluminum are widely used in almost in all sectors of the oil and gas industry. Carbon and low-alloy carbon steels are the first alternative to consider when selecting a material, not only for their cost but also due to availability. Therefore, significant efforts are made to improve the corrosion resistance of carbon and low-alloy steels. When the environment is too aggressive for carbon steels, one of the ways to reduce corrosion is to use inhibitors. However, in highly aggressive environments and high temperatures, more expensive materials such as corrosion-resistant alloys may be required [21–23]. Another key factor is the steel purity, as inclusions can serve as nucleation sites for cracks. Additionally, the content of phosphorus (P) and sulfur (S) must be minimized

The production of stainless steels and alloys is associated with significant consumption of scarce and expensive materials and components. Consequently, all industrially developed countries are not increasing the production of these materials but use modern coating technologies and enhancing the corrosion resistance of components. Also, they conduct research aimed at developing and creating corrosion-resistant and cost-effective materials.

To reduce the impact of aggressive environments, various anti-corrosion and wear-resistant coatings along with nanocoatings are applied [27, 28].

The challenge of using specialized passive metals and alloys lies in the relatively narrow range of protective film characteristics. With a slight change in operating conditions, the film is destroyed, leading to breakthroughs of localized corrosion at the site of the film rupture [24].

The oil and gas industry imposes high requirements on materials due to aggressive environments, high temperatures, pressures, and other factors. Functional nanostructured and metal matrix composite materials significantly meet these demands. In recent decades, substantial progress has been made in enhancing composite materials with matrices made from lightweight metals for their use in the most critical applications [29–31]. A significant part of these materials are composites based on copper, aluminum, and their alloys. The dispersion of functional fillers within the metallic matrix allows for achieving property levels to develop materials for specialized applications [32–35].

In many studies, the corrosive behavior of aluminum matrix composites reinforced with carbides [29], refractories [34], graphite [31], and other fillers [30] has been described.

Research methodology

In this work, we studied the effect of structure parameters on the corrosion resistance of aluminum, copper and their alloy compositions. We tested conventional and nanostructured samples of aluminum, copper, BrA9ZhZL bronze, AMg6 alloy and Al-Ti alloy containing 6.3 % (wt.) titanium. The following metal powders were used to synthesize the composite of primary aluminum (brand A0), copper M1 and technical titanium (VT1-00). The metal powders were ground in an agate mortar until homogeneous state during batching. The batch homogeneity was monitored using an optical microscope. The melting of metals and alloys was carried out in zirconium dioxide crucibles in a reducing atmosphere of an electric resistance furnace with a graphite heater. The structural processing of the studied metallic materials was carried out in the liquid phase according to a previously developed methodology [36]. The nanocrystalline nature of the metal and alloy samples was recorded using a ZEISS CrossBeam AURIGA dual-beam electron-ion microscope and atomic force microscopy (AFM) using a NEXT scanning probe microscope with an NSG30 cantilever.

Comparative corrosion resistance tests were conducted on three samples of the synthesized nanostructured and composite material, as well as three samples of aluminum grade A0 and copper grade M1 with similar geometric dimensions. The tests were carried out under static conditions, without forced circulation of the corrosive medium. A model electrolyte solution was used as the testing corrosive environment, containing 30 g/L of NaCl, with the addition of acetic acid to adjust the pH to 4.0. The final corrosion rate values were calculated as the arithmetic mean of the results of three corresponding tests with a relative error not exceeding 5 %. Before testing, cylindrical samples were polished to a mirror finish, rinsed with ethanol and, after drying, weighed with an accuracy of ± 0.0001 g. Then, three samples of the same metal or alloy with the same processing history were placed in one cell, ensuring complete immersion in the solution and preventing contact between the surfaces of the samples. Synthetic thread made of synthetic material was used to secure (suspend) the samples.

After test completion, the samples were removed from the cell, washed with warm distilled water water and ethyl alcohol, dried and weighed. Additionally, the appearance of the samples was recorded, and an assessment of their surface condition was conducted. The test period was 144 h, at the temperature of +22 °C, with a solution volume of 500 mL in the cell containing three samples.

The final corrosion rate values were calculated as the arithmetic mean of three corresponding tests with a relative error not exceeding 5 %.

In case of continuous uniform corrosion of metallic materials, corrosion resistance is characterized by such quantitative parameters as mass loss per unit area of surface and corrosion penetration depth. Accordingly, the rate of mass loss and the linear corrosion rate are calculated [37].

The rate of mass loss is the value V_c, which is the ratio:

$$V_c - \frac{m_1 - m_2}{St}, \qquad (1)$$

where m_1, m_2 are the mass of the sample before and after corrosion, respectively, g; t is the corrosion destruction time, h; S is the sample surface area, m^2.

Table 2

The results of the study on the corrosion resistance of copper, aluminum, and metal-matrix composite materials

№	Material	Sample	V_c, g/(m^2·h)	P, mm/g	$\overline{П}$, mm/g
1	Al	1	0.1318	0.4279	0.4397
		2	0.1371	0.4415	
		3	0.1377	0.4496	
2	Al/Ti	1	0.8251	2.7514	0.3974
		2	0.1232	0.3812	
		3	0.1321	0.4089	
3	AMg6	1	0.8251	2.7514	2.729
		2	0.8011	2.6582	
		3	0.8377	2.7775	
4	Cu (M1)	1	0.2045	0.2005	0.1983
		2	0.1964	0.1926	
		3	0.2061	0.2019	
5	BrA9ZhZL	1	0.0760	0.0878	0.0875
		2	0,0741	0.0855	
		3	0.0772	0.0893	

Mass losses due to corrosion can be converted into corrosion rate, expressed in mm/g:

$$P = \frac{8,76V_c}{\rho}, \tag{2}$$

where P is the corrosion rate, mm/year; ρ – metal density, g/cm^3; V_c – corrosion rate, g/(m^2.h); 8.76 – coefficient.

The density of metallic materials for use in corrosion rate calculations was determined by hydrostatic weighing.

Results and Discussion

The results of the corrosion resistance studies of aluminum, copper, their alloys, and the metal-matrix composite Al/Ti are summarized in Table 2.

It has been established that all studied samples exhibit uniform, continuous corrosion, characterized by an even distribution of damage on the metallic surface (Fig. 2).

Based on the obtained corrosion rate, it is possible to assess the corrosion resistance of metals using a ten-point scale according to All Union State standard 9.908-85 "Unified system for corrosion and aging protection. Metals and alloys. Methods for determining corrosion parameters and corrosion resistance" [37].

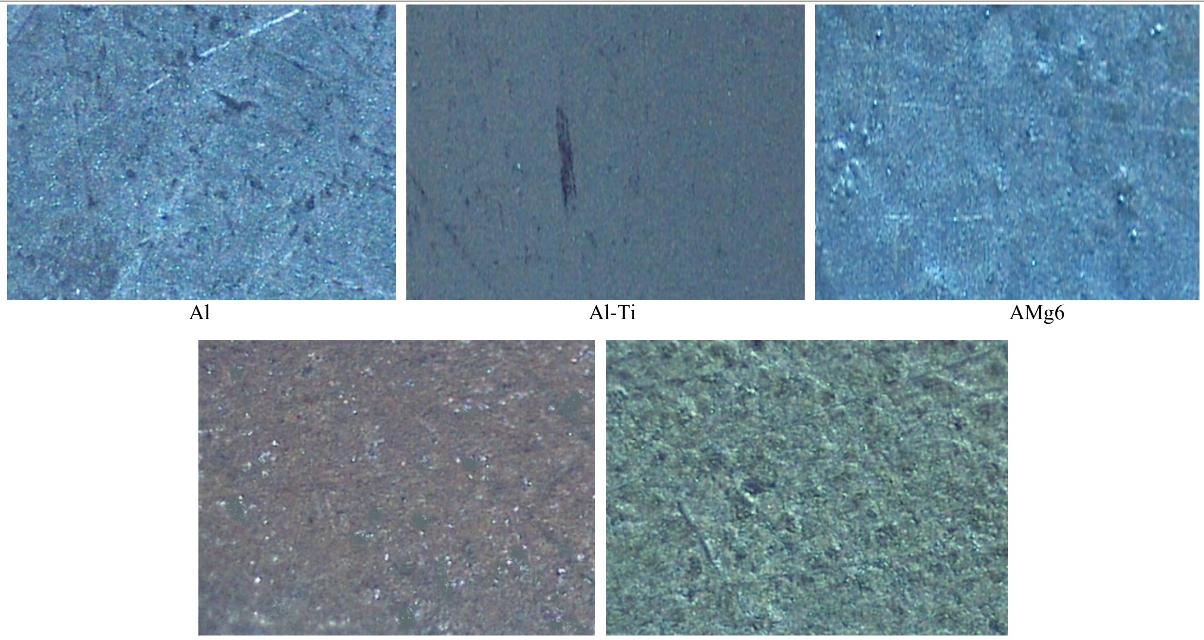
The corrosion resistance of C95200 bronze samples is rated at 4 points, while aluminum samples are rated at 5 points. At the same time, the corrosion rate (П, mm/year) of metals and alloys that underwent flow processing in a molten state is approximately 11 % less than of the same metals and alloys that did not undergo processing.

It is worth noting that the highest calculated value of the relative error in the corrosion tests, which is 4.8 %, was obtained for the aluminum-magnesium alloy 518.0 that underwent flow processing (Fig. 3).

At the same time, dispersed reinforcement of aluminum with titanium provides an increase in the corrosion resistance of the matrix metal by 9.6 %, which is significant when using the composite as a metal structural material.

Pure aluminum demostrates good corrosion resistance but poor mechanical properties; therefore, it is alloyed with other elements to enhance its strength. Solution hardening, dispersion strengthening, grain refinement, and work hardening are the main mechanisms for strengthening aluminum alloys. However, the processes of obtaining and work hardening lead to electrochemical inhomogeneities that cause localized corrosion. Consequently, there is a trade-off in Al alloys between mechanical and corrosion properties. The characteristics of the matrix and secondary phases (i.e., composition, amount, morphology, and distribution) play a crucial role in determining the corrosion characteristics.

The corrosion resistance of cast aluminum alloys has been studied by many researchers, for example, [39–41]. In terms of the corrosion process kinetics, aluminum alloys behave as a short-circuited system of multi-electrode elements [42]. The metal surface contains areas with different potential values. Surface areas that have reached the breakdown potential exhibit increased adsorption activity and electrical conductivity. Active ions adsorb in these areas, displacing oxygen and forming a "metal-anion" complex that enters the solution. Since the solubility of most alloying elements in aluminum is quite limited, the formation of secondary phases leads to



Al Al-Ti AMg6

Cu BrA9ZhZL

Fig. 2. Samples' surface after corrosion resistance tests (×200)

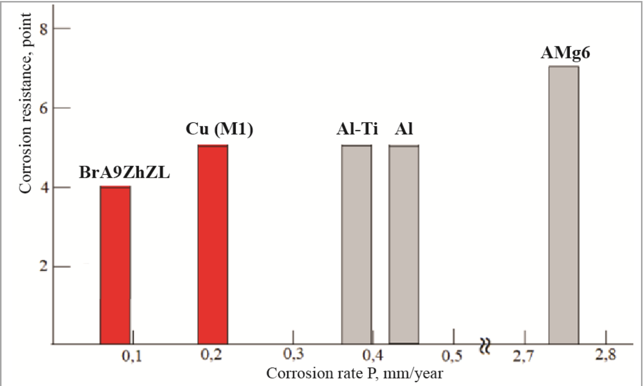


Fig. 3. Relative corrosion resistance of samples

localized corrosion, which is inevitable when using traditional processing methods. For instance, Al-5 at.% Cr and Al-5 at.% Ti alloys produced by casting exhibited large intermetallic crystal formations and high corrosion rates without a significant increase in strength. Therefore, non-traditional methods of alloy production that increase the solubility of alloying elements in the solid state are desirable. Techniques such as impulse electrodeposition or spraying may provide such benefits. Research on Al-5 at.% M, powder alloys obtained through cold pressing in 0.01 M NaCl, demonstrated good corrosion resistance of the alloy, which was attributed to the simultaneous influence of grain boundaries and solid solution strengthening [34]. Testing of AMg6 alloys, D16-T, and steel 08X17 in seawater showed 100 % surface corrosion damage but no intergranular corrosion and minimal mass loss [43]. The study of cast aluminum alloys revealed low corrosion resistance in alkaline salt and acidic environments. Pitting, uniform, fatigue, and intergranular corrosion were observed in Al-Mg alloys [39, 44].

The study of corrosion resistance of copper and bronze in a 3.5 % NaCl solution showed that bronze had an average corrosion resistance of 0.43265 mm/g, which was higher than that of brass and copper, both also at 0.43265 mm/g [44, 45].

The research has been conducted on the interaction between titanium and aluminum, where alloys were obtained through various methods, including reinforcing aluminum with a titanium matrix and reinforcing titanium with an aluminum matrix [29, 34].

Studies on the effects of relative humidity, temperature, precipitation, and pH on atmospheric corrosion indicated that pH has the most significant contribution to the overall corrosion process [21, 34, 43, 46].

Conclusion

The necessity for timely measures to improve the corrosion resistance of materials is confirmed by the reduction in the number of emergency situations and the increase in the stable operational lifespan of oil and gas field equipment. Aluminum matrix materials allow for an extended service life of components without using expensive and scarce metals.

To assess the condition of oil and gas field equipment, regular corrosion monitoring is essential. To minimize costs, the monitoring should be conducted only in areas most susceptible to corrosion damage.

The growing demand in the oil and gas industry for materials with unique physical, mechanical, and chemical properties is expanding the application areas for composite materials.

References

1. Bolotova Yu.V., Ruchkinova O.I. Corrosion of heat exchange equipment of petrochemical industries // Bulletin of PNIPU. - 2015. - Vol. 17, No. 4. - P. 102-119. DOI: 10.15593/2224-9877/2015.4.08
2. Povarova L.V., Muntyan V.S., Skiba A.S. Analysis of modern methods of protecting oilfield equipment from corrosion // Bulatovskie readings. - 2020. - Vol. 4. - P. 125-129.
3. Corrosion Strategy in Oil Field System / IA Abdalsamed, IA Amar, FA Altohami, FA Salih, MS Mazek, MA Ali, AA Sharif // Journal of Chemical Reviews. – 2020. – Vol. 2, no. 1. – P. 28–39. DOI: 10.33945/SAMI/JCR.2020.1.2
4. Al-Moubaraki AH, Obot IB Corrosion challenges in petroleum refinery operations: Sources, mechanisms, mitigation, and future outlook // Journal of Saudi Chemical Society. – 2021. – Vol. 25, no. 12. – P. 101370. DOI: 10.1016/J.JSCS.2021.101370
5. Kadhim MG, Ali MT A Critical Review on Corrosion and its Prevention in the Oilfield Equipment // Journal of Petroleum Research and Studies. – 2021. – Vol. 7, no. 2. – P. 162–189. DOI: 10.52716/JPRS.V7I2.195
6. Solovyeva VA, Almuhammadi KH, Badeghaish WO Current Downhole Corrosion Control Solutions and Trends in the Oil and Gas Industry: A Review // Materials. – 2023. – Vol. 16, no. 5. – P. 1795. DOI: 10.3390/ma16051795
7. Mapping the knowledge domains of research on corrosion of petrochemical equipment: An informetrics analysis-based study / Z. Lang, D. Wang, H. Liu, X. Gou // Engineering Failure Analysis. – 2021. – Vol. 129. – P. 105716. DOI: 10.1016/J.ENGFAILANAL.2021.105716
8. Corrosive Environmental Assessment and Corrosion-Induced Rockbolt Failure Analysis in a Costal Underground Mine / Q. Guo, J. Pan, M. Wang, M. Cai, X. Xi1 // International Journal of Corrosion. – 2021. – Vol. – 2019. – P. 9. DOI: 10.1155/2019/2105842
9. Vyboischik M.A., Ioffe A.V. Scientific foundations of development and methodology of creation of steels for production of oil field pipes of increased strength and corrosion resistance // Vector of science of Togliatti State University. - 2019. - No. 1 (47). - P. 13-20. DOI: 10.18323/2073-5073-2019-1-13-20
10. Dvadnenko M.V., Madzhigatov R.V., Rakityansky N.A. Impact of oil on the environment // International Journal of Experimental Education. - 2017. - No. 3-1. - P. 89-90.
11. Minina N.N., Dyakonova D.E., Izilyanov A.Yu. Environmental problems in oil production and ways to solve them // Notes of a scientist. - 2020. – No. 7. – P. 103–107.
12. Modern practice of application of anti-corrosion protection of oil well equipment / A.A. Daminov, V.V. Ragulin, A.I. Voloshin, A.G. Telin // Problems of collection, preparation and transportation of oil and oil products. - 2020. - No. 6 (128). - P. 30-44. DOI: 10.17122/ntj-oil-2020-6-30-44
13. Serebryakov A.N., Motuzov I.S. Corrosion of oilfield equipment and anti-corrosion protection measures at the Karakuduk oil field (western Kazakhstan) // Bulletin of RUDN. Series: Engineering research. - 2017. - Vol. 18, No. 2. - P. 174-181. DOI: 10.22363/2312-8143-2017-18-2-174-181
14. Fayomi OSI, Akande IG, Odigie S. Economic Impact of Corrosion in Oil Sectors and Prevention: An Overview // Journal of Physics: Conference Series.– 2019. – Vol. 1378. – P. 022037. DOI: 10.1088/1742-6596/1378/2/022037
15. Downhole corrosion inhibitors for oil and gas production – a review / M. Askari, M. Aliofkhazraei, R. Jafari, P. Hamghalam, A. Hajizadeh // Applied Surface Science Advances. – 2021. – Vol. 6. – P. 100128. DOI: 10.1016/j.apsadv.2021.100128
16. Tamalmani K., Husin H. Review on Corrosion Inhibitors for Oil and Gas Corrosion Issues // Applied Science. – 2020. – Vol. 10. – P. 3389. DOI: 10.3390/app10103389 www.mdpi
17. Mukatdisov N.I., Farkhutdinova A.R., Elpidinsky A.A. Methods of combating corrosion and advantages of inhibitor protection of oilfield equipment // Bulletin of Kazan Technological University. - 2014. - No. 3. - P. 279-282.
18. Mitigation of corrosion in petroleum oil well/tubing steel using pyrimidines as efficient corrosion inhibitor: Experimental and theoretical investigation / TK Sarkar, V. Saraswat, RK Mitra, IB Obot, M. Yadav // Materialstoday communications. – 2021. – Vol. 26. – P. 101862. DOI: 10.1016/j.mtcomm.2020.101862
19. Sanni O., Iwarere SA, Daramola MO Investigation of Eggshell Agro-Industrial Waste as a Potential Corrosion Inhibitor for Mild Steel in Oil and Gas Industry // Sustainability. – 2023. – Vol. 15, no. 7. – P. 6155. DOI: 10.3390/SU15076155
20. Tamalmani K., Husin H. Review on Corrosion Inhibitors for Oil and Gas Corrosion Issues // Applied Science. – 2020. – Vol. 10. – P. 3389. DOI: 10.3390/app10103389 www.mdpi
21. Steel corrosion in hydrogen sulfide-containing model environments of oil fields / A.S. Guzenkova, I.V. Artamonova, S.A. Guzenkov, S.S. Ivanov // Metallurgist. – 2021. – No. 5. – P. 36–39. DOI: 10.52351/00260827_2021_05_36
22. Erosion–Corrosion of AISI 304L Stainless Steel Affected by Industrial Copper Tailings / Á. Soliz, L. Cáceres, F. Pineda, F. Galleguillos // Metals. – 2020. – Vol. 10. – P. 1005–1021. DOI: 10.3390/met10081005
23. Anti-corrosion wear-resistant coatings on parts of oil field equipment / EN Eremin, VM Yurov, MK Ibatov, SA Guchenko, V.Ch. Laurynas // Procedia Engineering. – 2016. – Vol. 152. – p. 594–600. DOI: 10.1016/J.PROENG.2016.07.661
24. Heavy Loaded Parts of Petrochemical Equipment Destruction Cause Investigation / AB Laptev, SA Naprienko, R.ZH. Akhiyarov, AV Golubev // WSEAS Transactions on Applied and Theoretical Mechanics. – 2022. – Vol. 17. – P. 1–7. DOI: 10.37394/232011.2022.17.1
25. Kovalev M., Alekseeva E., Shaposhnikov N. Investigation of hydroabrasive resistance of internal anti-corrosion coatings used in the oil and gas industry // 2020 IOP Conf. Ser.: Mater. Sci. Eng. – 2020. – Vol. 889, no. 012020. DOI: 10.1088/1757-899X/889/1/012020
26. Olorundaisi E., Jamiru T., Adegbola AT Mitigating the effect of corrosion and wear in the application of high strength low alloy steels (HSLA) in the petrochemical transportation industry-a review // Materials Research Express. – 2019. – Vol. 6. – P. 1265k9. DOI: 10.1088/2053-1591/ab65e7
27. A Review on the Corrosion Behavior of Nanocoatings on Metallic Substrates / D. H. Abdeen, M.El. Hachach, M. Koc, M. A. Atieh // Materials. – 2019. – Vol. 12. – P. 210–252. DOI: 10.3390/ma12020210
28. Effect of structure: A new insight into nanoparticle assemblies from inanimate to animate / C. Huang, X. Chen, Z. Xue, T. Wang // Science advances. – 2020: eaba1321. DOI: 10.1126/sciadv.aba1321
29. Fabrication and Corrosion Behavior of Aluminum Metal Matrix Composites – A Review / R. A. Kumar, S. J. Akash, S. Arunkumar, V. Balaji, M. Balamurugan, AJ Kumar // IOP Conf. Series: Materials Science and Engineering. – 2020. – Vol. 923. – P. 012056. DOI: 10.1088/1757-899X/923/1/012056
30. Nanjan S., Murali JG Analyzing the Mechanical Properties and Corrosion Phenomenon of Reinforced Metal Matrix Composite // Mat. Res. – 2020. – Vol. 23, no. 2. DOI: 10.1590/1980-5373-MR-2019-0681
31. Corrosion Resistance of Al–CNT Metal Matrix Composites / VV Popov, A. Pismenny, N. Larianovsky, A. Lapteva, D. Safranchik // Materials. – 2021. – Vol. 14. – P. 3530–3542. DOI: 10.3390/ma14133530
32. Bikmukhametov M.V., Zhitnikov D.S. Composite materials as an engine of progress // Internauka. - 2020. - No. 45-2 (174). - P. 19–20.
33. Use of composite materials in the oil and gas industry / A.V. Isanova, A.A. Dolgikh, S.A. Petrov, R.A. Zadvitsky // Urban development. Infrastructure. Communications. - 2020. - No. 2 (19). - P. 39-44.
34. Microstructure and Corrosion Performance of Aluminum Matrix Composites Reinforced with Refractory High-Entropy Alloy Particulates / E. Ananiadis, KT Argyris, TE Matikas, AK Sfikas, AE Karantzalis // Appl. Sci. – 2021. – Vol. 11. – P. 1300. DOI: 10.3390/app11031300
35. Nenakhov A.I., Sergeenkova E.V. Possibilities of using composite materials in the field of energy for oil and product pipelines // Energy Policy. - 2022. - No. 10 (176). - P. 54-65. DOI: 10.46920/2409-5516.2022_10176.54
36. Apakashev RA, Khazin ML, Krasikov SA Effect of Nanostructuring of Aluminum, Copper, and Alloys on Their Basis Wear for Resistance and Hardness// Journal of Friction and Wear. – 2020. – Vol. 41, no. 5. – P. 428–431. DOI: 10.3103/s1068366620050037R.A
37. GOST 9.908-85. Unified system of protection against corrosion and aging. Metals and alloys. Methods for determining corrosion indices and corrosion resistance. – M.: IPK Publishing House of Standards, 1999. – 17 p.
38. Rohatgi PK, Xiang C., Gupta N. Aqueous corrosion of metal matrix composites // In Comprehensive Composite Materials II. – 2017. – P. 287–312. DOI: 10.1016/B978-0-12-803581-8.09985-9
39. Berlanga-Labari C., Biezma-Moraleda MV, Rivero PJ Corrosion of Cast Aluminum Alloys: A Review // Metals. – 2020. – Vol. 10, no. 10. – P. 1384. DOI: 10.3390/met10101384C
40. Excellent corrosion resistance and hardness in Al alloys by extended solid solubility and nanocrystalline structure / J. Esquivel, H. A. Murdoch, K. A. Darling, R. K. Gupta // Materials Research Letters. – 2018. – Vol. 6, no. 1 – P. 79–83. DOI: 10.1080/21663831.2017.1396262

41. Corrosion behavior of aluminum alloy in sulfur-associated petrochemical equipment H2S environment / X. Cao, Y. Lu, Z. Wang, H. Wei, L. Fan, R. Yang, W. Guo // Chemical Engineering Communications. – 2023. – Vol. 210, no. 2. – P. 233–246. DOI: 10.1080/00986445.2022.2030729

42. Sinyavskiy V.S., Valkov V.D., Kalinin V.D. Corrosion and protection of aluminum alloys. – M.: Metallurgy, 1979. – 224 p.

43. Varchenko E.A., Kurs M.G. Crevice corrosion of aluminum alloys and stainless steels in sea water // PROCEEDINGS OF VIAM. – 2018. – No. 7 (67). – P. 96–105. DOI: 10.18577/2307-6046-2018-0-7-96-105

44. Corrosion characterization of Cu-based alloy in different environments / R. Soenoko, PH Setyarini, S. Hidayatullah, MS Ma'arif, F. Gapsari // Metalurgija. – 2020. – Vol. 59, no. 3. – P. 373–376.https://hrcak.srce.hr/237045

45. Surface Characterization and Corrosion Behavior of 90/10 Copper-Nickel Alloy in Marine Environment / T. Jin, W. Zhang, N. Li, X. Liu, L. Han, W. Dai // Materials. – 2019. – Vol. 12. – P. 1869–1884. Doi: 10.3390/ma12111869

46. Mechanical and Corrosion Behavior of Al7075 (Hybrid) Metal Matrix Composites by Two Step Stir Casting Process / M. Sambathkumar, P. Navaneethakrishnan, K. Ponappa, KSK Sasikumar // Lat. Am. j. solids struct. – 2017. – Vol. 14, no. 2. – P. 243–255. DOI: 10.1590/1679-78253132

Библиографический список

1. Болотова Ю.В., Ручкинова О.И. Коррозия теплообменного оборудования нефтехимических производств // Вестник ПНИПУ. – 2015. – Т. 17, № 4. – С. 102–119. DOI: 10.15593/2224-9877/2015.4.08

2. Поварова Л.В., Мунтян В.С., Скиба А.С. Анализ современных методов защиты нефтепромыслового оборудования от коррозии // Булатовские чтения. – 2020. – Т. 4. – С. 125–129.

3. Corrosion Strategy in Oil Field System / I.A. Abdalsamed, I.A. Amar, F.A. Altohami, F.A. Salih, M.S. Mazek, M.A. Ali, A.A. Sharif // Journal of Chemical Reviews. – 2020. – Vol. 2, no. 1. – P. 28–39. DOI: 10.33945/SAMI/JCR.2020.1.2

4. Al-Moubaraki A.H., Obot I.B. Corrosion challenges in petroleum refinery operations: Sources, mechanisms, mitigation, and future outlook // Journal of Saudi Chemical Society. – 2021. – Vol. 25, no. 12. – P. 101370. DOI: 10.1016/J.JSCS.2021.101370

5. Kadhim M.G., Ali M.T. A Critical Review on Corrosion and its Prevention in the Oilfield Equipment // Journal of Petroleum Research and Studies. – 2021. – Vol. 7, no. 2. – P. 162–189. DOI: 10.52716/JPRS.V7I2.195

6. Solovyeva V.A., Almuhammadi K.H., Badeghaish W.O. Current Downhole Corrosion Control Solutions and Trends in the Oil and Gas Industry: A Review // Materials. – 2023. – Vol. 16, no. 5. – P. 1795. DOI: 10.3390/ma16051795

7. Mapping the knowledge domains of research on corrosion of petrochemical equipment: An informetrics analysis-based study / Z. Lang, D. Wang, H. Liu, X. Gou // Engineering Failure Analysis. – 2021. – Vol. 129. – P. 105716. DOI: 10.1016/J.ENGFAILANAL.2021.105716

8. Corrosive Environment Assessment and Corrosion-Induced Rockbolt Failure Analysis in a Costal Underground Mine / Q. Guo, J. Pan, M. Wang, M. Cai, X. Xi1 // International Journal of Corrosion. – 2021. – Vol. – 2019. – P. 9. DOI: 10.1155/2019/2105842

9. Выбойщик М.А., Иоффе А.В. Научные основы разработки и методология создания сталей для производства нефтепромысловых труб повышенной прочности и коррозионной стойкости // Вектор науки Тольяттинского государственного университета. – 2019. – № 1 (47). – С. 13–20. DOI: 10.18323/2073-5073-2019-1-13-20

10. Двадненко М.В., Маджигатов Р.В., Ракитянский Н.А. Воздействие нефти на окружающую среду // Международный журнал экспериментального образования. – 2017. – № 3-1. – С. 89–90.

11. Минина Н.Н., Дьяконова Д.Е., Изилянов А.Ю. Экологические проблемы при добыче нефти и пути их решения // Заметки ученого. – 2020. – № 7. – С. 103–107.

12. Современная практика применения противокоррозионной защиты оборудования нефтедобывающих скважин / А.А. Даминов, В.В. Рагулин, А.И. Волошин, А.Г. Телин // Проблемы сбора, подготовки и транспорта нефти и нефтепродуктов. – 2020. – № 6 (128). – С. 30–44. DOI: 10.17122/ntj-oil-2020-6-30-44

13. Серебряков А.Н., Мотузов И.С. Коррозия нефтепромыслового оборудования и мероприятия по противокоррозионной защите на нефтяном месторождении Каракудук (западный Казахстан) // Вестник РУДН. Серия: Инженерные исследования. – 2017. – Т. 18, № 2. – С. 174–181. DOI: 10.22363/2312-8143-2017-18-2-174-181

14. Fayomi O.S.I., Akande I.G., Odigie S. Economic Impact of Corrosion in Oil Sectors and Prevention: An Overview // Journal of Physics: Conference Series. – 2019. – Vol. 1378. – P. 022037. DOI: 10.1088/1742-6596/1378/2/022037

15. Downhole corrosion inhibitors for oil and gas production – a review / M. Askari, M. Aliofkhazraei, R. Jafari, P. Hamghalam, A. Hajizadeh // Applied Surface Science Advances. – 2021. – Vol. 6. – P. 100128. DOI: 10.1016/j.apsadv.2021.100128

16. Tamalmani K., Husin H. Review on Corrosion Inhibitors for Oil and Gas Corrosion Issues // Applied Scitnce. – 2020. – Vol. 10. – P. 3389. DOI: 10.3390/app10103389 www.mdpi

17. Мукатдисов Н.И., Фархутдинова А.Р., Елпидинский А.А. Методы борьбы с коррозией и преимущества ингибиторной защиты нефтепромыслового оборудования // Вестник Казанского технологического университета. – 2014. – № 3. – С. 279–282.

18. Mitigation of corrosion in petroleum oil well/tubing steel using pyrimidines as efficient corrosion inhibitor: Experimental and theoretical investigation / T.K. Sarkar, V. Saraswat, R.K. Mitra, I.B. Obot, M. Yadav // Materialstoday communications. – 2021. – Vol. 26. – P. 101862. DOI: 10.1016/j.mtcomm.2020.101862

19. Sanni O., Iwarere S.A., Daramola M.O. Investigation of Eggshell Agro-Industrial Waste as a Potential Corrosion Inhibitor for Mild Steel in Oil and Gas Industry // Sustainability. – 2023. – Vol. 15, no. 7. – P. 6155. DOI: 10.3390/SU15076155

20. Tamalmani K., Husin H. Review on Corrosion Inhibitors for Oil and Gas Corrosion Issues // Applied Science. – 2020. – Vol. 10. – P. 3389. DOI: 10.3390/app10103389 www.mdpi

21. Коррозия стали в сероводородродсодержащих модельных средах нефтяных месторождений / А.С. Гузенкова, И.В. Артамонова, С.А. Гузенков, С.С. Иванов // Металлург. – 2021. – № 5. – С. 36–39. DOI: 10.52351/00260827_2021_05_36

22. Erosion–Corrosion of AISI 304L Stainless Steel Affected by Industrial Copper Tailings / Á. Soliz, L. Cáceres, F. Pineda, F. Galleguillos // Metals. – 2020. – Vol. 10. – P. 1005–1021. DOI: 10.3390/met10081005

23. Anti-corrosion wear-resistant coatings on parts of oil field equipment / E.N. Eremin, V.M. Yurov, M.K. Ibatov, S.A. Guchenko, V.Ch. Laurynas // Procedia Engineering. – 2016. – Vol. 152. – p. 594–600. DOI: 10.1016/J.PROENG.2016.07.661

24. Heavy Loaded Parts of Petrochemical Equipment Destruction Cause Investigation / A.B. Laptev, S.A. Naprienko, R.ZH. Akhiyarov, A.V. Golubev // WSEAS Transactions on Applied and Theoretical Mechanics. – 2022. – Vol. 17. – P. 1–7. DOI: 10.37394/232011.2022.17.1

25. Kovalev M., Alekseeva E., Shaposhnikov N. Investigation of hydroabrasive resistance of internal anti-corrosion coatings used in the oil and gas industry // 2020 IOP Conf. Ser.: Mater. Sci. Eng. – 2020. – Vol. 889, no. 012020. DOI: 10.1088/1757-899X/889/1/012020

26. Olorundaisi E., Jamiru T., Adegbola A.T. Mitigating the effect of corrosion and wear in the application of high strength low alloy steels (HSLA) in the petrochemical transportation industry-a review // Materials Research Express. – 2019. – Vol. 6. – P. 1265k9. DOI: 10.1088/2053-1591/ab65e7

27. A Review on the Corrosion Behaviour of Nanocoatings on Metallic Substrates / D.H. Abdeen, M.El. Hachach, M. Koc, M.A. Atieh // Materials. – 2019. – Vol. 12. – P. 210–252. DOI: 10.3390/ma12020210

28. Effect of structure: A new insight into nanoparticle assemblies from inanimate to animate / C. Huang, X. Chen, Z. Xue, T. Wang // Science advances. – 2020: eaba1321. DOI: 10.1126/sciadv.aba1321

29. Fabrication and Corrosion Behaviour of Aluminium Metal Matrix Composites – A Review / R.A. Kumar, S.J. Akash, S. Arunkumar, V. Balaji, M. Balamurugan, A.J. Kumar // IOP Conf. Series: Materials Science and Engineering. – 2020. – Vol. 923. – P. 012056. DOI: 10.1088/1757-899X/923/1/012056

30. Nanjan S., Murali J.G. Analysing the Mechanical Properties and Corrosion Phenomenon of Reinforced Metal Matrix Composite // Mat. Res. – 2020. – Vol. 23, no. 2. DOI: 10.1590/1980-5373-MR-2019-0681

31. Corrosion Resistance of Al–CNT Metal Matrix Composites / V.V. Popov, A. Pismenny, N. Larianovsky, A. Lapteva, D. Safranchik // Materials. – 2021. – Vol. 14. – P. 3530–3542. DOI: 10.3390/ma14133530

32. Бикмухаметов М.В., Житников Д.С. Композиционные материалы как двигатель прогресса // Интернаука. – 2020. – № 45-2 (174). – С. 19–20.

33. Использование композитных материалов в нефтегазовой отрасли / А.В. Исанова, А.А. Долгих, С.А. Петров, Р.А. Задвицкий // Градостроительство. Инфраструктура. Коммуникации. – 2020. – № 2 (19). – С. 39–44.

34. Microstructure and Corrosion Performance of Aluminium Matrix Composites Reinforced with Refractory High-Entropy Alloy Particulates / E. Ananiadis, K.T. Argyris, T.E. Matikas, A.K. Sfikas, A.E. Karantzalis // Appl. Sci. – 2021. – Vol. 11. – P. 1300. DOI: 10.3390/app11031300
35. Ненахов А.И., Сергеенкова Е.В. Возможности применения композитных материалов в области энергетики для нефтепроводов и продуктопроводов // Энергетическая политика. – 2022. – № 10 (176). – С. 54–65. DOI: 10.46920/2409-5516.2022_10176.54
36. Apakashev R.A., Khazin M.L., Krasikov S.A. Effect of Nanostructuring of Aluminum, Copper, and Alloys on Their Basis Wear for Resistance and Hardness // Journal of Friction and Wear. – 2020. – Vol. 41, no. 5. – P. 428–431. DOI: 10.3103/s1068366620050037R.A
37. ГОСТ 9.908-85. Единая система защиты от коррозии и старения. Металлы и сплавы. Методы определения показателей коррозии и коррозионной стойкости. – М.: ИПК Издательство стандартов, 1999. – 17 с.
38. Rohatgi P.K., Xiang C., Gupta N. Aqueous corrosion of metal matrix composites // In Comprehensive Composite Materials II. – 2017. – P. 287–312. DOI: 10.1016/B978-0-12-803581-8.09985-9
39. Berlanga-Labari C., Biezma-Moraleda M.V., Rivero P.J. Corrosion of Cast Aluminum Alloys: A Review // Metals. – 2020. – Vol. 10, no. 10. – P. 1384. DOI: 10.3390/met10101384C
40. Excellent corrosion resistance and hardness in Al alloys by extended solid solubility and nanocrystalline structure / J. Esquivel, H.A. Murdoch, K.A. Darling, R.K. Gupta // Materials Research Letters. – 2018. – Vol. 6, no. 1 – P. 79–83. DOI: 10.1080/21663831.2017.1396262
41. Corrosion behavior of aluminum alloy in sulfur-associated petrochemical equipment H2S environment / X. Cao, Y. Lu, Z. Wang, H. Wei, L. Fan, R. Yang, W. Guo // Chemical Engineering Communications. – 2023. – Vol. 210, no. 2. – P. 233–246. DOI: 10.1080/00986445.2022.2030729
42. Синявский В.С., Вальков В.Д., Калинин В.Д. Коррозия и защита алюминиевых сплавов. – М.: Металлургия, 1979. – 224 с.
43. Варченко Е.А., Курс М.Г. Щелевая коррозия алюминиевых сплавов и нержавеющих сталей в морской воде // ТРУДЫ ВИАМ. – 2018. – № 7 (67). – С. 96–105. DOI: 10.18577/2307-6046-2018-0-7-96-105
44. Corrosion characterization of Cu-based alloy in different environment / R. Soenoko, P.H. Setyarini, S. Hidayatullah, M.S. Ma'arif, F. Gapsari // Metalurgija. – 2020. – Vol. 59, no. 3. – P. 373–376. https://hrcak.srce.hr/237045
45. Surface Characterization and Corrosion Behavior of 90/10 Copper-Nickel Alloy in Marine Environment / T. Jin, W. Zhang, N. Li, X. Liu, L. Han, W. Dai // Materials. – 2019. – Vol. 12. – P. 1869–1884. Doi: 10.3390/ma12111869
46. Mechanical and Corrosion Behavior of Al7075 (Hybrid) Metal Matrix Composites by Two Step Stir Casting Process / M. Sambathkumar, P. Navaneethakrishnan, K. Ponappa, K.S.K. Sasikumar // Lat. Am. j. solids struct. – 2017. – Vol. 14, no. 2. – P. 243–255. DOI: 10.1590/1679-78253132

Funding. The study had no sponsorship support.
Conflict of interest. The authors declare no conflict of interest.
The authors' contribution is equal.