

Chemically resistant nanostructured protective coatings for metal surfaces

© Alexander V. Pchel'nikov^a✉, Anatoly P. Pichugin^a

*Novosibirsk State Agricultural University,
160, Dobrolyubova St., Novosibirsk, 630039, Russian Federation*

✉ pchelaleksandr@mail.ru

Abstract: The aim of this study is to develop nanostructured protective coatings with high chemical resistance for metal surfaces. To modify paints and varnishes, compositions based on carbon nanotubes (CNTs), bismuth oxide nanoparticles, silicon dioxide, titanium dioxide, magnesium hydroxide and aluminum hydroxide were used. The introduction of nanomaterials into acrylic paint and varnish material helps to increase the adhesive strength of coatings, so the best effect was determined with the introduction of CNTs in the amount of 0.1 % – the adhesive strength increased from 2.0–2.2 MPa to 2.9–3.1 MPa with a change in the nature of the separation of the paint and varnish coating from the substrate from fully adhesive (100 %) to adhesive-cohesive. Evaluation of the chemical resistance of nanostructured paint and varnish coatings modified with CNTs showed that when the coatings were exposed to an herbicide solution, they retained their weight regardless of the concentration of the modifier, while their hardness did not change (H). Evaluation of the equilibrium swelling rate made it possible to determine that paint and varnish coatings modified with bismuth oxide nanoparticles and CNTs are resistant to solvents and acquire a more mesh structure in relation to coatings without additives. Scanning of various sections of the sample surfaces on atomic force microscope (AFM) showed that when modified with bismuth oxide and CNT nanoadditives, the surface becomes smoother, and the nanometer roughness decreases from 50–60 nm to 20–30 nm. A more significant reduction in protrusions is observed in coatings modified with CNTs, which indicates that the coating is strengthened by reducing the size of depressions and pores.

Keywords: nanomaterials; nanostructured coatings; paint and varnish coatings and materials; adhesive strength; chemical resistance; metal structures; carbon nanotubes; bismuth oxide.

For citation: Pchel'nikov AV, Pichugin AP. Chemically resistant nanostructured protective coatings for metal surfaces. *Journal of Advanced Materials and Technologies*. 2025;10(2):117-128. DOI: 10.17277/jamt-2025-10-02-117-128

Химостойкие наноструктурированные защитные покрытия для металлических поверхностей

© А. В. Пчельников^a✉, А. П. Пичугин^a

^a *Новосибирский государственный аграрный университет,
ул. Добролюбова, 160, Новосибирск, 630039, Российская Федерация*

✉ pchelaleksandr@mail.ru

Аннотация: Цель работы заключается в разработке наноструктурированных защитных покрытий с высокой химической стойкостью для металлических поверхностей. Для модификации лакокрасочных материалов применялись составы на основе углеродных нанотрубок (УНТ), наночастиц оксида висмута, диоксида кремния, диоксида титана, гидроксида магния и алюминия. Введение в акриловый лакокрасочный материал наноматериалов способствовало увеличению адгезионной прочности покрытий, так наилучший эффект определен при введении УНТ, в количестве 0,1 % – адгезионная прочность повышается с 2,0...2,2 до 2,9...3,1 МПа при изменении характера отрыва лакокрасочного покрытия от подложки с полностью адгезионного (100 %) на адгезионно-когезионный. Оценка химической стойкости наноструктурированных лакокрасочных покрытий с УНТ показала, что при воздействии на покрытия раствора гербицида, они сохраняют свою массу вне зависимости от концентрации модификатора, при этом их твердость не изменяется (H). Оценка равновесной степени набухания

позволила определить, что лакокрасочные покрытия с наночастицами оксида висмута и УНТ обладают устойчивостью к растворителям и приобретают более сетчатую структуру по отношению к покрытиям без добавок. Сканирование различных участков поверхностей образцов на АСМ показало, что при модификации нанодобавками оксида висмута и УНТ поверхность становится более гладкой, нанометровая шероховатость уменьшается с 50...60 до 20...30 нм. Более существенное уменьшение выступов наблюдается у покрытий модифицированных УНТ, что говорит об упрочнении покрытия за счет уменьшения размеров углублений и пор.

Ключевые слова: наноматериалы; наноструктурированные покрытия; лакокрасочные покрытия и материалы; адгезионная прочность; химическая стойкость; металлические конструкции; углеродные нанотрубки; оксид висмута.

Для цитирования: Pchel'nikov AV, Pichugin AP. Chemically resistant nanostructured protective coatings for metal surfaces. *Journal of Advanced Materials and Technologies*. 2025;10(2):117-128. DOI: 10.17277/jamt-2025-10-02-117-128

1. Introduction

The surfaces of various metal products and structures operating in industrial environments are constantly exposed to aggressive action of various environments: acids, alkalis, fuels and lubricants, salt solutions, etc. Thus, one of the most important properties of protective coatings of metal surfaces is chemical resistance. The use of chemical-resistant protective coatings is widespread in the oil and chemical industries, and is also relevant, for example, for anti-corrosion protection of structures at mineral fertilizer production plants [1–3].

The need to address the issues of developing chemical-resistant protective coatings for metals is explained by a number of factors [1, 3–5]:

- corrosion damage (active exposure to liquids and gases in chemical and petrochemical plants, under the influence of severe temperature loads, negatively affects the condition of metal structures, pipes, tanks and other equipment);
- economic losses caused by corrosion damage, leading to the need to replace or repair parts and equipment;
- threat to human safety, including in the event of damage to bridges, oil pipelines, aviation equipment;
- negative impact on the environmental system and human health due to uncontrolled destruction, which can lead to leaks of hazardous substances into the environment.

Hence, the use of chemically resistant coatings can increase the service life of individual elements, reduce the costs of repair work and reduce the likelihood of the development of corrosion changes inside structures.

One of the most effective methods for improving technological and operational characteristics of materials is their nanomodification, which has become the basis for this study and was discussed in the works of many researchers, who presented the results of using nanomodifiers to create highly

effective composite materials for various purposes [3–17].

Thus, the study aims to develop nanostructured protective coatings with high chemical resistance for metal surfaces.

2. Materials and Methods

2.1. Materials

Acrylic and pentaphthalic paints and varnishes (AC-182, PF-115 – manufactured by LKZ Kolorit Ltd., Russia) were used in the tests. They are widely used for painting metal products and structures and their choice was justified in other studies [3, 18, 19]. The paints and varnishes were modified using compositions based on carbon nanotubes (CNT) (Tuball Matrix 203 – Russia, OcSiAl), bismuth oxide nanoparticles (BO) (Dongguan SAT nano technology material Co., Ltd. – China), silicon dioxide (SiO₂) (Tarkosil T-20 – Russia), titanium dioxide (TiO₂) (Zhengzhou Kelai Chemical Co., Ltd – China), magnesium hydroxide (Mg(OH)₂) and aluminum hydroxide (Al(OH)₃) (Zibo Aotai New Material Technology Co., Ltd. – China). The method of dispersing nanomaterials is mechanical mixing [3].

2.2. Control methods

The chemical resistance of paint and varnish coatings was assessed in accordance with Russian Standard 9.403-2022. The adhesive strength of paint and varnish coatings was determined in accordance with Russian Standard 32299–2013. The hardness of the coatings was assessed in accordance with Russian Standard R 54586–2011.

Also, one of the simple and reliable methods for determining the chemical resistance, as well as the topological structure of coatings is the equilibrium swelling method or the Flory-Rehner method, based on the swelling of the coating in a solvent, followed by an assessment of the equilibrium swelling rate [16]:

$$\Delta\mu = RT \left(\ln(1-\varphi) + \varphi + x_1 \varphi^2 + \frac{\rho_2 V}{M_c} \left(\varphi^{1/3} - \frac{2\varphi}{f} \right) \right), \quad (1)$$

where ρ_2 is polymer density, $\text{g}\cdot\text{cm}^{-3}$; V is volume of absorbed liquid, cm^3 ; f is mesh functionality; M_c is average molecular weight of chain segments; x_1 is polymer-solvent interaction parameter (known for different polymer-solvent systems); RT is the energy required to transfer one molecule of solvent into the polymer; φ is volume fraction of polymer in the swollen sample.

The volume fraction of the polymer in the swollen sample is found using formula (2):

$$\varphi = \frac{m_0/\rho}{m_0/\rho + V_1}, \quad (2)$$

where V_1 is volume of solvent absorbed at equilibrium at the end of the experiment, cm^3 .

The main consequences of the calculations in accordance with the Flory-Rehner equation and the tests carried out are [20]:

- mesh polymer swelling is always limited;
- the degree of swelling of a mesh polymer depends on the thermodynamic affinity of the components and the density of the mesh;
- increasing the mesh density leads to a decrease in the degree of swelling.

The tests were carried out by processing the obtained data by calculating the equilibrium swelling rate of specimens, excluding the estimation of the mesh density parameter. Indicators for comparing the test results of the specimens were carried out by means of formulas 3 and 4, according to which the equilibrium swelling rate is calculated.

$$\alpha = \frac{m - m_0}{m_0} 100 \%; \quad (3)$$

$$\alpha = \frac{V \rho}{m_0} 100 \%, \quad (4)$$

where m is weight (volume) of swollen specimen, g; m_0 is weight (volume) of the initial specimen, g; V is volume of absorbed liquid, cm^3 ; ρ is solvent density, $\text{kg}\cdot\text{m}^{-3}$.

According to the equilibrium swelling method, the specimens were exposed in the solvent and the changes in the parameters of mass, thickness, length and width of the specimens were monitored at regular intervals. The tests were continued until the

equilibrium state was reached, when the parameters became unchanged. Based on the Flory-Rehner theory, an increase in the mesh density leads to a decrease in the degree of swelling, i.e. the smaller the equilibrium swelling rate, the more mesh-like the coating structure.

2.3. Analytic methods

The study of the linear dimensions of the elements of the micro- and nanorelief surface structures of the nanomodified coatings was carried out using an atomic force microscope (AFM) based on the INTEGRA Aura probe nanolaboratory platform of NT-MDT company. A semi-contact (intermittent-contact) method was used to produce images; to increase the goodness of cantilever oscillations and, consequently, to increase the sensitivity, reliability, and validity in the measurements of weak forces between the probe and the specimen, the study was carried out under low vacuum conditions.

3. Results and Discussion







When determining the effect of nanomaterials on the physical and mechanical properties of the resulting coatings, it was found that the best adhesion strength has coatings based on acrylic paint material (AC-182) than on the basis of pentaphthalic (PF-115). At the same time, the introduction of nanomaterials contributes to an increase in the adhesive strength of the coating. So, the best effect is determined by the introduction of CNTs, in the amount of 0.1 % – the adhesive strength increases from 2.0–2.2 to 2.9–3.1 MPa with a change in the nature of detachment of the paint coating from the substrate from fully adhesive (100 %) to adhesion-cohesive (Table 1).

Tests on the chemical resistance of paint coatings were carried out by exposing paint coatings to various chemical media (solvents, fuels and lubricants, acids, alkalis, etc.). At the first stage of the research rational concentration of chemical solutions was determined. So, for example, 40 % aqueous solution of herbicide (a mixture of dimethylamine, potassium, sodium salts) was chosen, at which changes in the properties of coatings occur, at which it is possible to most adequately trace the different effects of chemical solution on the coating. Nanostructured paint coatings based on AS-182 enamel showed the greatest chemical resistance, the results of the studies of which are presented in Table 2.

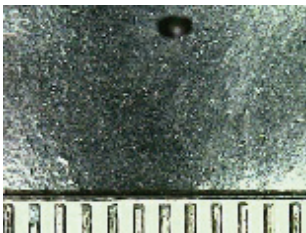
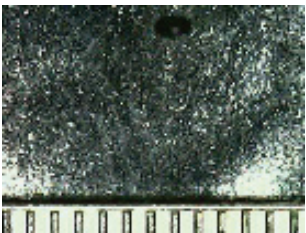
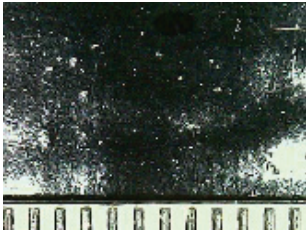
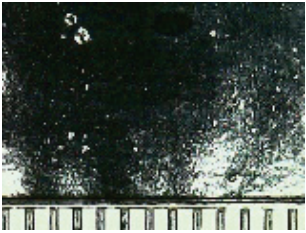
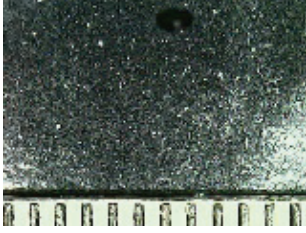

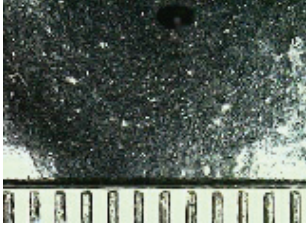

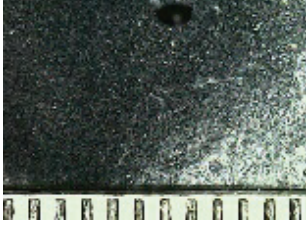
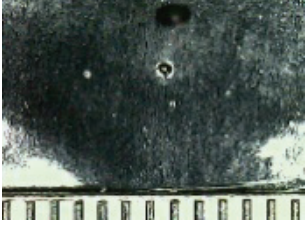
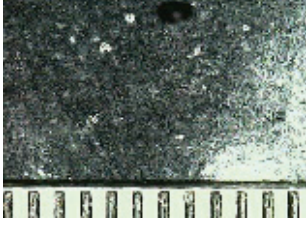
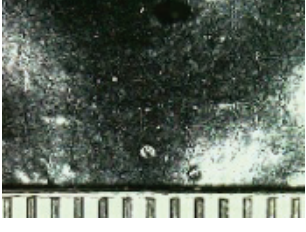
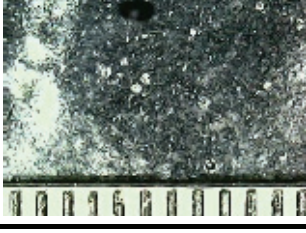
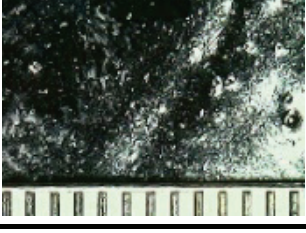
Table 1. Results of adhesive strength of paint and varnish coatings

Introduced additives	Adhesion strength, MPa / Detachment character (adhesive (A) – cohesive (K)), %	
	AC-182	PF-115
No additives	1.7 – 1.9 / A100 – K0	1.6 – 1.8 / A100 – K0
BO – 0.5 %	2.6 – 2.8 / A30 – K70	2.4 – 2.6 / A30 – K70
BO – 1 %	2.9 – 3.1 / A10 – K90	2.5 – 2.7 / A10 – K90
BO – 2 %	2.4 – 2.6 / A30 – K70	2.3 – 2.5 / A20 – K80
SiO ₂ – 0.5 %	2.0 – 2.2 / A80 – K20	1.9 – 2.1 / A80 – K20
SiO ₂ – 1 %	2.3 – 2.5 / A80 – K20	2.1 – 2.2 / A80 – K20
SiO ₂ – 2 %	2.0 – 2.2 / A80 – K20	1.9 – 2.1 / A20 – K80
CNTs – 0.01 %	2.7 – 2.9 / A90 – K10	2.4 – 2.6 / A70 – K30
CNTs – 0.05 %	2.9 – 3.1 / A90 – K10	2.8 – 3.0 / A70 – K30
CNTs – 0.1 %	3.2 – 3.4 / A50 – K50	3.0 – 3.2 / A75 – K25
Mg(OH) ₂ – 0.5 %	1.8 – 2.0 / A100 – K0	1.6 – 1.8 / A90 – K10
Mg(OH) ₂ – 1 %	2.0 – 2.2 / A80 – K0	1.7 – 1.9 / A100 – K0
Mg(OH) ₂ – 2 %	1.9 – 2.1 / A90 – K10	1.8 – 2.0 / A100 – K0
Al(OH) ₃ – 0.5 %	1.6 – 1.8 / A100 – K0	1.7 – 1.9 / A100 – K0
Al(OH) ₃ – 1 %	1.7 – 1.9 / A100 – K0	1.6 – 1.8 / A90 – K10
Al(OH) ₃ – 2 %	1.5 – 1.7 / A100 – K0	1.7 – 1.9 / A100 – K0

Table 2. Chemical resistance of nanostructured coatings based on enamel AC-182 when exposed to herbicides

Additive type	Before testing			After testing		
	Weight, g	Hardness	A micrograph specimen (X230)	Weight, g	Hardness	A micrograph specimen (X230)
1	2	3	4	5	6	7
No additives	2.173	HB		2.159	B	
CNTs – 0.01 %	2.104	H		2.104	H	
CNTs – 0.05 %	2.063	H		2.063	H	

Continuation of Table 2

1	2	3	4	5	6	7
CNTs – 0.1 %	2.116	2H		2.115	2H	
Mg(OH) ₂ – 0.5 %	2.169	H		2.162	H	
Mg(OH) ₂ – 1 %	2.189	H		2.186	HB	
Mg(OH) ₂ – 2 %	2.113	H		2.108	HB	
Al(OH) ₃ – 0.5 %	2.150	2H		2.143	2H	
Al(OH) ₃ – 1 %	2.138	2H		2.136	2H	
Al(OH) ₃ – 2 %	2.127	3H		2.120	2H	

Continuation of Table 2

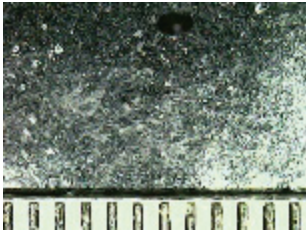
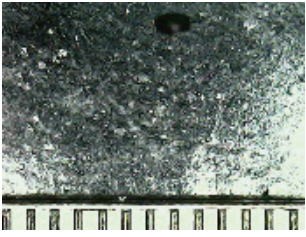
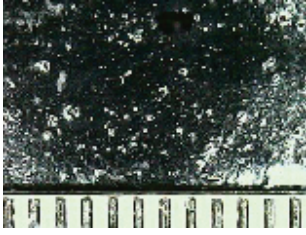

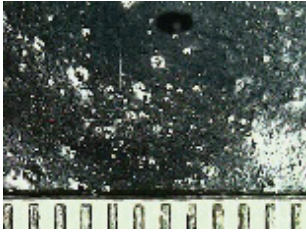
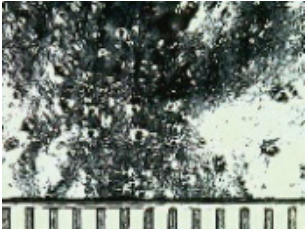
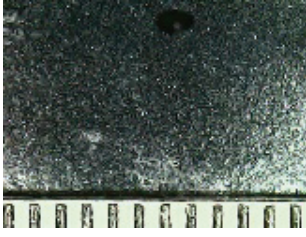
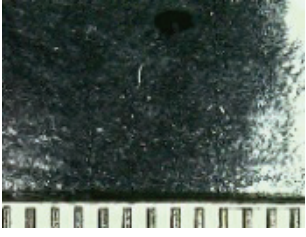
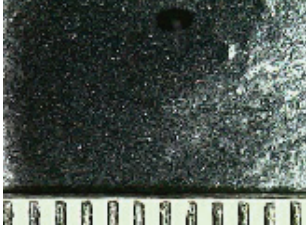
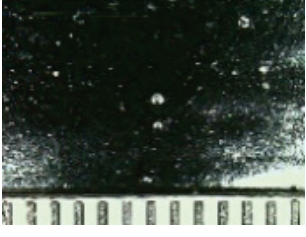
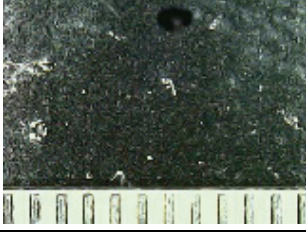
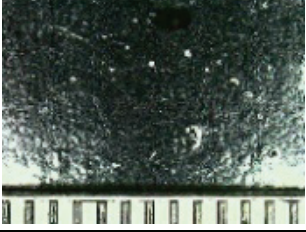
1	2	3	4	5	6	7
SiO ₂ – 0.5 %	2.084	H		2.080	H	
SiO ₂ – 1 %	2.126	2H		2.120	H	
SiO ₂ – 2 %	2.160	2H		2.151	H	
BO – 0.5 %	2.191	2H		2.190	H	
BO – 1 %	2.166	2H		2.166	H	
BO – 2 %	2.132	2H		2.132	H	

Table 2 presents data on chemical resistance of paint coatings with different additives before and after exposure to herbicide. The results of data analysis revealed that the mass of the specimen without additives decreased by 0.014 g, also the coating became softer, as evidenced by the change in hardness from HB to B. Nanostructured paint

coatings with carbon nanotubes retain mass according to the test results, and regardless of the concentration of the additive.
At the same time the hardness of such coatings does not change (H), which indicates high chemical stability of CNTs nanostructured coating. Also modification of the paint material with bismuth oxide

nanoparticles leads to chemically stable coatings, as evidenced by the mass retention of the specimens and insignificant change in their hardness from 2H to H.

According to the results of studies of the equilibrium swelling rate (Tables 3, 4, Fig. 1), it was also determined that the paint coating modified with

bismuth oxide nanoparticles and carbon nanotubes has resistance to solvents, and also acquires a more reticulated structure in relation to coatings without additives, which also depends on the amount of introduced additives.

Table 3. Results of tests of nanostructured coatings by the swelling method. Part 1

Specimen	Soaking time of specimens in solvent, min	Change in specimen weight, g	Change in specimen thickness, mm
No additives	0	0.47	1.13
	20	0.57	1.21
	40	0.60	1.23
	60	0.63	1.23
	80	0.63	1.24
CNTs 0,05 %	0	0.45	1.03
	20	0.55	1.12
	40	0.59	1.17
	60	0.60	1.17
	80	0.60	1.17
CNTs 0,1 %	0	0.51	1.23
	20	0.62	1.30
	40	0.67	1.33
	60	0.69	1.35
	80	0.69	1.35
TiO ₂ 0.5 %	0	0.59	1.33
	20	0.70	1.40
	40	0.78	1.45
	60	0.80	1.47
	80	0.81	1.47
TiO ₂ 1 %	0	0.63	1.56
	20	0.69	1.64
	40	0.77	1.66
	60	0.79	1.75
	80	0.81	1.81
BO 0.5 %	0	0.64	1.46
	20	0.74	1.535
	40	0.79	1.615
	60	0.82	1.72
	80	0.84	1.72
BO 1 %	0	0.42	1.0
	20	0.5	1.03
	40	0.53	1.07
	60	0.54	1.1
	80	0.56	1.1

Table 4. Results of tests of nanostructured coatings by the swelling method. Part 2

Specimen	Soaking time of specimens in solvent, min	Change in specimen length, mm	Change in specimen width, mm	Volume equilibrium swelling rate (α)
No additives	0	26.30	9.65	0.27
	20	27.05	9.90	
	40	27.60	10.20	
	60	27.80	10.35	
	80	28.20	10.40	
CNTs 0.05 %	0	26.70	9.55	0.22
	20	27.30	9.80	
	40	27.90	10.50	
	60	27.90	10.50	
	80	27.90	10.50	
CNTs 0.1 %	0	26.50	9.68	0.21
	20	27.40	9.77	
	40	27.50	10.20	
	60	27.50	10.30	
	80	27.50	10.30	
TiO ₂ 0.5 %	0	26.30	9.83	0.27
	20	26.60	10.25	
	40	27.65	10.55	
	60	27.70	10.80	
	80	27.70	10.80	
TiO ₂ 1 %	0	26.60	9.58	0.29
	20	27.50	9.64	
	40	28.20	9.81	
	60	28.30	10.00	
	80	28.50	10.00	
BO 0.5 %	0	26.55	10.10	0.24
	20	27.45	10.30	
	40	27.70	10.45	
	60	27.80	10.60	
	80	28.00	10.60	
BO 1 %	0	26.70	10.18	0.24
	20	26,8	10,82	
	40	27,00	11,00	
	60	27,6	11,05	
	80	27,6	11,15	

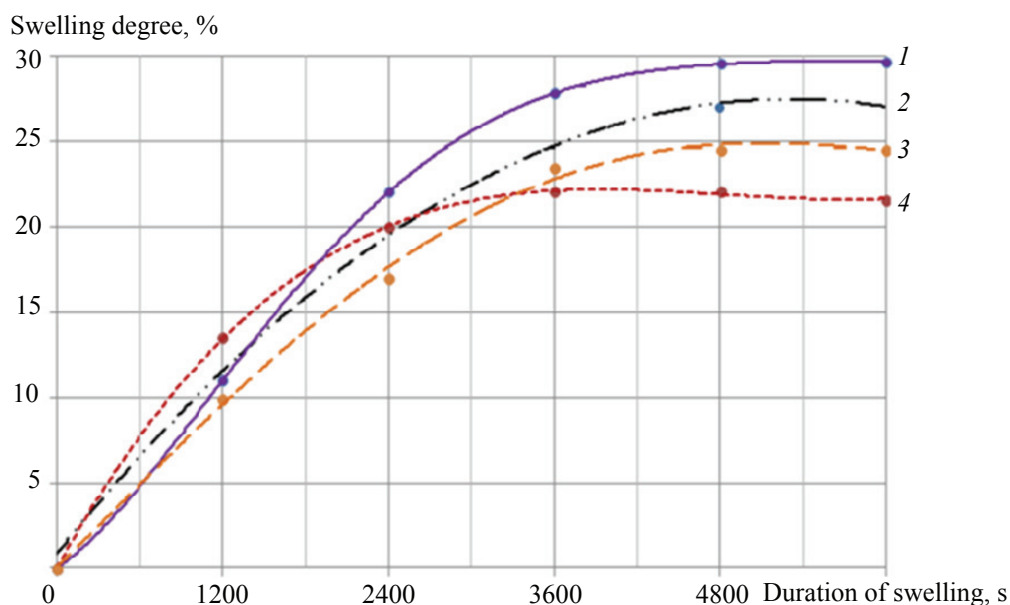


Fig. 1. The degree of swelling of modified acrylic protective coatings, depending on the duration of swelling:
 1 – modification TiO_2 1 %; 2 – without modifier; 3 – Bi_2O_3 1 % modification; 4 – CNTs modification 0.1 %

When bismuth oxide was added to the enamel, the meshiness of the coating increased, as indicated by the volume equilibrium swelling rate, which decreased from 0.27 to 0.24 at 0.5 and 1 % additives.

A more significant effect on the formation of dense molecular bonds was exerted by adding CNTs into the composition, and the index of the volume equilibrium swelling rate decreased from 0.27 to 0.22 at 0.05 % CNTs and to 0.21 at 0.1 % CNTs in the enamel composition.

The results of studies on the example of modifiers introduction into the paint material showed that nanomodification leads to the formation of denser mesh structures of coatings, which explain the increase in their physical and mechanical properties (adhesion strength, hardness, etc.) (Tables 1, 2) [3, 18, 19].

Scanning of various surface areas of specimens of nanostructured paint coatings, before chemical action on them, on the atomic force microscope showed that the surface becomes smoother nanometer roughness decreases from 50–60 nm (Fig. 2a) to 20–30 nm (Figs. 2b, c) when modified with bismuth oxide and carbon nanotubes. Moreover, a more significant reduction of protrusions is observed in CNT-modified coatings.

At the same time, at the joint introduction of bismuth oxide nanoparticles and carbon nanotubes, the number and size of protrusions are minimized and the R_a parameter decreases to 10–15 nm (Fig. 2d), which indicates a strengthening effect of the joint introduction and, consequently, hardening of the

coating by reducing the size of depressions and pores [3].

Thus, microstructural analysis allowed us to prove the existence of the optimal content of nanoadditives to enhance the quality parameters of protective paint coatings.

4. Conclusion

According to the results of this study it was found that by using nanoscale materials it is possible to produce effective nanostructured protective coatings capable of reliably protecting metal surfaces operating in a variety of aggressive chemical environments. It is most effective to apply nanostructured coatings when adding CNT-based compositions and bismuth oxide nanoparticles. It is more preferable to use acrylic paint materials to obtain chemoresistant nanostructured protective coatings. Thus, adding CNTs and bismuth oxide, the resulting coating has high adhesive strength (more than 3 MPa at cohesive detachment character up to 50% and higher), and also increased chemical resistance that is expressed in decrease of coating equilibrium swelling rate (from 0.27 to 0.21), preservation of specimen weight and its hardness (2H–H) caused by chemical media exposure. The increase in chemical resistance of such coatings is justified by the fact that they have a more hardened mesh structure with a minimum size of recesses and micropores in the surface.

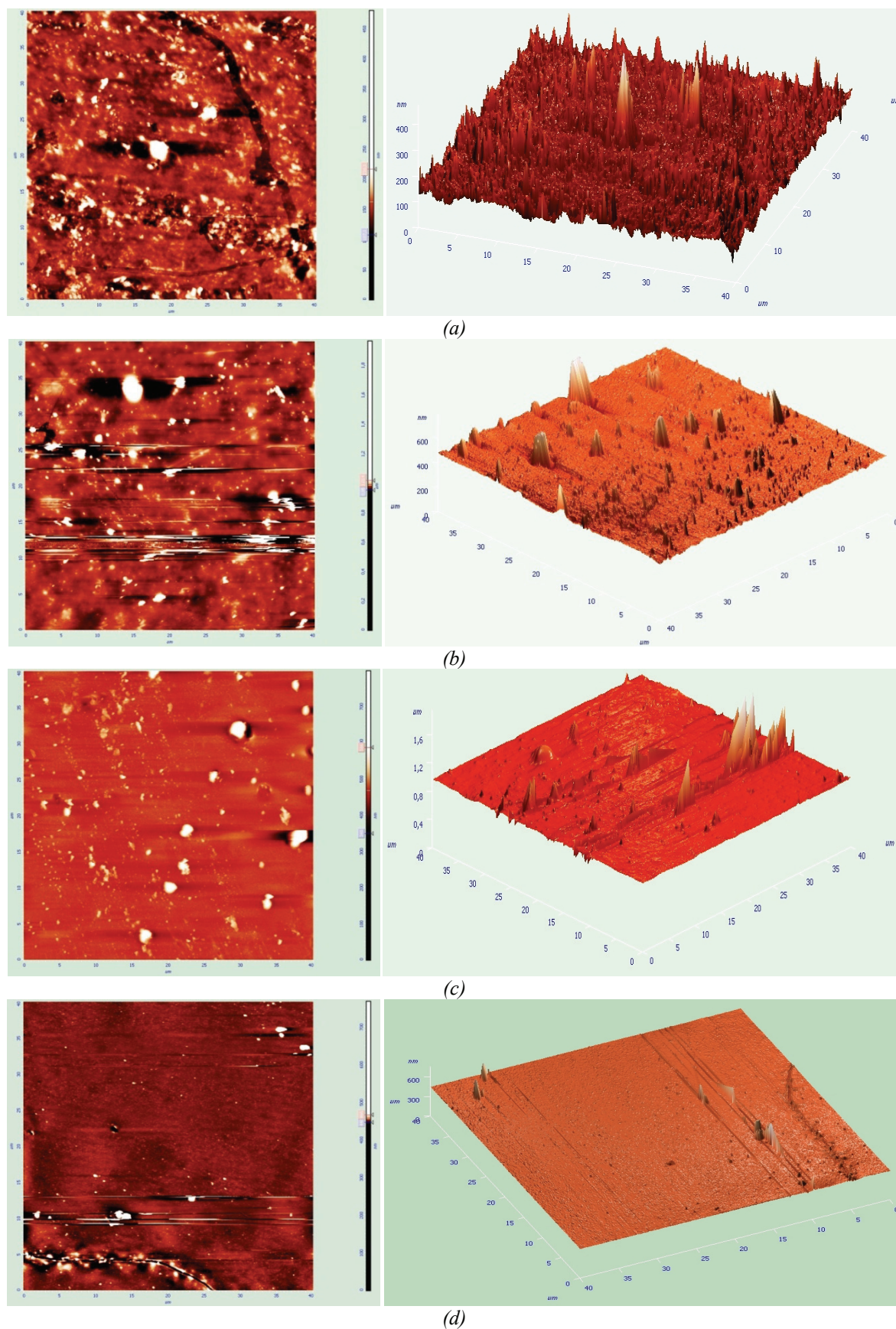


Fig. 2. AFM-images of nanomodified coatings:
a – without additives, *b* – BO 1 %, *c* – composition with CNTs 0.1 %, *d* – BO 1 % + composition with CNTs 0.1 %

5. Supplementary Material

A number of the data presented in this study are openly available at [https://gos_att.bstu.ru/shared/attachments/272578].

6. Funding

This study did not receive external funding.

7. Conflict of interest

The authors declare no conflict of interest.

References

1. Shneiderova VV, Migaeva GS, Kirillova TA, Kolesnikova PYu, et al. *Guidelines for the protection of building metal structures operating in aggressive environments and various climatic conditions*. Moscow: Stroyizdat; 1974. 207 p. (In Russ.)
2. Leviev LV, Prokopchuk NR. Anti-corrosion coatings with increased chemical resistance. *Trudy BGTU. No. 4. Khimiya, tekhnologiya organicheskikh veshchestv i biotekhnologiya*. 2015;4(177):134-138. (In Russ.)
3. Pichugin AP, Pchel'nikov AV, Khritankov VF, Tulyaganov AK. Evaluation of the efficiency of using nanoadditives in protective coatings. *Stroitel'nye Materialy*. 2023;3:20-26. DOI:10.31659/0585-430X-2023-811-3-20-26 (In Russ.)
4. Stolyarov RA, Memetova AE, Yagubov VS, Tkachev AG, et al. Conductive organic silicon materials and coatings containing multilayer carbon nanotubes. *Vestnik Tambovskogo gosudarstvennogo tekhnicheskogo universiteta*. 2022;28(1):153-161. DOI:10.17277/vestnik.2022.01.pp.153-161 (In Russ.)
5. Nelyubova VV, Kuzmin EO, Strokova VV. Structure and properties of nanodispersed silica synthesized by the sol-gel method. *Stroitel'nye Materialy*. 2022;12:38-44. DOI:10.31659/0585-430X-2022-809-12-38-44 (In Russ.)
6. Grebnov VS, Grebnova AB, Zubkov EM, Danilov YP. Influence of external influences on metal structural elements. *Promyshlennye i stroitel'nye tekhnologii*. 2016;7(9):11. (In Russ.)
7. Loganina VI. Evaluation of the probability of cracking of paint and varnish coatings under the influence of climatic factors. *Izvestiya vysshikh uchebnykh zavedeniy. Stroitel'stvo*. 2022;766(10):31-36. DOI:10.32683/0536-1052-2022-766-10-31-36 (In Russ.)
8. Vance ME, Kuiken T, Vejerano EP, McGinnis SP, et al. Nanotechnology in the real world: redeveloping the nanomaterial consumer products inventory. *Beilstein Journal of Nanotechnology*. 2015;6(1):1769-1780. DOI:10.3762/bjnano.6.181
9. Erofeev VT, Ivlev VI, Sigachyov AF, Fomin NE, et al. Mechanical properties of epoxy resin with additives soot and nanotubes. *Materials Physics and Mechanics*. 2021;47(1):20-30. DOI:10.18149/MPM.4712021_2
10. Fischer JE. Carbon nanotubes: a nanostructured material for energy storage. *Chemical Innovation*. 2000;30(9):21.
11. Ma PC, Siddiqui NA, Marom G, Kim JK. Dispersion and functionalization of carbon nanotubes for polymer-based nanocomposites: a review. *Composites Part A: Applied Science and Manufacturing*. 2010;41(10):1345-1367. DOI:10.1016/j.compositesa.2010.07.003
12. Nizina TA, Balykov AV, Korovkin DV, Volodin VG. Optimization of compositions of cement fiber fine-grained concretes containing carbon nanomodifiers. *Nanoindustriya*. 2017;7(78):82-91. DOI:10.22184/1993-8578.2017.78.7.82.91 (In Russ.)
13. Khozin VG, Nizamov RK, Abdrakhmanova LA. Modification of construction polymers (polyvinyl chloride and epoxy) with single-walled carbon nanotubes. *Stroitel'nye Materialy*. 2017;(1-2):55-61. (In Russ.)
14. Kozhukhova NI, Strokova VV, Chizhov RV, Kozhukhova MI. Methodology for assessing the reactivity of acidic aluminosilicates with a nanocrystalline structure. *Stroitel'nye materialy i izdeliya*. 2019;2(3):5-11. (In Russ.)
15. Lygdenov VT, Nomoev AV, Syzrantsev VV. Influence of nanodispersed silicon dioxide powder of the Tarkosil T-20 brand on the strength characteristics of the paint and varnish coating made of HV-16 enamel. *Vestnik Buryatskogo gosudarstvennogo universiteta. Khimiya. Fizika*. 2019;(2-3):7-11. DOI:10.18101/2306-2363-2019-2-3-7-11 (In Russ.)
16. Loganina VI, Sergeeva KA. Assessment of superhydrophobic properties of coatings on acrylic resin basis. *Regional'naya arkhitektura i stroitel'stvo*. 2020;1(42):98-103. (In Russ.)
17. Loganina VI, Svetalkina MA, Ariskin MV. Evaluation of the stress state of paint coatings depending on their surface roughness. *Izvestiya vysshikh uchebnykh zavedeniy. Stroitel'stvo*. 2023;2(770):36-43. DOI:10.32683/0536-1052-2023-770-2-36-43 (In Russ.)
18. Pichugin AP, Khritankov VF, Pchel'nikov AV, Romashev DV. Protective properties of compositions with nanoscale and special additives from radiation impacts. *Izvestiya vysshikh uchebnykh zavedeniy. Stroitel'stvo*. 2021;12(756):24-33. DOI:10.32683/0536-1052-2021-756-12-24-33 (In Russ.)
19. Pchel'nikov AV, Pichugin AP, Khritankov VF, Ilyasov AP. The effect of nano-additives on increasing the adhesive strength of protective coatings to steel structures and equipment. *Izvestiya vysshikh uchebnykh zavedeniy. Stroitel'stvo*. 2021;7(751):103-113. DOI:10.32683/0536-1052-2021-751-7-103-113 (In Russ.)
20. Kuleznev VN, Shershnev VA. *Chemistry and physics of polymers*. Moscow: Vyshaya shkola; 1988. 312 p. (In Russ.)

Information about the authors / Информация об авторах

Alexander V. Pchel'nikov, D. Sc. (Eng.), Associate Professor, Head of the Department, Novosibirsk State Agricultural University (NSAU), Novosibirsk, Russian Federation; ORCID 0000-0001-6138-5272; e-mail: pchelaleksandr@mail.ru

Anatoly P. Pichugin, D. Sc. (Eng.), Professor, Chief Researcher, NSAU, Novosibirsk, Russian Federation; Scopus ID 57213826487; e-mail: gmunsau@mail.ru

Пчельников Александр Владимирович, доктор технических наук, доцент, заведующий кафедрой, Новосибирский государственный аграрный университет (НГАУ), Новосибирск, Российская Федерация; ORCID 0000-0001-6138-5272; e-mail: pchelaleksandr@mail.ru

Пичугин Анатолий Петрович, доктор технических наук, профессор, главный научный сотрудник, НГАУ, Новосибирск, Российская Федерация; Scopus ID 57213826487; e-mail: gmunsau@mail.ru

Received 10 January 2025; Revised 25 February 2025; Accepted 03 March 2025



Copyright: © Pchel'nikov AV, Pichugin AP, 2025. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).
