Protective properties of PEO coatings modified by corrosion inhibitors on aluminum alloys

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Abstract

The protective properties of PEO coatings on aluminum alloys belonging to various alloying systems (Al–Mg, Al–Mg–Cu–Zn, Al–Mn) in chloride media were studied. Coatings with varoius thickness (8–40 µm) was obtained by oxidation of flat samples in borate, silicate and borate–phosphate–tungstate electrolytes. It was shown that coatings on aluminum alloys doped with manganese or magnesium (3003 and 5083) have a slightly higher resistance to pitting corrosion in chloride environments compared to copper-based alloys 2024 and 7075. According to polarization studies and corrosion tests, filling of the coatings studied with IFKHAN-25 and IFKHAN-39 corrosion inhibitors increases by more than an order the time of protection of the specimens made of various types of aluminum alloys. It was observed that chemical sorption of corrosion inhibitors is the determining factor in increasing the protective ability of PEO coatings in the entire range of thicknesses. Hydrophobization of coatings filled with corrosion inhibitors increases their corrosion resistance in chloride environments to an even greater extent.

Key words: aluminum alloys, PEO coating, corrosion inhibitors, filling of coatings.

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1. Introduction

Plasma electrolytic oxidation (PEO) is widely used for the formation of protective coatings on valve metals [1-3]. The functional properties of these coatings are determined by the composition of the electrolytes and the mode of oxidation [3-6]. However, a characteristic feature of PEO coatings is their high porosity in comparison with traditional anodic films on aluminum alloys. For example, coatings obtained in silicate electrolytes and widely used in practice and in laboratory studies are characterized by 2-15% porosity. The porosity of the inner and outer layers of a coating depends on its thickness and on the concentrations of the electrolyte components [7-9]. Attempts were made to reduce the negative impact of this factor on the protective properties of PEO coatings by tuning the oxidation conditions [10] or by modification of oxide layers with various oxides, nanocarbon, or highly dispersed Teflon [11–13]. However, on the one hand, the defects (porosity) of coatings produced by PEO can be the reason for their low corrosion resistance in corrosive environments, and on the other hand, the porous structure is a substrate having an adsorption ability. For example, it was shown that if conversion coatings were produced on aluminum alloys by chemical oxidation and filled with corrosion inhibitors, the latter played a considerable role in improvement of the protective properties [14–16]. A similar approach was also implemented to enhance the protective ability of PEO coatings produced on aluminum alloys in borate–phosphate–tungstate electrolytes [17, 18]. The present work summarizes the results of our earlier research on the effect of filling with corrosion inhibitors and a hydrophobic agent on the protective properties of PEO coatings with various thicknesses, compositions and structures, formed in some aqueous electrolytes on aluminum alloys.

2. Materials and methods

2.1. Sample preparation, composition of electrolytes, coating formation

Coatings were obtained on flat samples (50×50 mm) of aluminum alloys 5083 (AMg5), 2024 (D16), 7075 (V95) and 3003 (AMtsM). Before coating the samples, they were chemically polished in a mixture of concentrated acids, H_3PO_4 : H_2SO_4 : $HNO_3 = 4:2:1$, at 90–100°C, washed with running cold water, and rinsed with distilled water. Coatings were formed in the following electrolytes:

(No. 1) 50 g/l Na₃PO₄·12H₂O + 26 g/l Na₂B₄O₇·10H₂O + 4 g/l Na₂WO₄·2H₂O [19]; (No. 2) 7.1 g/l Na₂SiO₄·5H₂O + 3.6–5 g/l KOH [20]; (No. 3) 20 g/l K₂B₄O₇·4H₂O [21].

The coating were obtained in anodic–cathodic polarization mode: the effective density of anodic and cathodic currents was 5–15 A/cm²; the duration of the anodic and cathodic pulses was $t_A = t_C = 0.02$ s; the treatment was carried out for to 10–90 min. A stainless steel bath served as the cathode. The electrolyte was stirred with a mechanical stirrer; the solution temperature during the PEO treatment did not exceed 30°C. After oxidation, the samples with coatings were washed with running water, rinsed with distilled water and dried in air.

The coatings were formed using a computer-controlled multi-functional current source created on the basis of a commercial reverse thyristor unit "TER-4/460H-2-2UHL4" (Russia).

2.2. PEO coating characterization, corrosion and electrochemical tests methods

The thickness of the coatings formed was evaluated using a "VT-201" thickness gauge (Russia). The measurement results are shown in Table 1.

Aluminum alloy	Electrolyte	Thickness, µm
3003		24.6±2.0
2024	No. 1	8.3 ± 1.7
7075		$9.9 {\pm} 1.0$
5083		12.3 ± 3.5
5083	No. 2	13±2
2024		13 ± 2

Table 1. Thickness of coatings on aluminum alloys.

Note: electrolyte No. 1 – coatings were formed at i = 5 A/dm² and t = 10 min; electrolyte No. 2 – coatings were formed at i = 15 A/dm² and t = 20 min for 5083 aluminum alloy and t = 25 min for 2024 aluminum alloy.

The chemical composition of the coatings and the micrographs their surfaces and cross-section images were studied by X-ray microanalysis (CAMEBAX) equipped with a scanning electron microscope (SEM). The energy of the electron beam was 15 keV, the size of the analyzed spot on the sample was $50 \times 50 \ \mu\text{m}^2$, and the surface analysis depth was 1 μ m.

The coatings were filled by immersion of samples for 1 h into a solution containing corrosion inhibitors and distilled water (95–100°C). Hydrophobization of the coatings was achieved by dipping into a solution of low molecular weight polytetrafluorethylene (PTFE) followed by drying for one day at 80°C.

Anodic polarizing curves of alloys with a PEO coating (working area 0.5 cm²) were recorded in a standard thermostatically controlled electrochemical cell at $t = 20\pm2^{\circ}$ C in a borate buffer solution (pH 7.36) containing 0.01 M NaCl. Pyrographite was used as the auxiliary electrode, and the potential of the working electrode was measured relative to a saturated Ag/AgCl electrode with subsequent recalculation to the normal hydrogen electrode scale. Polarization of the electrode (1 mV/s) was usually started from the free corrosion potential (E_c) after its exposure for 20–30 min in the solution being studied.

The corrosion currents of the specimens (working area 6 cm²) were measured at $t = 50\pm2^{\circ}$ C in 5% NaCl solution with addition of 0.2 g/l CuCl₂ acidified with acetic acid to pH 3.1 (ASTM B368, ASTM B538). Two samples were placed in a thermostatic cell parallel to each other at a distance of 1 cm. The back side of each sample and the current leads were insulated with a waterproof lacquer. The instantaneous corrosion rate (i_{cor}) was measured with an Expert-004 corrosion meter using the two-electrode scheme [17]. The comparative protective ability of coatings was judged from the time of a sharp rise in corrosion current on the "corrosion current–time" plots.

The corrosion tests of samples of alloys with the coatings of interest were performed by immersing them in 3% NaCl with addition of 0.1% H₂O₂. During the tests, daily inspections of the samples were carried out and the time of appearance of the first corrosion damage was recorded.

3. Experimental results and discussion

3.1. The choice of electrolytes for PEO

It was of interest to obtain data for PEO coatings formed in electrolytes that are used in laboratory practice or serve as a basis for semi-industrial or industrial technologies. In view of this, we studied the PEO coatings formed in a phosphate-borate-tungstate electrolyte (PBW, No. 1) [19, 22]. In these electrolytes, it is possible to create both protective/decorative coatings and coatings with catalytic [23] or magnetic properties [24] on aluminum and titanium alloys. These coatings find application in industrial practice [2]. Silicate-alkaline electrolytes (No. 2) are widely used in laboratory studies, and a number of industrial and semi-industrial technologies have been developed using these electrolytes [3, 25–27]. The borate electrolyte allows wear-resistant coatings to be formed on aluminum alloys [21, 22, 28, 29]. They are also used as a base for a number of functional coatings, for example, catalytically active ones [30] or coatings with indicator properties [31].

3.2. Coatings formed in the phosphate–borate–tungstate electrolyte

The corrosion potentials in chloride solution of 3003 alloy without and with PEO coatings obtained in electrolyte No. 1 are close to each other and range from -0.4 to -0.35 V. As one can see from the polarization curves (Figure 1), the potential of local anodic activation $(E_{\rm pt})$ of a sample of this alloy with a coating is only 0.2 V higher compared with an uncoated sample. Apparently, the protective effect of the coating is so small due to its high porosity, including through porosity. The latter assumption is supported by the fact that the $E_{\rm pt}$ of a sample with a coating filled in pure distilled water decreases to the level of 3003 alloy without a coating. Yet another reason for the lack of effect of increasing the protective ability of coatings with their filling in hot water, unlike conversion coatings obtained by chemical oxidation [14–16] or traditional anodizing [32], apparently lies in the structure of aluminum oxides, which are hydrated poorly and thus do not seal the oxide layer.

However, the situation with filling PEO coatings on 3003 alloy changes dramatically upon addition of the IFKhAN-25 corrosion inhibitor to the filling solution [33, 34]. Thus, E_{pt} of the coating filled with this inhibitor increases to 0.8 V and its passivity domain reaches 1.4 V (Figure 1). Such an increase in the resistance to local anodic activation of the coating in chloride media is caused by adsorption of the inhibitor on it, as confirmed by the data of X-ray microanalysis of the surfaces of the filled and original coatings (Table 2). As one can see in the photomicrographs of these coatings, their structure and porosity almost do not change after the filling, however, the elemental composition of the coating includes carbon, indicating the presence of adsorbed organic inhibitor on the coating surface and in the pores.



Figure 1. Anodic polarization curves of 3003 alloy in 0.01 M NaCl (pH 7.4) without (1) and with PEO coating (2), and with subsequent filling of PEO in water (3) and in the IFHAN-25 solution (4). Coatings were formed at i = 5 A/dm² and t = 10 min.

The surface morphologies of the same coatings on 2024 and 7075 alloys (Table 2) differs markedly from that of the 3003 alloy. Probably, there is no through porosity in them, while the aluminum oxides forming the basis of the coating can undergo hydration during the filling in pure distilled water, that provides a significant effect of increasing E_{pt} in chloride solution (Figures 2 and 3). Filling the coating on 7075 alloy in solutions with IFKhAN-25 or IFKhAN-39 inhibitors [33, 34] increases their resistance to local anodic activation in this environment to an even greater extent. The effects of increasing E_{pt} of the coatings on 2024 alloy in pure water and in solutions of inhibitors are less significant in comparison with the 7075 alloy, which is probably due to the different structure and hence adsorption ability of these heterooxide layers. This is confirmed by the results of X-ray microanalysis of the coatings on 2024 alloy contains less carbon which indicates the adsorption of organic inhibitor in comparison with the coatings on 7075 alloy (Table 2).

Aluminum alloy	Filling solution	Photomicrographs of surface	Content of main elements in coating, %wt*.
3003	Without filling	Алгси <u>1880</u> _ 40 µm _ 1	P 2.7; Mn 0.4; W 1.8; Na 0.4; Al 49.0
5005	IFHAN-25	ΑΜCINES 3:800	P 2.4; Mn 0.4; W 2.3; Na 0.4; Al 45.2; C 3.3
2024	Without filling	D16 x800	P 5.9; Mn 0.3; W 2.9; Na 0.7; Al 36.7
2024	IFHAN-25		P 5.5; Mn 0.4; W 3.0; Na 1.1; Al 42.9; C 13.5

Table 2. Photomicrographs of the surfaces ($\times 800$) and elemental composition of coatings formed in electrolyte No. 1.

Aluminum alloy	Filling solution	Photomicrographs of surface	Content of main elements in coating, %wt*.
	IFHAN-39	С16-39 x800 р 40 µm 1	P 4.2; Mn 0.3; W 2.8; Na 0.5; Al 37.9; C 11.8
	Without filling		P 5.9; W 3.9; Na 0.7; Al 42.5
7075	IFHAN-25	E35-25 x800 μ 40 μm	P 4.7; W 2.3; Na 1.4; Al 24.5; C 27.7
	IFHAN-39	Б95-39 x800 — 40 µm	P 5.4; W 3.4; Na 0.9; Al 29.8; C 18.8

Aluminum alloy	Filling solution	Photomicrographs of surface	Content of main elements in coating, %wt*.
5092	Without filling	AlfG x800 μ 40 μm	P 4.4; Mg 0.5; W 2.9; Na 0.6; Al 39.9
3083	IFHAN-25	АМЗ-25 x800 1 40 µт — 1	P 2.6; Mg 0.4; W 1.8; Na 0.4; Al 33.4; C 21.6

*The rest is oxygen. Coatings were formed at $i = 5 \text{ A/dm}^2$ and t = 10 min.



Figure 2. Anodic polarization curves of 2024 alloy in 0.1 M NaCl (pH 7.4) with PEO (1) and with subsequent filling of PEO in water (2), in the IFHAN-25 solution (3) and in IFHAN-39 solution (4). Coatings were formed at i = 5 A/dm² and t = 10 min.



Figure 3. Anodic polarization curves of 7075 alloy in 0.1M NaCl (pH 7.4) with a PEO (1) and with subsequent filling of PEO in water (2), in the IFHAN-25 solution (3) and in IFHAN-39 solution (4). Coatings were formed at i = 5 A/dm² and t = 10 min.

The coatings formed on 5083 alloy are apparently the densest among all the alloys studied, so they are characterized by significantly higher E_{pt} values in the initial state (Figure 4). When filling this structure of the coating in pure distilled water, probably only its outer layer is condensed (hydrated), and this does not lead to a significant increase in E_{pt} , in contrast to coatings on 2024 and 7075 alloys. However, after adding the IFKhAN-25 or IFKhAN-39 inhibitors to the filling solution, the E_{pt} of samples with such coatings increases by 0.7 V and 0.5 V, respectively. In addition to the protective effect of the inhibitors, this effect is also achieved due to their surface active properties, contributing to the hydration of aluminum oxides, as shown by the change in the coating structure after filling (Table 2).

3.3. Coatings formed in the silicate–alkaline electrolyte

PEO coatings on 5083 and 2024 alloys obtained in silicate electrolyte (No. 2) have low electrical conductivity, therefore the method of their testing by means of polarization curves is not applicable in this case. However, it has been shown [35] that analysis of the plots of corrosion currents of samples with coatings on aluminum, filled with inhibitors, *versus* exposure time in test environments (of CASS and FACT types) allows for a comparative estimation of their protective properties.



Figure 4. Anodic polarization curves of 5083 alloy in 0.1 M NaCl (pH 7.4) with a PEO (1) and with subsequent filling of PEO in water (2), in IFHAN-25 solution (3) and in IFHAN-39 solution (4). Coatings were formed at i = 5 A/dm² and t = 10 min.

As can be seen from Figures 5 and 6, in the initial state the coatings quite rapidly lose their barrier properties upon immersion in the test solution. In fact, a sharp rise in corrosion current of a 5083 alloy sample with the initial coating occurs and, accordingly, the first pits are formed on the 5th minute of exposure to the solution, while in the case of a coating on 2024 alloy corrosion currents start to grow rapidly at the first minutes of the experiment and stabilize only at 102 μ A/cm². Treatment of coatings on 5083 alloy in solutions of IFKhAN-25 or IFKhAN-39 inhibitors suppresses pit formation, and a sharp jump of the corrosion rate is observed only after 40 minutes of exposure of samples to the solution. According to X-ray microanalysis, the increase in corrosion resistance of the coating is due to adsorption of the inhibitor (Table 3). However, the most effective protection is provided by additional treatment of the coating in a PTFE solution, which stabilizes the corrosion rate at the level of 17 μ A/cm² for the duration of the experiment (120 minutes), and only 2–3 pits are observed on the samples after the tests.

Treatment of the coating on 2024 alloy (Figure 5) in a solution of IFKhAN-25 inhibitor prevents the formation of corrosion damage for 15 minutes, while treatment in a solution of IFKhAN-39 inhibitor prevents it for 30 minutes. Apparently, the less efficient filling of the coatings on 2024 alloy is associated with reduced adsorption of the inhibitors in comparison with coatings on the 5083 alloy, as evidenced by the data of X-ray microanalysis (Table 3). Additional treatment of the inhibitor-filled oxide film in a PTFE solution allows the corrosion stability in the test solution to be increased up to 100 minutes, and it is only in the last 20 minutes of the experiment that pit embryos are formed on the coating.

Aluminum		Coating filled in IFHAN-25 solution			
alloy, electrolyte	filling	Surface	Outer edge of the polished section	Center of the polished section	Inner edge of the polished section
5083, electrolyte No. 3	O 47.7 Mg 2.7 Al 49.3	O 47.2 Mg 2.7 Al 47.2 C 2.9	O 34.6 Mg 2.1 Al 52.2 C 10.8 (point 1)	O 40.9 Mg 3.1 Al 44.0 C 12.1 (point 2)	O 40.4 Mg 1.9 A1 48.4 C 9.3 (point 3)
5083, electrolyte No. 2	O 44.6 Mg 2.3 Al 35.1 Si 18.0	O 45.6 Mg 2.0 A1 30.2 Si 13.2 C 8.9		■2 ■3	
2024, electrolyte No. 2	O 43.6 Al 33.5 Si 14.6	O 44.2 A1 32.5 Si 17.5 C 5.8	Photomicrograph coating formed	(×400) of a cross-pol on 5083 aluminum al IFHAN-25 solution	lished section of a loy and filled in

Table 3. Elemental composition of coatings formed in electrolytes No. 2 and No. 3.

Notes. Electrolyte No. 2 – coatings were formed at i=5 A/dm² and t=20 min for 5083 aluminum alloy and t=25 min for 2024 aluminum alloy. Electrolyte No. 3 – coatings were formed at i=15 A/dm² and t=90 min.



Figure 5. Instantaneous corrosion currents of 5083 alloy in 5% NaCl solution with addition of 0.2 g/l CuCl₂ and acetic acid to pH 3.1 with PEO (1) and with subsequent filling in: 2 – IFHAN-25 solution, 3 – IFHAN-39 solution, 4 – IFHAN-25 solution and application of PTFE layer, 5 – IFHAN-39 solution and application of PTFE layer. Coatings were formed in electrolyte No. 2 at i = 5 A/dm² and t = 20 min.



Figure 6. Instantaneous corrosion currents of 2024 alloy in 5% NaCl solution with addition of 0.2 g/l CuCl₂ and acetic acid to pH 3.1 with PEO (1) and with subsequent filling in: 2 – IFHAN-25 solution, 3 – IFHAN-39 solution, 4 – IFHAN-25 solution and application of PTFE layer, 5 – IFHAN-39 solution and application of PTFE layer. Coatings were formed in electrolyte No. 2 at i = 5 A/dm² and t = 25 min.

3.4. Coatings formed in borate electrolyte

The beneficial effect of filling with corrosion inhibitors was studied on PEO coating with fixed thickness. However, taking into account that as the oxide thickness increases during alloy oxidation, the oxide structure and surface morphology may change, it seemed expedient to study its effect on the protective properties of filled PEO coatings. For this purpose, coatings with thickness of $7-40 \mu m$ were obtained in borate electrolyte (No. 3) on 5083 alloy (Table 4). Coatings with various thicknesses were obtained by changing the time of PEO treatment.

Oxidation time, min	Thickness, μm
10	$7{\pm}0.6$
20	10 ± 1
40	30±1
60	35±1
90	$40{\pm}2$

Table 4. Thickness of coatings on 5083 aluminum alloy formed in electrolyte No. 3.

Note. Coatings were formed at $i = 15 \text{ A/dm}^2$.

As can be seen from Figure 7, the thinnest of the investigated coatings (7 µm) show nearly no protective properties. Even the initial corrosion current on it is $7 \,\mu A/cm^2$. Subsequently, the corrosion currents grow rapidly to reach $60-70 \,\mu\text{A/cm}^2$ during the first 30 minutes of the test in 5% NaCl solution with addition of 0.2 g/l CuCl₂, acidified with acetic acid to pH 3.1. During this time, numerous dark blue pits appear on coating surface that are contact-deposited copper, which confirms the breakdown of the oxide coating. Filling the coating in a solution of IFKhAN-25 corrosion inhibitor allows its protective properties in the test solution to be increased to 15 minutes. Subsequently, the corrosion currents increase to reach values of the non-filled background sample. Deposition of a hydrophobic PTFE layer on the coating surface contributes to a significant reduction in corrosion currents throughout the tests. They do not exceed $3 \,\mu \tilde{A}/cm^2$ in the first 60 minutes of exposure to the test solution, after which the corrosion currents slowly begin to increase. After 120 minutes of testing, 2-3 dark blue points of contact-deposited copper were observed on the surface of PTFE-treated samples. This suggests that a PTFE layer is insufficient for full protection of a PEO coating and coatings treated in this way would not withstand longer corrosion tests. Only filling in a solution of a corrosion inhibitor followed by treatment of the coating in a PTFE solution makes it possible to reduce the corrosion currents on samples to values within a few hundredth µA/cm². No contact-deposited copper was found after the testing period on such surfaces.



Figure 7. Instantaneous corrosion currents of 5083 alloy in 5% NaCl solution with addition of 0.2 g/l CuCl₂ and acetic acid to pH 3.1 with PEO (1) and subsequent filling in: 2 - IFHAN-25 solution, 3 - only application of a PTFE layer, <math>4 - IFHAN-25 solution and application of a PTFE layer. Coatings were formed in electrolyte No. 3 at $i = 15 \text{ A/dm}^2$ and t = 10 min.

Increasing the coating thickness up to 40 µm makes it possible to slightly increase the protective properties (Figure 8), namely, to 5 minutes in the case of 10 and 20 µm coatings and to 20 minutes for 35 and 40 µm coatings. In fact, the same effect can be achieved by filling the 7 µm coating in a solution of IFKhAN-25 inhibitor, which is economically more advantageous in comparison with the energy costs for growing an oxide film for 60-90 minutes. What is more, thicker coatings are still porous, as evidenced by the effect of the increase in their protective properties after filling in a solution of IFKhAN-25 inhibitor. As can be seen from Figure 9, the time till the appearance of the first sites of contact-deposited copper is: 20 minutes for a 10 µm coating, 25-30 minutes for 30 µm, 50 minutes for 35 µm, and 70 minutes for 40 µm. Apparently, a crucial role in the increase in protective properties of coatings is played by penetration of the inhibitor into the oxide film, rather than just its adsorption on the coating surface. However, like in the case of 7 µm coatings, the most complete protection in the test solution is achieved by joint treatment of the coatings in a solution of IFKhAN-25 inhibitor and PTFE (Figure 10). The level of corrosion currents for all the oxide films studied is almost the same and does not exceed $0.1 \,\mu\text{A/cm}^2$. As can be seen from the data of X-ray spectral microanalysis of a coating cross section after filling in an IFKhAN-25 solution (Table 3), the inhibitor is adsorbed both across the thickness of the coating and at the oxide-metal interface.



Figure 8. Instantaneous corrosion currents of 5083 alloy in 5% NaCl solution with addition of 0.2 g/l CuCl₂ and acetic acid to pH 3.1 with PEO coatings of different thickness: $1 - 7 \mu m$, $2 - 10 \mu m$, $3 - 30 \mu m$, $4 - 35 \mu m$, $5 - 40 \mu m$.



Figure 9. Instantaneous corrosion currents of 5083 alloy in 5% NaCl solution with addition of 0.2 g/l CuCl₂ and acetic acid to pH 3.1 with PEO coatings of different thickness and subsequent filling in IFHAN-25 solution: $I - 7 \mu m$, $2 - 10 \mu m$, $3 - 30 \mu m$, $4 - 35 \mu m$, $5 - 40 \mu m$.



Figure 10. Instantaneous corrosion currents of 5083 alloy in 5% NaCl solution with addition of 0.2 g/l CuCl₂ and acetic acid to pH 3.1 with PEO coatings of different thickness and subsequent filling in IFHAN-25 solution and application of a PTFE layer: $1 - 7 \mu m$, $2 - 10 \mu m$, $3 - 30 \mu m$, $4 - 35 \mu m$, $5 - 40 \mu m$.

3.5. The results of corrosion tests in 3% NaCl

In general, the results of corrosion tests of samples with the coatings being studied (3% NaCl + 0.1% H₂O₂) matched those of polarization measurements. The first corrosion damage in the form of pits on the surface of samples with the initial coatings obtained in electrolyte No. 1 was observed after 2 days of testing on 2024 and 7075 alloys and after 4– 5 days on 5083 and 3003 alloys. For the coatings filled with the solution of IFKhAN-25, the start of pit formation was delayed to 7–8 days on all the alloys, and an additional hydrophobization of the coating by PTFE (1–2 μ m) increased this time to 15–17 days. It should be noted that a similar hydrophobic treatment of the original coating without filling with the inhibitors did not lead to an increase in their protective properties, as the formation of small pits was observed after 2–4 day of testing. Filling the coatings in the IFKhAN-39 solution increased the time before pit formation on 2024 and 7075 alloys to 11 and 15 days, respectively.

In the case of the silicate electrolyte (No. 2), the first corrosion damage on the samples without treatment occurs on days 2 and 10 on 5083 and 2024 alloys, respectively. Filling the coatings in solutions of corrosion inhibitors increases their durability to 8 days for the 5083 alloy and to 14 days for the 2024 alloy. Additional hydrophobization of coatings filled in the solution of IFKhAN-25 inhibitor allows increasing their corrosion resistance to 18 days on the 2024 alloy and to 48 days on the 5083 alloy (Table 5).

Aluminum alloy, electrolyte	Filling solution	Time to appearance of the first corrosion defects, days
	Without filling	2
	IFKhAN-39	10
5083, electrolyte No. 3	IFKhAN-39 + PTFE layer	25
	IFKhAN-25	46
	IFKhAN-25 + PTFE layer	52
	Without filling	10
	IFKhAN-39	14
5083, electrolyte No. 2	IFKhAN-39 + PTFE layer	20
	IFKhAN-25	14
	IFKhAN-25 + PTFE layer	48
-	Without filling	2
	IFKhAN-39	8
2024, electrolyte No. 2	IFKhAN-39 + PTFE layer	8
	IFKhAN-25	8
	IFKhAN-25 + PTFE layer	18

Table 5. Results of corrosion tests.

Note. Electrolyte No. 2 – coatings were formed at i=5 A/dm² and t=20 min for 5083 aluminum alloy and t=25 min for 2024 aluminum alloy. Electrolyte No. 3 – coatings were formed at i=15 A/dm² and t=90 min.

The principal contribution of filling with corrosion inhibitors to the protective properties of PEO coatings can be demonstrated by the following example. Filling a sample with a coating thickness of 7 μ m in a solution of IFKhAN-25 inhibitor allows the time of the first appearance of pits on the specimen to be increased to 13 days, which is 2.5 times longer compared to the 40 μ m coating without treatment (Table 6).

Even higher durability under the corrosion test conditions is observed for the coatings treated jointly with IFKhAN-25 inhibitor and PTFE, namely, up to 42 days in the case of $30-40 \mu m$ coatings. We can assume that the effect of inhibitor "locking" within the coating operates here, and it starts to work after the protection of a PTFE film decreases.

Thickness, μm	Filling solution	Time to appearance of the first corrosion defects, days
	Without filling	2
_	IFKhAN-25	13
/	Only PTFE layer	5
	IFKhAN-25 + PTFE layer	25
	Without filling	2
10	IFKhAN-25	24
10	Only application of a PTFE layer	5
	IFKhAN-25 + PTFE layer	35
	Without filling	3
20	IFKhAN-25	27
30	Only application of a PTFE layer	8
	IFKhAN-25 + PTFE layer	42
	Without filling	5
35	IFKhAN-25	27
	Only application of a PTFE layer	8
	IFKhAN-25 + PTFE layer	42
	Without filling	5
40	IFKhAN-25	29
40	Only application of a PTFE layer	11
	IFKhAN-25 + PTFE layer	42

 Table 6. Results of corrosion tests.

Conclusions

- 1. In all the cases studied, filling of PEO coatings on aluminum alloys with IFKhAN-25 and IFKhAN-39 inhibitors effectively increases their protective ability.
- 2. Filling of the coatings with the corrosion inhibitor is a determining factor in increasing the protective ability in the entire range of coating thicknesses.
- 3. The greatest protective properties are observed for PEO coatings filled with a corrosion inhibitor solution followed by PTFE treatment. Hydrophobization of the original coatings without inhibitor filling leads to an insignificant increase in their protective properties.

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