COMMODITY BULLETIN
Journal homepage: https://c-bulletin.com.ua/en
DOI: 10.62763/cb/1.2026.09

Article's History: Received: 03.02.2026 Revised: 01.05.2026 Accepted: 28.05.2026 Published: 29.05.2026

ISSN 2310-5283; e-ISSN 3041-1432 Vol. 19, No. 1, 2026, 9-16

UDC 620.22:621.7(075.8)

Factors influencing the formation plasma electrolytic oxidation coatings synthesised on a titanium and zirconium alloys

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Abstract. The research presented in this article is relevant due to the need to improve prediction and control of oxide-ceramic coating formation on titanium and zirconium alloys used in aggressive and high-load environments. The aim was to investigate electrophysical regularities of coating formation during plasma electrolytic oxidation of titanium and zirconium alloys and the influence of electrolyte composition and current density on synthesis voltage. Methods included galvanostatic anodic and anodic-cathodic modes, time-resolved voltage and current recording, comparison of electrolytes expressed in grams per liter, and analysis of current-voltage dependences during coating synthesis. It was established that coating formation on zirconium alloy proceeded in two stages and was unstable at low electrolyte concentrations, while increased potassium hydroxide and liquid glass improved stability and uniformity. Titanium alloy demonstrated a more uniform synthesis process with lower voltage levels than zirconium alloy due to higher conductivity and more stable coating growth behaviour. Decreasing current density reduced anodic and cathodic voltage components, while additives such as chromium oxide, glycerin and hydrogen peroxide influenced stability and magnitude of synthesis voltage. Optimal conditions were identified at balanced current density ratios and moderate electrolyte concentrations, ensuring stable discharge behaviour and improved coating quality. Results can be used by materials engineers to optimise plasma electrolytic oxidation regimes for producing corrosion-resistant and mechanically stable coatings

Keywords: electrophysical parameters; synthesis voltage; current density; electrolyte; cathode; anode

Introduction

In technology, many types of metal functional elements prematurely lose their operability, especially if they operate in aggressive environments or under conditions of cavitation-erosion wear. Practically the only way to increase the reliability and durability of elements and devices is to strengthen their surface by applying corrosion and abrasion-resistant coatings. The development of new environmentally friendly technologies for applying protective coatings is certainly one of the important problems of materials science.

Scientists are constantly improving existing methods of surface hardening of metals in order to create new effective surfaces with increased performance characteristics. Thus K. Sarakinos *et al.* (2010) in their work

Suggested Citation:
Imbirovych, N., & Feshchuk, Yu. (2026). Factors influencing the formation plasma electrolytic oxidation coatings synthesised on a titanium and zirconium alloys. *Commodity Bulletin*, 19(1), 9-16 . doi: 10.62763/cb/1.2026.09.

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investigated a new method such as HIPIMS (high-power pulsed magnetron sputtering). The proposed method allows generating an ultra-dense plasma with unique properties, such as a high degree of ionisation of sputtered atoms and non-standard transfer of ionised particles relative to the target. However, this method allows creating coatings of small thickness, requires high accuracy to the surface and places high demands on its pre-treatment. Plasma electrolytic treatment belongs to relatively new methods of surface treatment of metals and allows the formation of multifunctional coatings with a wide range of properties. The development of new environmentally friendly technologies for applying highly effective and reliable coatings to protect and strengthen metal products is currently one of the most urgent tasks of modern science and technology due to the increasing severity of operating conditions. Scientists H. Bai *et al.* (2021), Y.X. Ou *et al.* (2023) have proven that coatings effectively improve the performance properties of metals. In their work, they investigate synthesised coatings on titanium alloys, which are modified with nanoparticles by introducing them into the electrolyte, and show that plasma electrolytic oxidation (PEO) is an effective method of modifying the surface of titanium alloys to improve corrosion properties, the effect of such modification on the roughness, adhesion, and thickness of the coatings.

Titanium and its alloys are of great interest for advanced engineering applications through to their excellent properties, such as a join high strength-to-weight ratio, corrosion resistance, biocompatibility, and others. The authors P. Canepa *et al.* (2020), with the aim of increasing the biocompatibility of titanium alloys, saturated their coatings with calcium and phosphorus. X. Han *et al.* (2023) in their work explain that surface modification is an important and determining factor for improving the biocompatibility of implants. They consider various surface modification methods that allow to increase the porosity of the surface. The main attention is paid to some of the most promising methods for modifying the surface of titanium implants: mechanical methods, such as acid etching and grinding, as well as coatings, such as hydrogen peroxide treatment using fluoride and chloride ions, hydroxyapatite, nitride, metal oxides and silver. Experimentally, it has been shown that these methods increase the biocompatible properties of titanium implants. Researchers X. Li *et al.* (2025) used a cost-effective mesh-shaped powder metallurgy method to produce a titanium-based alloy with high corrosion resistance. The titanium alloy Ti–24Nb–4Zr–8Sn (Ti2448) they developed has a low Young's modulus and high corrosion resistance, which is 3.5 times higher than that of the Ti–6Al–4V (Ti64) alloy, which is widely used in implantology and is characterised by high biocompatibility. In their work, E.S. Krishna *et al.* (2021) emphasise the importance of using titanium alloys in implantology due to their high biocompatible properties and describe the main directions in implantology where titanium alloys are used. These include total joint replacement, dental and maxillofacial implants. Composites exhibit hybrid properties and offer more flexibility to choose different composition to achieve desired properties in the end product. They emphasise in their work that adding ceramic additives to a composite titanium alloy can significantly increase its biocompatible properties and reduce the risks of rejection of such implants.

However, titanium is a highly chemically reactive element, and its corrosion resistance in various environments is ensured only by a thin natural oxide layer, which can be damaged under mechanical loading. As a result, the unprotected substrate is exposed to a corrosive/erosive environment, making it highly susceptible to premature failure. These properties of natural titanium oxide films have attracted the attention of scientists to the idea of applying protective coatings to the surface of such alloys. For example, A. Fattah-alhosseini & M. Molayei (2023) in their work investigated the properties of PEO coatings on a titanium alloy with a preliminary azure surface treatment. The authors investigated that such treatment leads to an improvement in the anti-corrosion, wear-resistant and biocompatible properties of titanium alloys. K. Kombayev *et al.* (2025) used the method of microplasma sputtering of tantalum coatings on a titanium alloy such as Grade 5. They found that the coatings created by this method allow the formation of coatings with high hardness, which is twice the hardness of the base, and has a fairly high thickness, which is 250 μm. Chemical vapor deposition (CVD) is also used to improve the characteristics of various metal surfaces, including titanium alloys. M. Molaei & A. Fattah-alhosseini *et al.* (2024) investigated the results of modifying plasma-electrolytic coatings on titanium alloy with ZrO_2 nanoparticles. The results of the conducted studies revealed improved corrosion and wear-resistant properties of the synthesised coatings. The authors found that the nanoparticles were included in the coating on the surface or in the pores. It was found that a higher content of zirconium oxide nanoparticles in the amount of 5 g/l improves the wear resistance of the coatings by 8%.

Zirconium and its alloys that have superior properties including biocompatibility, good corrosion resistance, chemical stability, high fracture toughness, high flexural strength and lower cytotoxicity are one of the best choices for dental and orthopedic implant materials. The authors N. Attarzadeh & C.V. Ramana (2021), investigated the growth processes of coatings and identified methods for controlling the properties of the surface layer. It was found that PEO coatings are formed in two stages, which the authors divided into pre-spark and spark regions. A. Fattah-alhosseini *et al.* (2021) in their article conducted a detailed review of clinical

and research conditions dedicated to zirconium alloys and PEO coatings based on them. Comparative analysis of the wetting angle, by which osseointegration is assessed, showed that zirconium alloys with PEO coatings are characterised by a lower wetting angle, which leads to the elimination of the possibility of capsule formation around the implant with such a coating and is positive for its rapid engraftment in the in vivo environment. The authors M. Molaei *et al.* (2021) found that the treatment of the synthesised coating containing ZrO_2 with UV radiation leads to an increase in biocompatibility. The implant coated with ZrO_2 together with bone is characterised by higher strength and higher ability to rapidly form new bone within 12 weeks due to the content of Ca-P compounds and porous structure. The authors note that the coatings have a high antibacterial effect.

However, it should be noted that the natural oxide films that are created on the surface of the valve metals under consideration are not characterised by a high thickness, which is several nanometers. In the works of D. Chopra *et al.* (2022) the problem of artificial modification of the surface of such alloys in order to create high-temperature ceramics, which are also distinguished by high mechanical properties, is presented. One of the promising and innovative methods for modifying the surface of valve metals has recently been considered the PEO method. In this work, a PEO method is developed to improve the surface properties of Ti and Zr alloys. Surfaces modified with PEO have the appearance of ceramic coatings, which are characterised by good functional properties, such as bioactivity or photocatalytic behaviour. In the works of N.Yu. Imbirovych *et al.* (2023), Z. Li *et al.* (2021) and other authors note the high corrosion-resistant and mechanical properties of the obtained coatings. The authors note that oxidation technologies improve the natural oxide layer formed on the surface of Ti and Zr. In general, the oxide layer on a titanium alloy consists of titanium dioxide, including anatase, rutile. Rutile is the most stable form of titanium dioxide. A coating is synthesised on a zirconium alloy, the basis of which consists of zirconium dioxide. The composition of the coating synthesised on the surfaces also includes electrolyte components, which also affect their properties.

A large number of publications on PEO in recent years demonstrate the relevance of this coating method and the constant progress of research both in the theoretical understanding of processes and in improving the technological foundations of coating formation. To date, many issues in this area remain unresolved, such as the influence of the material composition on the synthesis mechanism and properties of the obtained coatings, as well as the influence of the electrolyte composition, current density and synthesis time on the formation of coatings obtained by the plasma-electrolytic oxidation method. The resolution of these issues will accelerate the practical implementation of this technology to solve specific engineering problems.

Therefore, the task of this work was to establish the stages of the synthesis process of plasma-electrolytic coatings on zirconium and titanium alloys, to identify the main dependencies of the influence of the electrolyte composition on the change in the synthesis voltage and to establish the time parameters of the initial sparking stage, which is characterised by a rapid increase in voltage, which is explained by the breakdown of the natural protective barrier film on metals.

Materials and Methods

The development of anodising technology and research of anodic coating were carried out on plate samples made of zirconium and titanium alloys Zr-2.5%Nb and Grade 5 respectively. The studies presented in this work were conducted using the well-known method of recording voltage changes in the process of coating synthesis over time. Researchers such as M. Aliofkhazraei *et al.* (2021), K. Hurle *et al.* (2021), K. Kombayev *et al.* (2024) investigated the energy parameters of the coating process on zirconium and titanium alloys.

The formation of the anodic-spark coating was carried out in galvanostatic mode (anode and anode-cathode). The power supply provided an increase in the voltage amplitude for the anodic half-period to 800 V, and for the cathode to 400 V at the average values of the anodic (I_a) and cathodic (I_k) currents recorded in a certain process. The cathode was a stainless steel bath. The current density was 10-30 A/dm^2, and the ratio of the cathodic and anode currents varied in the range from 1 to 1.5. Using voltmeters and ammeters, the time dependence of the amplitude values of the anodic (U_a) and cathodic ($U_к$) voltages and current values was recorded.

PEO was carried out in different electrolytes, the composition of which was (g/l): KOH – 3; 2; 5; 10; liquid glass – 2; 5; 15; GrO_3 – 0.1; glycerin – 18; 10; H_2O_2 – 10. The electrolyte in which the coating was synthesised was mixed with air, which was supplied to the electrolyte bath. When studying the influence of the electrolyte composition, the latter was changed according to the experimental conditions. After the process was completed, the samples were washed with running and distilled water, dried and analysed. The Faraday section is an integral part of the process at the pre-spark stage, and its duration depends on the method of implementation of the process and the speed of voltage rise to the spark potential.

Results and Discussion

The electrical parameters of the synthesis of the oxide ceramic coating (OCC) are selected mainly experimentally, without proper theoretical justification. However, it is the current density and voltage that determine the nature and intensity of the discharges and the temperature conditions on the alloy surface, and affect the

functional characteristics of the formed coating. The formation of the OCC on a zirconium alloy occurs in two stages: in the first seconds, the anode voltage U_a increases by approximately 5...10 V (Fig. 1a, stage I), here the formation of the primary oxide film occurs by an electrochemical mechanism. The only reaction at the anode under a voltage of up to 100 V is the anodic growth of the oxide. In this case, the overvoltage of oxide formation is less than the decomposition voltage of the electrolyte. When it is reached, electrons are injected into the oxide layer, and oxygen begins to be released at the anode. Thus, the second stage of the formation of the spark discharge channel in the "metal - oxide - electrolyte" system begins. With a further increase in the voltage in the process of coating synthesis, a breakdown by electrons of this channel occurs.

During the synthesis of anodic-spark coating on zirconium alloy in galvanostatic mode, a slight increase in the anodic U_a and cathodic U_k voltages is observed with increasing KOH and liquid glass concentrations in the electrolyte (Fig. 1a, b). With increasing KOH and liquid glass concentrations (Fig. 1b, stage II), as well as in a more concentrated electrolyte (Fig. 1c, d, stage II), the coating formation process stabilises and proceeds evenly. Only with the addition of 10 g/l H_2O_2 at the coating formation stage does the voltage begin to gradually decrease (Fig. 1e, f, section II).

Reducing the current density lowers the anodic component of the synthesis voltage. The coating synthesised in an electrolyte of 3 g/l KOH + 2 g/l liquid glass at a current ratio of 20/20 A/dm^2 has an anodic voltage of 160...140 V (Fig. 1a, curve 1). If the current ratio is slightly reduced to 10/15 A/dm^2, the synthesis voltage decreases by 10...12 V (Fig. 1e, curve 2). At I_a/I_k = 10/10 A/dm^2, it is even lower by 8 V (Fig. 1a, curve 3), and the difference between curves 1 and 3 is 20...28 V.

For a higher concentration of KOH and insufficient glass up to 10 g/l and 15 g/l, respectively, the component anode voltages have values higher by 5...10 V. Adding even a small amount of GrO_3 (0,1 g/l) to such an electrolyte significantly reduces the formation of voltage at the anode. Under such conditions, it is 15...20 V lower (Fig. 1e, curves 1, 2). Increasing the electrolyte concentration by adding 10 g/l of glycerin to the already existing one has practically no effect on its value (Fig. 1d, curves 1, 2, 3). When adding 10 g/l of H_2O_2 to such an electrolyte, the process of coating formation does not proceed evenly (Fig. 1e, curve 1), the anode voltage is 140 V and drops to 125 V.

At a current ratio of I_a/I_c = 1, it is lower by 5 V. A higher glycerin content (18 g/l) increases the anodic and cathodic voltage components by approximately 10 V, and also stabilises the synthesis process on a zirconium alloy (Fig. 1f). Thus, the electrophysical parameters of the synthesis process of OCC on zirconium alloy depend on the composition of the electrolyte and the ratio of the anodic to cathodic current density. Thus, in the least concentrated electrolyte, which contains alkali and liquid glass, the synthesis proceeds unevenly, which affects the quality of the coating. Such a coating does not completely cover the metal surface, and therefore is not of high quality. Further increase in the electrolyte concentration by increasing the content of the main composition of KOH and liquid glass and introducing additional chromium oxide and glycerin stabilises the synthesis process, and from the assessment of the quality of the appearance, such a coating is of high quality. The introduction of hydrogen peroxide into the electrolyte slightly changes the voltage-current dependence.

In such an electrolyte, during the oxidation process, the anodic component of the voltage decreases with the synthesis time, which is reflected in the microhardness of the coating. Such a coating has better microhardness and greater thickness. The ratio of currents does not change the nature of the current-voltage dependences, i.e. it does not affect the stability of the synthesis process. A decrease in currents lowers the anodic and cathodic components of the voltage. And this, in turn, affects the properties of the coatings. The most favorable conditions for the formation of the oxide are formed at the ratio of current densities I_a/I_k = 1,5 and at a relatively low electrolyte concentration of 10 g/l KOH+15 g/l liquid glass. The time dependences of the current-voltage characteristics during the synthesis in different electrolytes of oxide-ceramic coatings on a titanium alloy are shown in Figure 2.

The study of the synthesis voltage of the coating was carried out in the system titanium alloy - alkaline electrolyte with the addition of liquid glass with electrolyte components of different concentrations. As in zirconium alloys, in the first 3-5 minutes, when spark discharges are formed, the components of the anode and cathode voltages increase by 5...10 V. The increase in voltage is observed in all studied systems with the same regularity, which depends on the concentration of KOH and liquid glass (Fig. 2a, b). After the plasma is formed, the character of the curve changes and it slightly decreases. In the galvanostatic mode, in the section A - B of stable formation of the oxide coating, the dependence of the voltage on the synthesis time in the given range is rectilinear. With increasing current, the voltage at the anode increases. In this case, the increase in voltage is accompanied by a decrease in the electrolyte concentration, which, obviously, is accompanied by a possible localisation of current carriers on the molecules of liquid glass (since the latter are also electron donors) and a decrease in their mobility.

Thus, in an electrolyte of lower concentration at a current density of 20/20 A/dm^2 the anodic component of the voltage is 150...140 V (Fig. 2a, curve 1), and at Ia/Ic=5/10 A/dm^2 it drops to 100...110 V (curve 4). When forming oxide in an electrolyte of composition 10 g/l KOH + 15 g/l liquid glass at a current density of 5/10 A/dm^2 (Fig. 2b), the anodic voltage reaches 88...102 V.

With the same ratio of currents, but in an electrolyte less concentrated at the anode, the oxide is formed at a voltage 12...18 V lower than in a more concentrated one. The same situation is true for other modes.

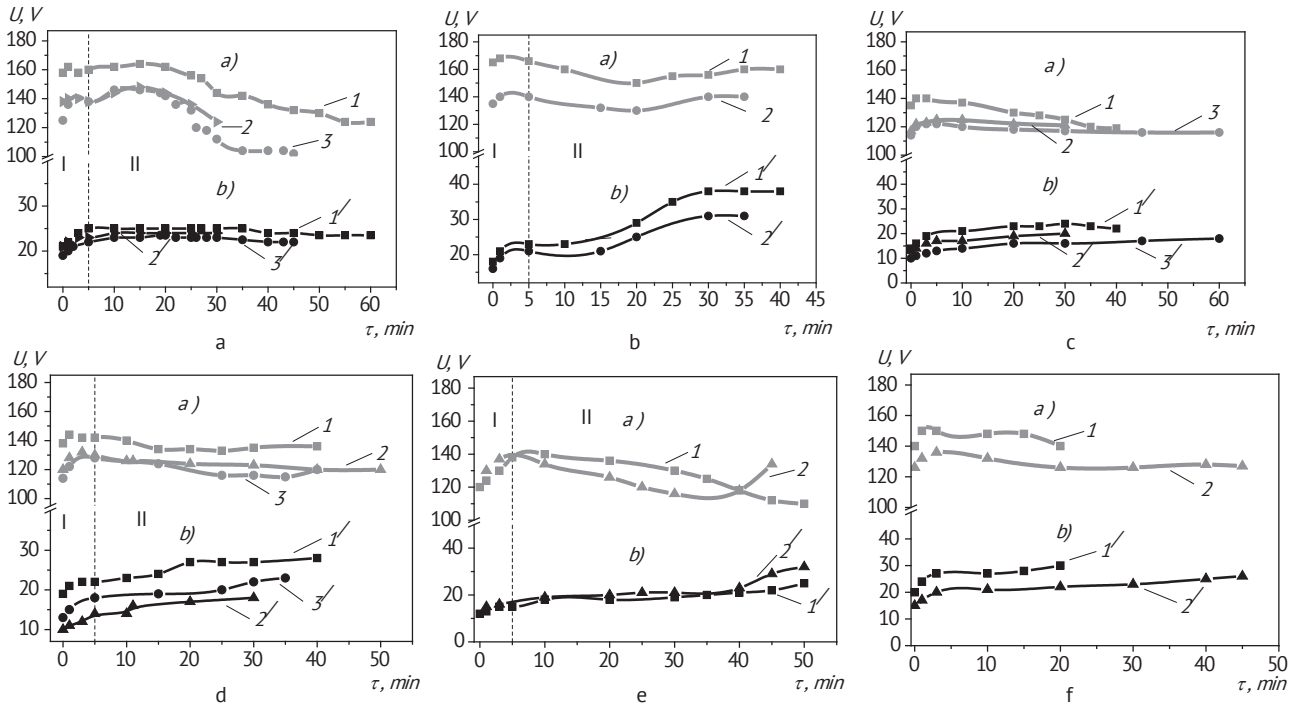

Figure 1. *Dependence of anodic (a) and cathodic (b) voltages on synthesis time on zirconium alloy electrodes in an electrolytes*

Note: *a – 3 g/l KOH+2 g/l liquid glass at different current densities: 1, 1′ – 20/20 A/dm², 2, 2′ – 10/15 A/dm², 3, 3′ – 10/10 A/dm²; b – 10 g/l KOH + 15 g/l liquid glass + 0,1 g/l GrO_3 at different current densities: 1, 1′ – 20/20 A/dm², 2, 2′ – 10/15 A/dm², 3, 3′ – 10/10 A/dm²; c – 10 g/l KOH+15 g/l liquid glass + 0,1 g/l GrO_3 + 10 g/l glycerin at different current densities: 1, 1′ – 20/30 A dm², 2, 2′ – 10/15 A/dm², 3, 3′ – 10/10 A/dm²; d – 10 g/l KOH+15 g/l liquid glass + 0,1 g/l GrO_3 + 10 g/l glycerin + 10 H_2O_2 at different current densities: 1, 1′ – 10/15 A/dm², 2, 2′ – 10/10 A/dm²; e – 10 g/l KOH + 15 g/l liquid glass + 0,1 g/l GrO_3 + 18 g/l glycerin + 10 H_2O_2 at different current densities: 1, 1′ –20/30A/dm², 2, 2′ –10/15 A/dm²*

Source: *developed by the authors*

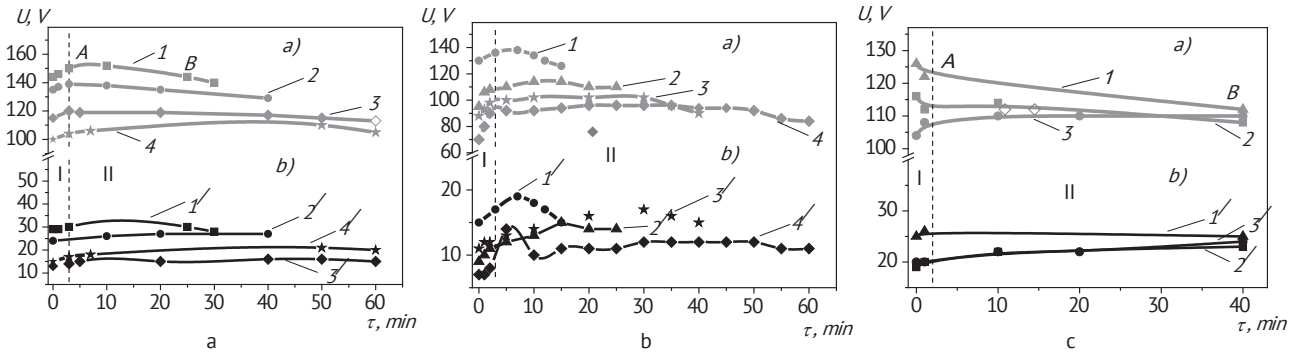

Figure 2. *Voltage curves depending on the synthesis time of oxide-ceramic coatings on titanium alloys in different electrolytes*

Note: *a – 5 g/l KOH+5 g/l liquid glass; b – 10 g/l KOH+15 g/l liquid glass; c – 5 g/l KOH + 5 g/l liquid glass+KF*

Source: *developed by the authors*

The introduction of 0.1 g/l of KF into the electrolyte lowers the anodic component of the voltage compared to the least concentrated electrolyte by 19...22 V. Further doping of the electrolyte with 0,2 and 0,5 g/l of KF, as expected, lowers the voltages at which the oxide is formed (Fig. 2c). It is known that the current density has a significant effect on the voltage of the synthesis of the anodic coating. As expected, an increase in the current density during anodic spark oxidation leads to an increase in the voltage (Fig. 2). This pattern is

observed at all electrolyte concentrations. Thus, at an electrolyte concentration of KOH 5 g/l and liquid glass 5 g/l, an increase in current density leads to an increase in voltage by 10...15 V. In an electrolyte with a higher concentration of its components, the voltage with an increase in current density also increases by 10...15 V.

Therefore, the OCC on a titanium alloy is synthesised more evenly compared to its synthesis on a zirconium alloy. Obviously, this is due to the conductivity of the electrolyte. Coatings synthesised on a titanium alloy have a much smaller thickness than on a zirconium alloy, so their conductivity increases, and the synthesis process proceeds evenly. The most favorable conditions for the formation of a coating on a titanium alloy are created when using low electrolyte concentrations.

The results presented in this work make it possible to establish several stages of the formation of the oxide coating on titanium and zirconium alloys. Thus, according to the results of the studies, it was found that the increase in current is accompanied by the breakdown of the oxide natural film. The results of the studies are investigated with data obtained by such scientists as M. Aliofkhazraei *et al*. (2021). The voltage value in the process of coating synthesis (second stage of synthesis) on the surface of the titanium alloy under different operating modes is within 90 ... 150 V. According to the comparative analysis of the synthesis of PEO coatings in electrolytes of different composition, it is noted that in the electrolyte with a higher concentration of components, the synthesis voltage decreases, which is also consistent with the results of studies of the electrophysical parameters of the PEO process by M. Aliofkhazraei *et al*. (2021).

The value of the voltage at the anode during the synthesis of zirconium alloy differs from the values obtained by V. Aubakirova *et al*. (2022) and is lower in this work. However, it is noted that the composition of the electrolyte is decisive for establishing energy dependencies. In the work of V. Aubakirova *et al*. (2022) more complexly alloyed electrolytes were used, and therefore the system requires more energy to introduce the components of the electrolyte composition into the oxide coating. It should also be noted that the different reactivity of each of the components changes the value of the synthesis voltage, however, the dependence between voltage and time is consistent with other works of researchers.

Conclusions

Studies of the current-voltage dependences during the synthesis of OCC on zirconium and titanium alloys showed that the synthesis process on a titanium alloy proceeds more evenly compared to its synthesis on a zirconium alloy. According to the electrophysical parameters, it was established that the stability of the formation of OCC on a zirconium alloy depends on the composition of the electrolyte, and an increase in the concentration of electrolyte components from 3 g/l KOH and 2 g/l of liquid glass to 10 g/l of alkali and 15 g/l of liquid glass stabilises the process of coating formation, which has a positive effect on its quality, and the introduction of chromium oxide, glycerin and hydrogen peroxide into the electrolyte reduces the components of the anodic and cathodic voltages.

When synthesising OCC on a titanium alloy, increasing the content of electrolyte components from 5 g/l KOH and 5 g/l liquid glass to 10 g/l KOH and 15 g/l liquid glass also leads to a decrease in the components of the anodic and cathodic voltages, and it was also found that a decrease in the anodic and cathodic currents reduces the components of the anodic and cathodic voltages at which the coating is formed. The following works will be related to the correlation dependencies between the parameters of the synthesis process and the properties of the obtained coatings. This will make it possible to establish the optimal coating application modes. Conceptually, it can be established that the electrophysical parameters of the process of plasma electrolytic synthesis of oxide-ceramic layers significantly depend on both the composition of the electrolyte and the processing modes and the nature of the base material. Increasing the concentration of electrolyte components helps stabilise the process of coating formation, reduce the anodic and cathodic voltages and create more favorable conditions for the formation of high-quality oxide layers. At the same time, titanium alloys are characterised by a more uniform course of the synthesis process compared to zirconium ones, which indicates a higher stability of the formation of coatings on their surface. Future research should focus on establishing quantitative correlation models between electrophysical synthesis parameters and the functional properties of oxide-ceramic coatings, as well as optimising electrolyte composition and processing regimes to achieve controlled, stable, and reproducible coating formation on titanium and zirconium alloy substrates.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

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Фактори, що впливають на формування плазмо-електролітних оксидних покриттів, синтезованих на титанових та цирконієвих сплавах

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Анотація. Дослідження, представлене в цій статті, є актуальним через необхідність підвищення керованості та прогнозування процесів формування оксидно-керамічних покриттів на титанових і цирконієвих сплавах, що застосовуються в агресивних умовах експлуатації та високонавантажених конструкціях. Метою роботи було дослідження електрофізичних закономірностей формування покриттів під час плазмово-електролітичного оксидування титанових і цирконієвих сплавів та визначення впливу складу електроліту і густини струму на синтезну напругу. У роботі використано гальваностатичні анодно- та анодно-катодно режими, часову реєстрацію напруги і струму, порівняльний аналіз складу електролітів у грамах на літр та оцінювання вольт-амперних залежностей під час синтезу покриттів. Встановлено, що формування покриттів на цирконієвому сплаві відбувалося у два етапи та було нестабільним за низьких концентрацій електроліту, тоді як підвищення вмісту гідроксиду калію і рідкого скла забезпечувало стабілізацію процесу та рівномірність покриття. Показано, що титановий сплав забезпечував більш рівномірний перебіг синтезу та нижчі рівні напруги порівняно з цирконієвим завдяки вищій провідності та стабільнішому росту оксидного шару. Виявлено, що зменшення густини струму знижувало анодну та катодну складові напруги, а добавки до електроліту, такі як оксид хрому, гліцерин і пероксид водню, впливали на стабільність і величину синтезної напруги. Визначено оптимальні умови формування покриттів за збалансованих співвідношень густини струму та середніх концентрацій електроліту, що забезпечувало стабільний режим розрядів і покращення якості покриття. Отримані результати можуть бути використані інженерами-матеріалознавцями для оптимізації режимів плазмово-електролітичного оксидування з метою отримання корозійностійких та механічно стабільних захисних покриттів

Ключові слова: електрофізичні параметри; напруга синтезу; густина струму; електроліт; катод; анод