

Article

Optimization of Plasma Electrolytic Oxidation Technological Parameters of Deformed Aluminum Alloy D16T in Flowing Electrolyte

Liubomyr Ropyak ^{1,*}, Thaer Shihab ^{2,3}, Andrii Velychkovych ⁴ , Vitalii Bilinskyi ¹, Volodymyr Malinin ⁵ and Mykola Romaniv ¹

¹ Department of Computerized Engineering, Ivano-Frankivsk National Technical University of Oil and Gas, 76019 Ivano-Frankivsk, Ukraine

² Medical Instruments Techniques Engineering Department, Technical College of Engineering, Al-Bayan University, Baghdad 10070, Iraq

³ Department of Welding, Ivano-Frankivsk National Technical University of Oil and Gas, 076019 Ivano-Frankivsk, Ukraine

⁴ Department of Construction and Civil Engineering, Ivano-Frankivsk National Technical University of Oil and Gas, 15 Karpatska Str., 076019 Ivano-Frankivsk, Ukraine

⁵ Department of Physical Principles for Surface Engineering, G.V. Kurdyumov Institute for Metal Physics, National Academy of Sciences of Ukraine, 36 Academician Vernadsky Boulevard, 003142 Kyiv, Ukraine

* Correspondence: l_ropjak@ukr.net

Abstract: The prospects of plasma electrolytic oxidation (PEO) technology applied for surface hardening of aluminum alloys are substantiated. The work aims to optimize the technological process of PEO for aluminum in flowing electrolyte. The design of the equipment and the technological process of the PEO for aluminum deformed alloy D16T in flowing silicate–alkaline electrolyte have been developed. Oxide coatings were formed according to various technological parameters of the PEO process. The properties of the oxide coatings were evaluated, respectively, by measurements of coating thickness, geometric dimensions of the samples, microhardness, wear tests, and optical and scanning electron microscopy. To study the influence of the technological parameters of the PEO process of forming oxide coatings on geometrical, physical, and mechanical properties, planning of the experiment was used. According to the results of the conducted experiments, a regression equation of the second order was obtained and the response surfaces were constructed. We determined the optimal values of the technological parameters of the PEO process: component concentration ratio ($\text{Na}_2\text{SiO}_3/\text{KOH}$), current density, flow rate, and electrolyte temperature, which provide the oxide coating with minimal wear and sufficiently high physical and mechanical properties and indicators of the accuracy of the shape of the parts. The research results showed that the properties of oxide coatings mainly depend on almost all constituent modes of the PEO process. Samples with Al_2O_3 oxide coating were tested during dry friction according to the “ring–ring” scheme. It was established that the temperature in the friction zone of aluminum samples with an oxide coating is lower compared to steel samples without a coating, and this indicates high frictional heat resistance of the oxide coating.

Keywords: plasma electrolytic oxidation; aluminum; coating; technological process; experiment planning; microhardness; wear and tear; cone-likeness; friction heat resistance of materials



Citation: Ropyak, L.; Shihab, T.; Velychkovych, A.; Bilinskyi, V.; Malinin, V.; Romaniv, M. Optimization of Plasma Electrolytic Oxidation Technological Parameters of Deformed Aluminum Alloy D16T in Flowing Electrolyte. *Ceramics* **2023**, *6*, 146–167. <https://doi.org/10.3390/ceramics6010010>

Academic Editors: Amirhossein Pakseresht and Kamalan Kirubakaran Amirtharaj Mosas

Received: 6 November 2022

Revised: 29 December 2022

Accepted: 5 January 2023

Published: 10 January 2023



Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. 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/>).

1. Introduction

Today, aluminum alloys are widely used in the automotive, aerospace, and radio electronics industries, nuclear engineering, mining, oil and gas production, as well as in construction and other areas of modern engineering [1–3]. Relatively high ratios between strength characteristics and specific weight, high thermal conductivity, good machinability

by cutting and plastic deformation, and high corrosion resistance are the most important properties that make aluminum alloys technologically attractive and cost-effective structural materials [4–6].

However, in many cases, insufficient wear resistance, heat resistance, and vulnerability to thermal shock remain the restraining factors that significantly limit the scope of application of aluminum alloys [7–9]. Aluminum parts are usually operated at temperatures up to 230 °C because, at higher temperatures ($T > 0.4 T_m$, where T_m is the melting temperature of the alloy), diffusion processes occur, especially grain boundary diffusion, which begins to play an important role, which leads to extensive growth grains during deformation [10,11]. Attention should also be paid to the problem of hydrogen embrittlement of aluminum alloys, which occurs in modern tanks with high-pressure hydrogen [12], the danger of sulfide corrosion cracking of critical parts of drilling, oil and gas industrial and pumping equipment [13], as well as problems regarding the interaction of biological environments with metal implants [14–16].

In order to take advantage of the significant advantages and eliminate certain disadvantages of aluminum alloys for specific practical applications, engineers use constructive, operational, and technological methods.

Design methods include selection of rational forms of parts from aluminum alloys [17], rational choice of the alloy grade [18,19], as well as conducting stress state studies [20], temperature calculations of layered compositions [21,22], and use of monitoring of damage to coatings [23–25].

Some customers are skeptical about protective coatings of working surfaces of products because, in practice, application of coatings sometimes faces the problem of their premature destruction [26,27]. Abnormal conditions during operation can cause accelerated reduction in the service life of machine components with protective coatings [28,29]. Therefore, “base material–coating” compositions should always be required to combine special properties (for example, heat resistance and wear resistance) with a sufficient margin of strength [30–32]. Here, first, it is necessary to evaluate the strength of the “base material–coating” composition as a two-layer deformable body under the action of operational loads [33,34].

Thus far, significant progress has been made in the field of mechanics of thin films, coatings, and overlays in the presence of singular stress fields caused by sharp defects or localized loads. The influence of the curvature and shape of the damaged surface on the strengthening effect of the applied coating was studied in works [35,36] using the theory of thin shells. Stress concentration near crack-like defects in coating itself was the subject of studies described in publications [37,38]. 1D [39–41] and 2D [42,43] models are used to develop analytical methods for assessing the stress state of layered coatings under local loading. An example of such an analysis of a ceramic–aluminum coating under an arbitrarily oriented load concentrated along a line is [44].

Among the technological methods, the choice of methods of mechanical processing of parts to reduce manufacturing errors, including considering technological heredity [45] to ensure long-term operation throughout the life cycle of products [46] with coatings, deserves attention. To protect aluminum alloys from wear corrosion at elevated temperatures, various methods of surface strengthening are used [47,48], namely titanium modification during ultrasonic shock treatment [49], silicon carbide during laser surface treatment [50], formed coating by electric spark alloying method [51], high-speed oxygen-fuel HVOF coating [52], electrochemical chromium plating [53], hard anodizing [54], and plasma electrolytic oxidation (PEO), which is also known as micro-arc oxidation (MAO) [55–58].

It is known that, among metal coatings, the most widespread are chrome, and, among non-metallic coatings, oxide. PEO can be a promising alternative [59] to replace use of environmentally harmful chrome plating processes for both aluminum [53] and other metals [60–62].

Among several strengthening methods, PEO should be singled out, which is intensively developed and is currently one of the most popular, environmentally friendly, and

fairly cost-effective technologies for forming oxide layers on aluminum and its alloys [55–58], as well as other metals, for example, titanium [63,64], magnesium [65], and steels [66]. In addition, PEO is one of the fundamental ways to improve the operational properties of products by modifying the working surfaces of aluminum parts in order to transform the surface layer into a hard wear-resistant and heat-resistant oxide ceramic [55–58]. PEO is a technological process of forming ceramic layers on the surface of aluminum alloys in an electrolyte under high voltages in the mode of spark and micro-arc discharges, which enables obtaining higher-quality oxide coatings that are firmly attached to the base of the part, comparable to hard anodizing and plasma spray ceramic [67]. The PEO process is accompanied by discharges that develop under the influence of a strong electric field in a system consisting of a part (substrate), an oxide layer, a vapor–gas envelope, an electrolyte, and an electrode (usually a galvanic bath made of stainless steel) [58]. Electrical breakdown in this system leads to emergence of a plasma state in the discharge channel, in which, during plasma–chemical reactions, the substrate material is transformed into chemical compounds consisting of the substrate material itself (including alloying elements), oxygen, and electrolyte components [56,57]. When applying rational technological parameters of the PEO process, we obtain a multifunctional wear-resistant and heat-resistant oxide ceramic coating that has a reliable chemical and metallurgical connection with the main material of the part [55–58,63–65,67].

Aluminum deformed alloy D16T has fairly high mechanical properties compared to other aluminum alloys, and its products are widely used in industry and everyday life. This alloy belongs to the aluminum alloys of the Al–Cu–Mg system, and it is subject to hardening and natural aging. Intermetallics formed in the microstructure are the main factor in the strengthening mechanism of this alloy. However, these intermetallics lead to microelectrochemical inhomogeneity of the alloy, which leads to pitting corrosion, intergranular corrosion, or delamination [68–70]. Therefore, deformed alloys of such a system are used clad with a layer of aluminum and/or subjected to PEO [71]. Predicting the phase composition of multicomponent Al-based alloys during PEO within certain thermodynamic approaches [72–74] or first-principles calculations [75,76] is complicated due to formation of metastable gradient structures, whose redistribution requires detailed statistical analysis.

Microstructural properties, part surface morphology, wear resistance, heat resistance, frictional heat resistance, and other operational properties of oxide ceramic coatings formed by the PEO method depend on the component composition of the electrolyte [56–58,77] and technological process parameters [56–58,78–80]. In particular, in [81], the influence of technological parameters of PEO on corrosion properties of oxide coatings was investigated. Researchers [82–84] studied the tribological characteristics of coatings formed by PEO under various types of lubrication and established high wear resistance during friction in a pair with carbon steel and revealed the effect of hydrogen on the wear resistance of steels in contact with PEO layers synthesized on aluminum alloys during tests in mineral lubricant [85]. A number of studies are devoted to study of thermal conductivity, thermal protective properties [56,86–89], and thermal shock resistance [90] of oxide ceramic coatings on various materials, the results of which demonstrate low thermal conductivity and high protective properties of these coatings, including taking into account the thermal conductivity of the substrate [91]. Papers [92,93] report on use of aluminum oxide to reinforce composite coatings to improve their protective properties.

Thus, depending on the selected material of the substrate, electrical parameters of the PEO process (current density, ratio of anode and cathode currents, voltage, frequency, time), chemical composition, concentration, and temperature of the electrolyte, it is possible to obtain oxide ceramic coatings with a complex of physical and mechanical properties that most fully satisfy the specific operational requirements of consumers [55–58]. The complexity of choosing rational technological parameters of PEO is due to the diversity of the chemical composition of aluminum alloys, as well as the component composition of electrolytes, temperature, and electrical regimes of coating formation. However, there is

practically no information in the literature about the tribological and thermal characteristics of parts with oxide coatings and the processes of formation of PEO coatings in the flowing electrolyte. Therefore, development of PEO strengthening processes for formation of oxide ceramic coatings on the surface of parts made of heterogeneous alloys is an urgent problem. Use of the experiment planning methodology during development of various technologies enables significantly reducing the number of experiments and establishing optimal process modes [94–100]. The technological process of PEO should be optimized specifically for the selected brand of deformed aluminum alloy and depending on the field of application and the desired operational properties of the parts covered with enveloping ceramic coatings.

The study aims to determine the optimal technological parameters of the PEO process and the component composition of the electrolyte to ensure formation of a wear-resistant oxide ceramic coating on aluminum deformed alloy D16T in the flowing electrolyte.

To achieve the goal, the following tasks should be addressed:

- Develop a mathematical model of oxide coating forming and study the influence of the PEO technological parameters on the physical and mechanical properties of oxide coatings and the geometric dimensions of parts;
- Determine the optimal technological parameters to provide the maximum microhardness, minimal wear with low cone-likeness of the cylindrical surface of the coated part, as well as justify the placement of parts taking into account their shape in the electrochemical cell during PEO;
- Conduct microscopic studies of the oxide coating;
- Investigate the frictional heat resistance of the oxide coating.

2. Materials and Methods

2.1. Research Materials and Equipment

The authors studied the strengthening process of PEO samples made of aluminum deformed alloy D16T (State Standard GOST 4784–2019 Aluminum and aluminum alloys are deformable. Marks (ISO 209:2007, NEQ)) of the Al–Cu–Mg system, hardened and naturally aged). Chemical composition and properties are presented in Tables 1 and 2, respectively.

Table 1. Chemical composition of the aluminum deformed alloy D16T, mass.%.

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Ti+Zr	Others Elements	Al
0.50	0.50	3.8–4.9	0.3–0.9	1.2–1.8	0.10	0.25	0.15	0.20	0.15	The rest

Table 2. Physical and mechanical properties of the aluminum deformed alloy D16T.

σ_{UTS} , MPa	σ_Y , MPa	δ_5	E , GPa	HB	α , degree ⁻¹	λ , W/(m·degree)	ρ , kg/m ³	C , J/(kg·degree)
390–420	255–275	10–12	72	105	0.0000229	130	2770	0.922

Manufacturing of parts with operational surfaces strengthened with PEO coatings was carried out by the developed technological process (Figure 1).

Based on a review of scientific and technical literature, patents, and the results of our own preliminary studies of the PEO process, we chose a water-based silicate–alkaline electrolyte for experiments. For preparation of electrolytes, chemically pure components were used: potassium hydroxide (KOH), State Standard GOST 9285–78 and sodium silicate (Na₂SiO₃), and State Standard GOST 13078–81. The electrolyte was prepared by simply mixing the components in distilled water, which was obtained using water distiller DE-4-2.

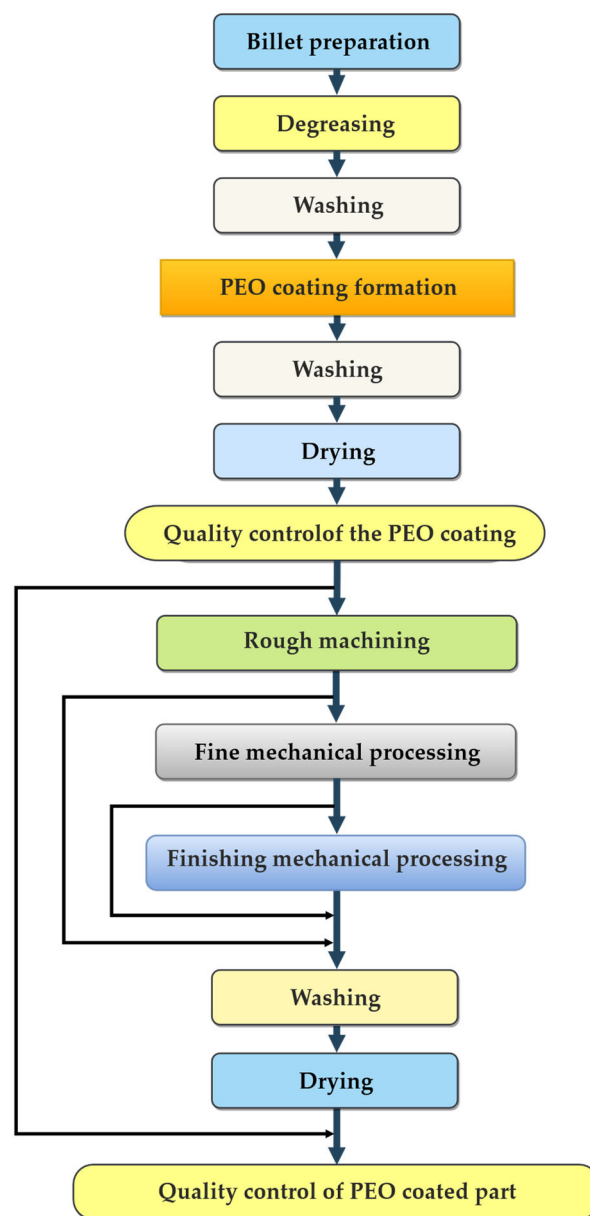


Figure 1. Structural diagram of manufacturing of parts with operational surfaces strengthened with PEO coatings.

PEO of aluminum deformed alloy D16T was carried out on a device developed by us, which enables formation of oxide coatings on parts in a flowing electrolyte. The installation includes an alternating current power source (voltage up to 1000 V), a system for measuring voltage and current values in the cathodic and anodic periods, an electrolyte circulation system, variable electrochemical cells with stainless steel electrodes, an electrolyte cooling system, an exhaust ventilation system, and a damage blocking system electric current. Before forming the PEO coating, the aluminum alloy samples were subjected to mechanical processing to obtain a surface roughness of $Ra = 0.8\text{--}1.1\text{ }\mu\text{m}$. In the studies, the average value of $Ra = 0.9\text{ }\mu\text{m}$ was taken. During formation of the oxide coating, the cylindrical sample was placed vertically, coaxially with the axis of the electrochemical cell. Technological modes of coating formation are shown in Table 3. The thickness of the formed working layer of the oxide coating was approximately $300\text{ }\mu\text{m}$.

Table 3. Coding of factors and levels of their variation during PEO experiments.

Levels of Factors	Coded Values				Natural Values			
	x_1	x_2	x_3	x_4	Concentration Ratio ($\text{Na}_2\text{SiO}_3/\text{KOH}$), C	Current Density, i , A/dm^2	Flow Rate, v , cm/s	Electrolyte Temperature, T , $^\circ\text{C}$
The main level	0	0	0	0	4.4	5	75	50
Interval of variation	1	1	1	1	1.3	2	40	15
The upper level	+1	+1	+1	+1	5.7	7	115	65
The lower level	−1	−1	−1	−1	3.1	3	45	35
Star points (+)	+1.4826	+1.4826	+1.4826	+1.4826	6.3	8	141.7	72.2
Star points (−)	−1.4826	−1.4826	−1.4826	−1.4826	2.6	2	8.3	27.8

2.2. Microstructure Observation and Mechanical Properties Measurement

The microhardness of coatings and the base was measured on transverse microsands using a PMT-3 hardness tester. The load on the diamond Vickers pyramid was 0.5 N and 1.0 N with the holding time of 12 s to 15 s.

The cone-likeness of the coated part is the deviation of the profile of the longitudinal section for which the components are rectilinear, but not parallel, determined from the dependence:

$$Y_C = (d_{\max} - d_{\min})/2, \quad (1)$$

where $d_{\max}$ and $d_{\min}$ are the maximum and minimum diameter of the coated part, respectively. Measurements were carried out using a clock-type indicator with a division price of 1 μm .

The total thickness of oxide coatings was determined on cross-sectional microsections with an optical microscope MIM-7 and PMT-3 hardness tester using an eyepiece micrometer with a resolution of 1 μm .

We conducted the microscopic studies of oxide coatings, PEO-formed on aluminum alloy D16T, at the Center for collective use of scientific instruments “Center for Electron Microscopy and X-ray Microanalysis” of the Karpenko Physico-mechanical Institute of the National Academy of Sciences of Ukraine, Lviv. We used a ZEISS Stemi 2000-C (Germany) optical microscope, and ZEISS EVO 40XVP (ZEISS Group, Jena, Germany) scanning electron microscope with a micro X-ray spectral analysis system and an INCA ENERGY 350 (Oxford Instruments, Abingdon, UK) energy dispersive X-ray spectrometer. Before conducting electron microscopic studies, we applied a monolayer of gold to the surface of the samples to increase their conductivity.

2.3. Wear Test

Wear tests of samples with PEO coatings were carried out on a bench for researching friction pairs during reciprocating motion, which simulates the real operating conditions of elements of metal–rubber friction pairs of piston pumps: cylinder sleeve–piston seal; piston rod–seal; plunger–seal [101]. The amount of weight loss due to wear samples was determined by the gravimetric method: weighing the test specimens on the analytical axis of VLA-200g-M (weight accuracy of 0.1 mg) before and after the test. Before each weighing, the samples were thoroughly wiped with ethyl alcohol and dried. The arithmetic mean value from three tests for wear of the PEO ceramic coatings was chosen as the resulting value for determining the wear resistance.

Evaluation of the frictional heat resistance of oxide coatings formed by PEO was carried out according to recommendations (State Standard GOST 23.210–80 Ensuring the wear resistance of products. The method of evaluating the frictional heat resistance of materials). Experiments were carried out on the machine for testing materials for friction UMT-1 (PA “Tochprilad”, Ivanovo, USSR) during dry friction of samples according to the

“ring–ring” face scheme. Dimensions of the samples: outer diameter $D = 28$ mm, inner diameter $d = 20$ mm, $h = 15$ mm, area of the nominal friction surface of the stationary sample $A = 2.9$ cm². The rotation frequency of the moving sample is 1000 min^{−1}, with an accuracy of $\pm 5\%$. The load on the sample is 200 N, with an accuracy of $\pm 4\%$. The temperature in the friction contact zone was measured using an automatic electronic potentiometer of accuracy class 0.5 using a chromel–copel (E) thermocouple of the ChK type, the measurement range of which is from -50 to $+600$ °C. The essence of the method is that the rotating and stationary ring samples of the studied pair of materials are installed coaxially, pressed against each other by end working surfaces with a given axial force, and the temperature of frictional heating is controlled. A stationary ring sample is mounted in a hinge assembly to ensure self-alignment. For comparative tests, structural steel alloyed 40ChN (State Standard GOST 4543–2016), $\lambda = 44$ W/(m·degree) was used. The frictional heat resistance of materials (coatings) is judged by the dependence of the temperature change on the test time. The duration of the tests, after the samples were run-in, was monitored with a stopwatch.

2.4. Methods of Planning Experimental Research

Experiment planning was used to optimize the technological parameters of the PEO process in the flowing electrolyte.

To conduct experimental studies, the results of which allow to calculate the coefficients of the regression equations, that is, the dependences for microhardness Y_H , wear Y_W , and the cone-likeness Y_C :

$$Y_H = f(C, i, v, T); Y_W = f(C, i, v, T); Y_C = f(C, i, v, T) \quad (2)$$

of PEO coatings on D16T aluminum alloy from the technological parameters of the process: the mass ratio of the concentration of the components of the electrolyte $\text{Na}_2\text{SiO}_3/\text{KOH}$ —sodium silicate and potassium hydroxide (C), current density (i , A/dm²), electrolyte flow rate (v , cm/s), and electrolyte temperature (T , °C) chose an orthogonal central composite plan of the second order.

In our case, for four experimental factors $k = 4$ and two experiments in the center of plan $n_0 = 2$, the total number of experiments was $N = 2^4 + 2 \times 4 + 2 = 26$.

Orthogonal central composite planning of PEO experiments was carried out on five coded levels with a step equal to $\alpha = 1.4826$: $-\alpha$; -1 ; 0 ; $+1$; $+\alpha$.

The selected factors meet all the requirements for them. The accuracy of maintaining the technological parameters of the PEO process was 3 – 5% . The intervals of variation are given in Table 3.

The order of experiments was chosen from a series of random numbers to exclude the influence of unregulated and uncontrollable factors.

To simplify the calculations, when determining the coefficients of the regression equations and their evaluation, a transition was made from the natural values of the factors to coded values (Table 3). Each experiment was repeated three times at the same level of factors and the arithmetic mean value of the initial parameter in each experiment was calculated (Table 4).

A second-order polynomial was used to describe the response function (optimization parameter) of the investigated technological process of forming PEO coatings in the flowing electrolyte:

$$Y = b_0 + \sum_{i=1}^k b_i x_i + \sum_{i \neq j}^k b_{ij} x_i x_j + \sum_{i=1}^k b_{ii} x_i^2, \quad (3)$$

where b_0 , b_i , b_{ij} , b_{ii} —regression coefficients, x_i —factors of the experiment, $k = 4$.

The coefficients of the regression equation were calculated in matrix form according to known formulas.

Table 4. Plan-matrix of experimental results of the PEO process.

Experiment Number	Levels of Factors					The Average Value of the Optimization Parameters		
	x_0	x_1	x_2	x_3	x_4	Microhardness Y_{Hr} , GPa	Wear Y_W , g	Cone-likeness Y_C , μm
1	+1	−1	−1	−1	−1	13.93	0.277	15.8
2	+1	−1	−1	−1	+1	14.84	0.287	15.3
3	+1	−1	−1	+1	−1	15.11	0.260	10.4
4	+1	−1	−1	+1	+1	14.99	0.272	10.9
5	+1	−1	+1	−1	−1	13.89	0.238	13.1
6	+1	−1	+1	−1	+1	17.73	0.215	11.4
7	+1	−1	+1	+1	−1	16.32	0.234	10.4
8	+1	−1	+1	+1	+1	19.00	0.207	8.2
9	+1	+1	−1	−1	−1	15.37	0.241	13.1
10	+1	+1	−1	−1	+1	13.53	0.258	15.3
11	+1	+1	−1	+1	−1	17.44	0.230	9.3
12	+1	+1	−1	+1	+1	15.47	0.245	8.7
13	+1	+1	+1	−1	−1	19.40	0.201	10.4
14	+1	+1	+1	−1	+1	19.86	0.198	11.4
15	+1	+1	+1	+1	−1	21.95	0.182	7.1
16	+1	+1	+1	+1	+1	20.29	0.196	6.5
17	+1	−1.4826	0	0	0	13.91	0.268	12.1
18	+1	+1.4826	0	0	0	19.65	0.207	7.4
19	+1	0	−1.4826	0	0	14.08	0.287	11.1
20	+1	0	+1.4826	0	0	21.51	0.192	8.8
21	+1	0	0	−1.4826	0	18.91	0.213	14.2
22	+1	0	0	+1.4826	0	19.86	0.205	7.6
23	+1	0	0	0	−1.4826	18.68	0.215	7.7
24	+1	0	0	0	+1.4826	19.63	0.207	8.8
25	+1	0	0	0	0	21.51	0.192	8.3
26	+1	0	0	0	0	21.98	0.188	8.4

The significance of the obtained coefficients of the regression equations was checked by Student's t -test. The coefficient was considered statistically significant under the condition that $|b_s| > t \cdot S(b_i)$, where the t -test, selected from the reference table for the significance level of 0.05 and degrees of freedom f_E ; $S(b_i)$ —coefficient error (here, b_i is considered b_0, b_i, b_{ij}, b_{ii}). Statistically insignificant coefficients were discarded and regression equations were refined. The resulting regression equations were tested for adequacy using Fisher's F -test.

The calculated value F_c was compared to that selected from the reference table (F_{tabl}) for the f_{ad} and f_E degrees of freedom using 0.05 significance level.

If the condition of regression equation $F_c < F_{tabl}$ is fulfilled, it can be considered adequate at the accepted level of significance 0.05.

On the basis of the obtained regression equations, response surfaces were constructed and the levels of the same output of parameter Y on the horizontal plane were calculated. To determine the optimal values of the technological parameters of the PEO process in the flowing electrolyte, we took the partial derivatives from the regression equations, equated them to zero, and solved the system of equations. Note that more general systems of equations with partial derivatives are considered in the article [102]. Based on the obtained regression equations, the response surfaces of the optimization parameters (microhardness Y_H , wear Y_W , and cone-likeness Y_C) were constructed from two variable technological parameters, with the other two fixed at the basic level (C , i , v , and T).

3. Results and Discussion

3.1. Optimization of the PEO Process Technological Parameters

Ensuring the quality of the working surface of cylindrical parts and improving the operational properties of products is achieved by using PEO in the flow electrolyte. In order to substantiate the technological parameters of the PEO process in the flowing electrolyte and to establish the laws of their influence on the physical and mechanical properties of the coating, parameters of the shape of the part and laboratory experimental studies of samples with coatings formed according to the developed PEO technology were conducted. We studied the change in microhardness, wear, and cone-likeness of the cylindrical surface of the part with PEO coating depending on the mass ratio of the concentrations of the electrolyte components C , the current density i , the electrolyte flow rate v , and the temperature of the electrolyte T . In order to evaluate the quality indicators of the PEO coatings, the microhardness of the coating was measured, tested on wear during reciprocating motion, and the cone-likeness of cylindrical parts was determined.

The unknown coefficients of the regression equation were determined by the matrix method in coded form. The significance of the coefficients of the regression equation was checked at the 0.05 level using Student's t -test. Statistically insignificant coefficients were discarded. After that, they were recoded according to a known method into natural values.

Response functions (optimization parameter) reflecting the dependence of the microhardness of the oxide coating Y_H , wear Y_W , and cone-likeness Y_C of the cylindrical surface depending on the mass ratio of the concentrations of the electrolyte components C , the current density i , and the electrolyte flow rate v , the temperature of the electrolyte T , based on the results of the orthogonal of the central composite planning of the experiment in the natural values of the variable factors, the regression equation of the second order takes the following form for:

- microhardness Y_H :

$$Y_H = -33.1213 + 12.2770C + 2.2724i + 0.5159T - 1.2249C^2 - 0.3538i^2 - 0.0037T^2 + 0.2905Ci - 0.0411CT + 0.0174iT; \quad (4)$$

- wear Y_W :

$$Y_W = 46.4174 - 7.1806C - 3.0236i - 0.1534v + 0.6687C^2 + 0.2752i^2 + 0.0007v^2; \quad (5)$$

- cone-likeness Y_C :

$$Y_C = 0.7054 - 0.1151C - 0.0470i - 0.0002iT + 0.00115C^2 + 0.0041i^2. \quad (6)$$

After checking the adequacy of the obtained second-order models for this PEO technological process, the Fisher test was applied. Therefore, as $F_c < F_{tabl}$, it satisfies the requirements for the hypothesis about the adequacy of the regression equations, which was accepted.

The obtained second-order regression equations in natural values can be directly used to calculate microhardness Y_H , wear Y_W , and cone-likeness Y_C of parts with an oxide coating depending on the change in the mass ratio of concentrations of electrolyte components C , current density i , A/dm², electrolyte flow rate v , cm/s, and electrolyte temperature T , °C, which are, respectively, within the following limits:

$$2.6 \leq C \leq 6.3; 2 \leq i \leq 8; 8.3 \leq v \leq 141.7; 8 \leq T \leq 72.2$$

To analyze the influence of the technological parameters of the PEO process in the flow electrolyte (variable factors) on the optimization parameters, response surfaces and their two-dimensional sections were constructed depending on two variable factors (the other two factors were at a constant basic level) (Figures 2–4).

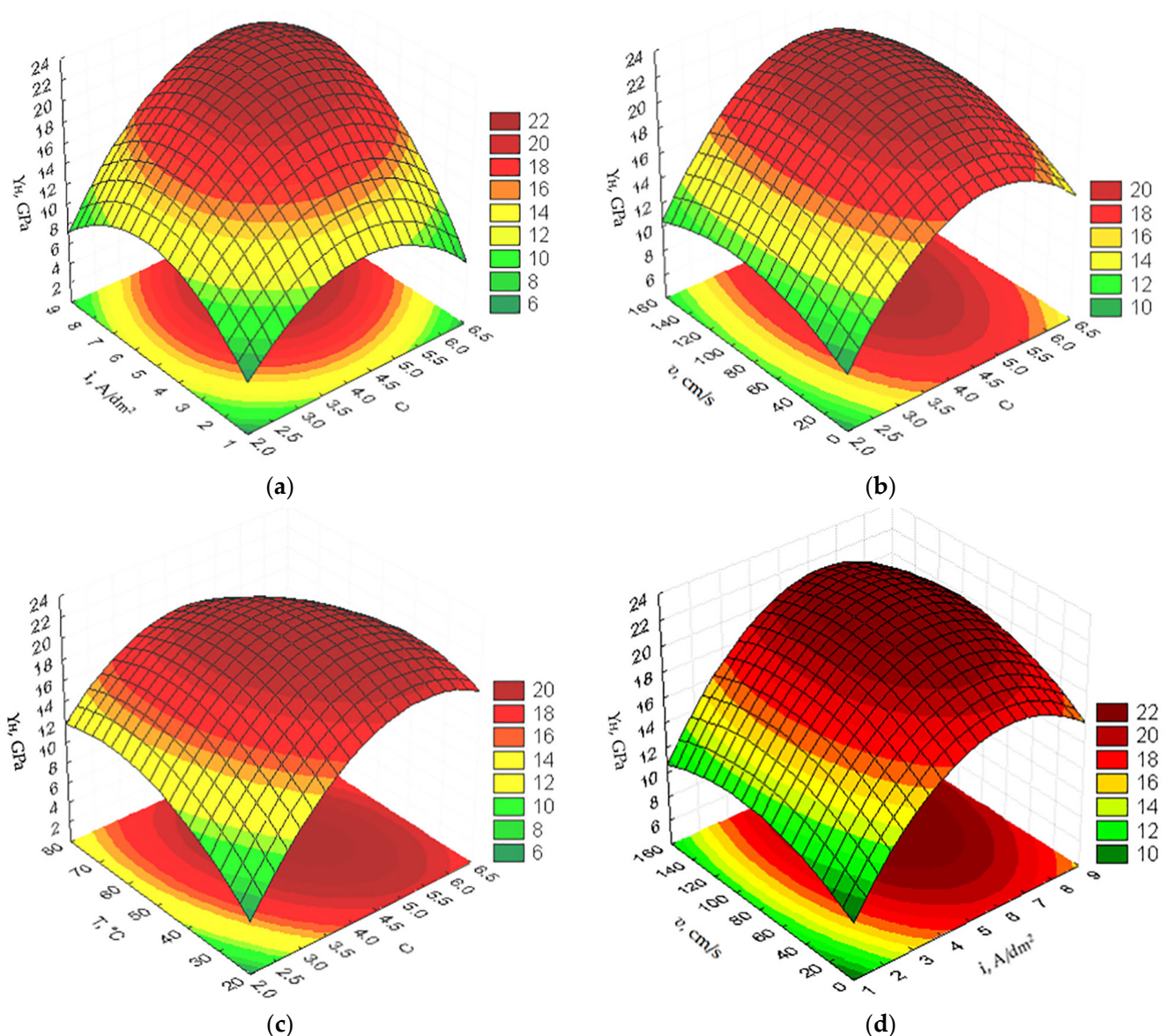


Figure 2. Cont.

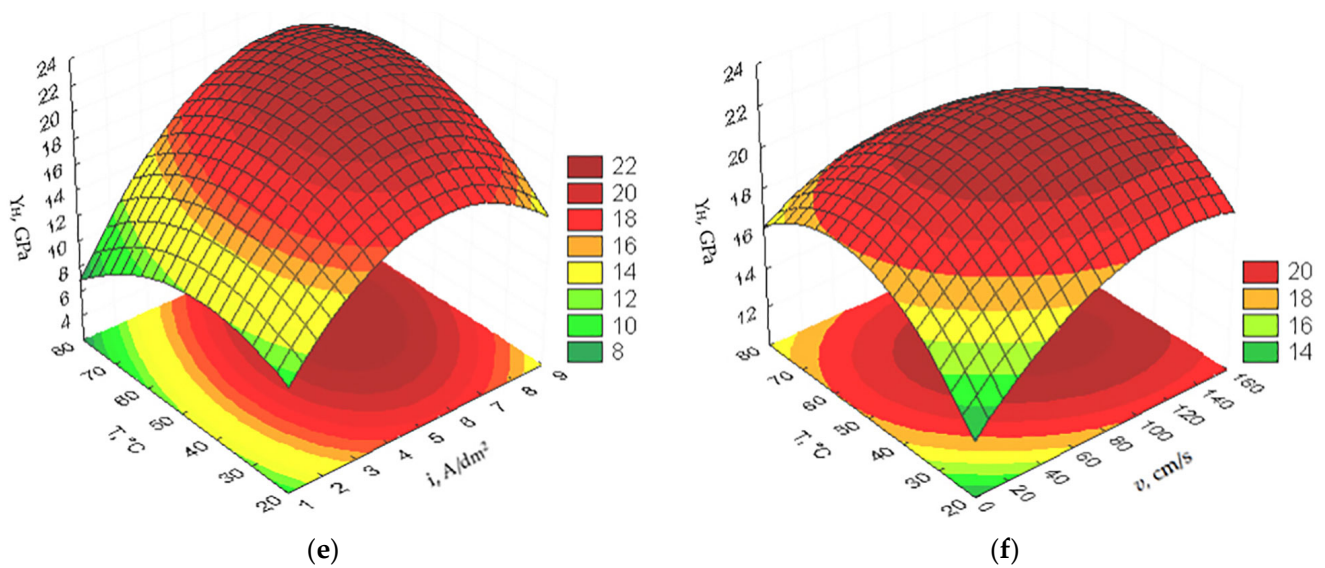


Figure 2. Response surfaces of dependence of the microhardness Y_H coating on the technological parameters of the PEO process in the flowing electrolyte: (a)— C , i , $v = 75$ cm/s, $T = 50$ °C; (b)— C , v , $i = 5$ A/dm², $T = 50$ °C; (c)— C , T , $i = 5$ A/dm², $v = 75$ cm/s; (d)— i , v , $C = 4.4$, $T = 50$ °C; (e)— i , T , $C = 4.4$, $v = 75$ cm/s; (f)— v , T , $C = 4.4$, $i = 5$ A/dm².

Analysis of the obtained second-order regression Equations (4)–(6) and constructed response surfaces (Figures 2–4) shows that the values of the optimization parameters microhardness, wear, and cone-likeness for the oxide coating depend on almost all the technological parameters of the PEO process C , i , v , T .

In addition, the optimal values of the technological parameters of the PEO process in the flow electrolyte for the D16T alloy were determined to ensure the maximum microhardness, minimal wear of the coating, and minimal cone-likeness of the cylindrical surface of the PEO-coated part, which are presented in Table 5.

Table 5. Optimal values of technological parameters of the PEO process.

Optimization Parameters		Technological Parameters			
Name	Optimal Value	Concentration Ratio (Na ₂ SiO ₃ /KOH), C	Current Density, i , A/dm ²	Flow Rate, v , cm/s	Electrolyte Temperature, T , °C
		3.1	Minimum Values		35
			Optimal Values		
Microhardness Y_H , GPa	18.56	5.04	6.63	106.77	49.92
Wear Y_W , g	0.185	4.98	6.61	103.96	53.59
Cone – likeness Y_C , μm	10.6	5.07	5.82	119.52	55.16
		5.7	Maximum Values		65
			7	115	

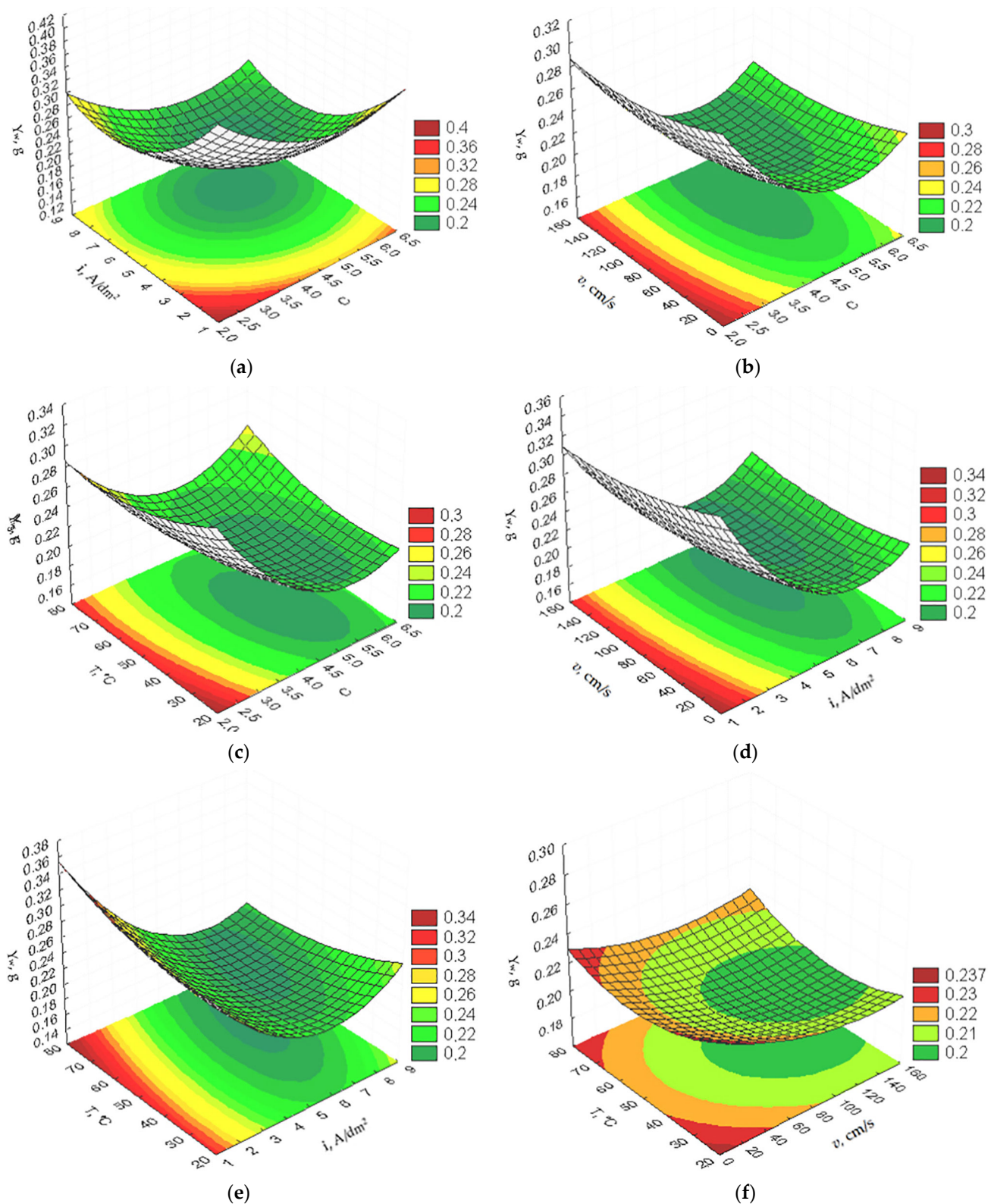


Figure 3. Response surfaces of dependence of the wear Y_W coating on the technological parameters of the PEO process in the flowing electrolyte: (a)— C , i , $v = 75$ cm/s, $T = 50$ °C; (b)— C , v , $i = 5$ A/dm², $T = 50$ °C; (c)— C , T , $i = 5$ A/dm², $v = 75$ cm/s; (d)— i , v , $C = 4.4$, $T = 50$ °C; (e)— i , T , $C = 4.4$, $v = 75$ cm/s; (f)— v , T , $C = 4.4$, $i = 5$ A/dm².

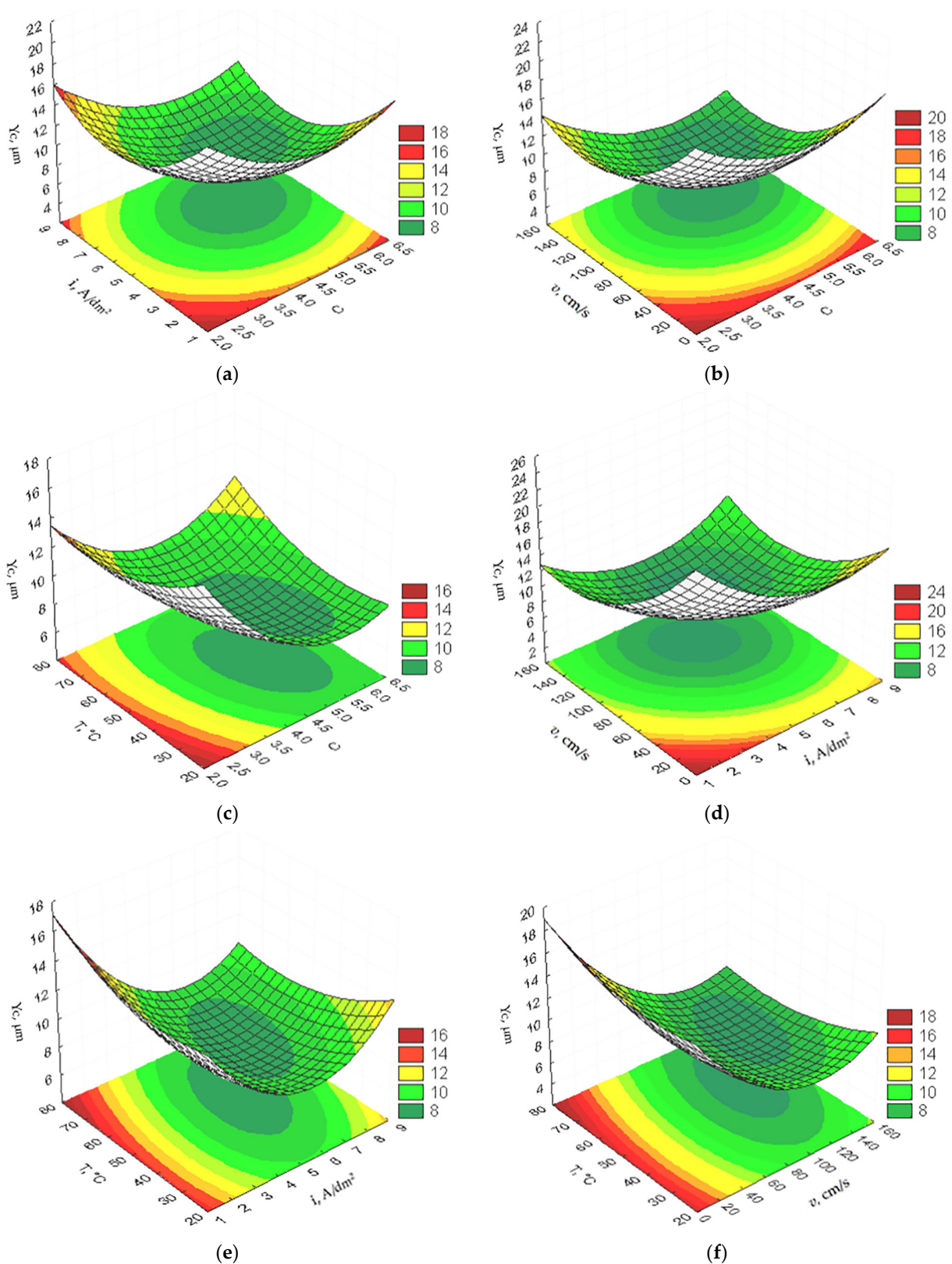


Figure 4. Response surfaces of dependence of the cone-likeness Y_C surface coating on the technological parameters of the PEO process in the flowing electrolyte: (a)— C , i , $v = 75$ cm/s, $T = 50$ °C; (b)— C , v , $i = 5$ A/dm², $T = 50$ °C; (c)— C , T , $i = 5$ A/dm², $v = 75$ cm/s; (d)— i , v , $C = 4.4$, $T = 50$ °C; (e)— i , T , $C = 4.4$, $v = 75$ cm/s; (f)— v , T , $C = 4.4$, $i = 5$ A/dm².

It should be noted that, at the maximum value of microhardness of the formed oxide coating, its minimal wear is ensured, and the optimal values of the technological parameters of the PEO process are within the factor space (Table 5). For the optimization parameters of cone-likeness, the optimal values of technological parameters of the process are also within the factor space.

Analysis of the results of planning the experiment provided in Table 5 shows that the optimal values of the technological parameters of PEO in the flow electrolyte for the optimization parameters microhardness of the oxide coating Y_H , wear Y_W , and cone-likeness Y_C differ from each other. For the first two parameters of optimization—microhardness and wear, the optimal values of the technological parameters of the process practically coincide and are within the range of variation of the factors. That is, with maximum microhardness, minimal wear of the oxide ceramic coating is ensured. The optimal values of the technological parameters to ensure the minimum cone-likeness are slightly different from the optimal technological parameters to ensure the maximum microhardness and minimal wear. At the same time, in order to obtain the minimum value of Y_C , the optimal value of the electrolyte flow rate is beyond the range of variation of the factors, even taking into account the value of the star arm.

Premchand, C. et al. [103] studied the influence of the ratio of electrolyte components on the corrosion resistance of PEO coatings and found that excellent corrosion resistance is achieved when the coating is formed in an aqueous electrolyte with the same concentration ratio of the components ($\text{Na}_2\text{SiO}_3/\text{KOH}$) = 1.

Since wear resistance is an important operational characteristic for products that are operated in abrasive environments, the optimal values of the technological parameters of the PEO process in the flowing electrolyte were taken to be those that ensure the minimum amount of wear of parts $Y_W = 0.185$ g; $C = 4.98$; and $i = 6.61$ A/dm²; $v = 103.96$ cm/s; $T = 53.59$ °C. By substituting these values of the optimal technological parameters of PEO into the Formulas (4)–(6), we obtained a calculated value of microhardness $Y_H = 17.96$ GPa; i.e., its value is slightly smaller than that obtained during the optimization $Y_H = 18.56$ GPa and cone-likeness $Y_C = 10.9$ µm; i.e., its value is slightly greater than that obtained during the optimization $Y_C = 10.6$ µm (Tables 5 and 6). The necessary cone-likeness of the cylindrical surface in accordance with the technical requirements for production of parts, depending on their functional purpose, is expediently obtained during further machining operations—diamond grinding.

Table 6. Calculated values of the optimization parameters: Y_H , Y_C according to the optimal values of the technological parameters of the PEO process, which ensure minimal wear Y_W .

Optimization Parameters		Technological Parameters				Optimization Parameters Deviation, %
Name	Optimal Value	Concentration Ratio (Na ₂ SiO ₃ /KOH), C	Current Density, i, A/dm ²	Flow Rate, v, cm/s	Electrolyte Temperature, T, °C	
		Optimal Values				
		4.98	6.61	103.96	53.59	
		The Values of the Optimization Parameters are Calculated				
Microhardness Y _H , GPa	18.56		17.96		3.35	
Wear Y _W , g	0.185		0.185		0	
Cone – likeness Y _C , μm	10.6		10.9		2.91	

It should be noted that, during PEO in the flowing electrolyte of cylindrical parts in a vertical position, the maximum increase in diameter for the outer surfaces of the shafts and a decrease for the inner surfaces of the bushings was observed in the lower part of the parts. To eliminate cone-likeness and increase the accuracy of cylindrical surfaces, considering technological heredity, during strengthening with oxide ceramic coatings, the

parts must be measured and mounted in a vertical position in the electrochemical cell before starting PEO in such a way that the minimum diameter of the shaft is from below, and, for the sleeve during application coating on the inner surface, its maximum diameter was from below.

Analysis of the results presented in Table 6 shows that the calculated values of the optimization parameters for microhardness and cone-likeness, obtained for the optimal values that ensure the minimum amount of wear, differ from their optimal values by 3.35% and 2.91%, respectively.

Thus, the obtained results of the study show the possibility of targeted control of the technological parameters of the PEO process in the flowing electrolyte by changing the technological parameters considering the technological heredity of manufacturing blanks of aluminum deformed alloy parts.

The obtained research results prove the possibility of practical application of the optimal values of the technological parameters of the PEO process in the flow electrolyte for serial production of parts, such as bodies of rotation, for example, cylinder sleeves and pump plungers at machine-building enterprises.

3.2. Microscopic Studies

We formed PEO coating (Figure 5) according to the obtained optimal values of technological parameters. According to Figure 5, PEO coatings have a uniform structure and do not have visible defects, such as pores, microcracks, and others.

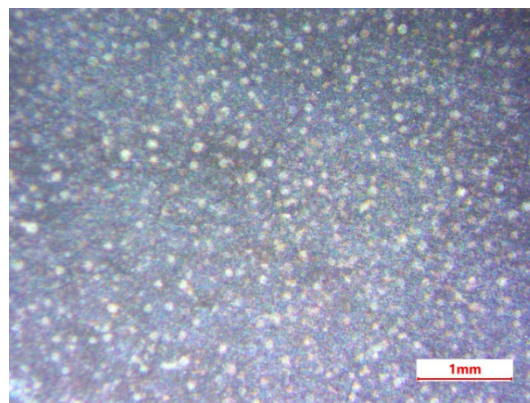


Figure 5. Optical micrograph of the PEO coating after finishing mechanical processing.

Figure 6 shows the results of studying the morphology and composition of PEO coatings by SEM/EDS methods.

The interface between the base metal (D16T) and the PEO coating is shown in Figure 6a. As can be seen from the figure, the interface zone is characterized by integrity and the absence of significant delamination, indicating a high level of chemical bonding. It is caused by direct synthesis of the oxide phase from the base metal due to electrolyte elemental composition during the PEO process.

As can be seen from Figure 6b, the coating has the layered pancake-shaped structure typical of PEO coatings (Sikdar, S. et al.) [58]. The chemical composition analysis indicates the presence of key components for oxide formation (Al and O) and the components of the electrolyte (K, Na, Si) (Figure 6c). At the grain boundaries, there are many evenly distributed small pores formed as a result of gas migration during plasma discharge. The thickness of the PEO coatings was 180–210 μm , which determines the heat-protective properties of oxide ceramic coatings. The mechanism of formation of PEO coatings on aluminum alloys is described in publications [55–58].

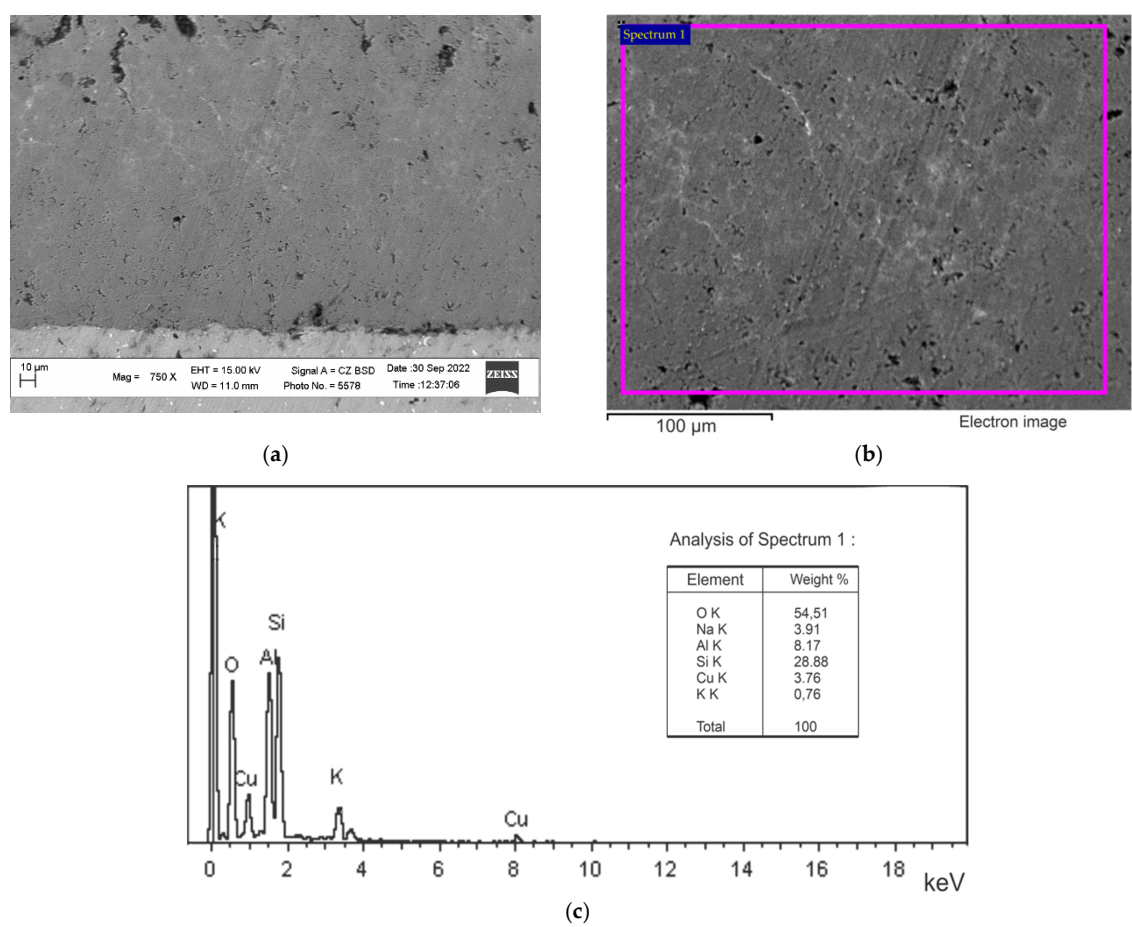


Figure 6. SEM micrograph of the interface between the PEO coating and the base alloy D16T (a) and the EDS analysis of the PEO coating: (b)—area of EDS analysis; (c)—resulting spectrum and chemical composition at the analyzed area.

3.3. Frictional Heat Resistance

The results of evaluation of the frictional heat resistance of PEO coatings during the tests of the samples using the “ring–ring” end friction scheme are presented in Figure 7.

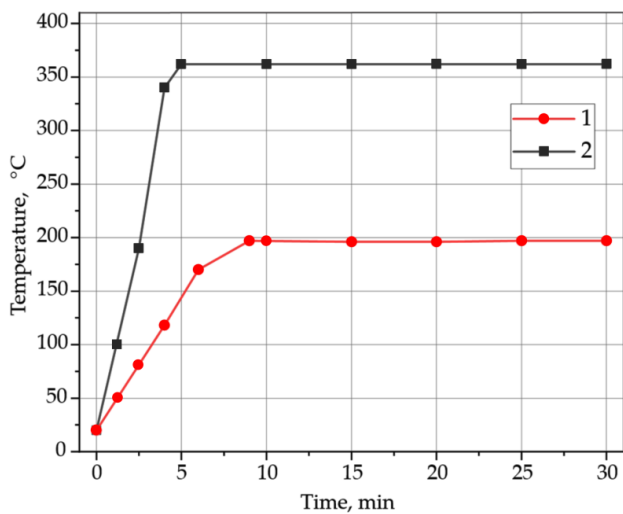


Figure 7. Dependence of the temperature in the friction zone according to the “ring–ring” scheme on the duration of the tests: 1—D16T alloy with PEO coating; 2—steel 40ChN.

From the graphic dependences (Figure 7) of temperature changes in the friction zone on the duration of the tests, the temperature in the contact zone of the samples with the PEO coating stabilizes approximately 9–10 min after the start of the tests, reaches values from 192 to 197 °C, and practically does not change during further wear oxide coating (30 min). During testing of samples made of 40ChN steel, a higher temperature was established in the contact zone, which reached rather high values from 345 to 362 °C, in a less short period of time from 4 min to 6 min after the start of the tests. This attests to the high heat-shielding properties of the oxide ceramic coating and is consistent with the results of research by Curran J. et al. [88], where a low coefficient of thermal conductivity of PEO coatings is indicated, the value of which is from 0.5 to 1.5 W·m⁻¹·K⁻¹. Oxides in the composition of the ceramic coating formed by PEO provide high heat-shielding properties of the composition and protection of the base made of aluminum deformed alloy D16T from temperature effects and wear.

Further research is planned to study the effect of heating on the occurrence of thermal stresses in PEO ceramic coatings.

4. Conclusions

As a result of studies of the PEO technological process PEO in the flowing electrolyte of aluminum deformed alloy D16T:

- A mathematical model of the PEO process was built, based on which it was established that the optimal values of the technological parameters to ensure obtaining the maximum microhardness and minimal wear practically coincide, and, for cone-likeness, they do not coincide either with the optimal technological parameters for microhardness and wear or with each other;
- It was established that, in order to ensure high operational performance of parts with an oxide coating, optimization should be carried out according to minimum wear, which is achieved with the following values of the optimal technological parameters of the PEO process: mass ratio of concentrations of electrolyte components $C = 4.98$; current density $i = 6.61$ A/dm²; electrolyte flow rate in the electrochemical cell $v = 103.96$ cm/s; temperature of the electrolyte $T = 53.59$ °C; and necessary cone-likeness of the surface of the aluminum part should be obtained during further machining operations;
- Vertical mounting of cylindrical parts in the electrochemical cell is justified in order to eliminate the cone-likeness in the PEO process that arose during the previous operations of mechanical processing of the workpiece; for shafts, the minimum diameter of the surface on which the oxide coating is formed is from below, and, for bushings, respectively, from below, the maximum internal diameter to increase the accuracy of parts with oxide coatings since during formation of the oxide coating there is a maximum increase in diameter for external surfaces and a decrease for internal surfaces from bottom to top;
- The results of the SEM analysis of the microstructure of the oxide ceramic coating indicate the presence in the composition of oxides formed from the chemical elements of the alloy material and electrolyte components, the presence of pores, as well as the absence of through cracks;
- Research results showed high friction heat resistance of the oxide ceramic coating, which provides protection of aluminum alloy parts during dry friction, while the temperature stabilization time in the friction zone for a pair of samples with an oxide ceramic coating on the D16T alloy is twice as long as for a pair of samples with steel 40ChN.

Author Contributions: Conceptualization, L.R., A.V. and V.B.; methodology, L.R., T.S., A.V. and V.B.; software, L.R., A.V. and V.B.; validation, L.R., T.S., A.V., V.B. and M.R.; formal analysis, L.R., A.V., V.M. and M.R.; investigation, L.R., A.V., V.M., V.B. and M.R.; resources, L.R., T.S. and V.B.; data curation, L.R. and A.V.; writing—original draft preparation, L.R., A.V. and V.B.; writing—review and editing, L.R. and A.V.; visualization, L.R., T.S., A.V. and V.B.; supervision, L.R. and A.V.; project administration, L.R. and A.V.; funding acquisition, L.R. and A.V. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Ministry of Science and Education of Ukraine for the grant to implement projects 0121U109591 and 0122U002082.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Acknowledgments: The authors are grateful for help in statistical data processing hab. inż. Michał Bembenek, AGH, Department of Manufacturing Systems, Faculty of Mechanical Engineering and Robotics, AGH University of Science and Technology, Krakow, Poland. The authors are also grateful for thorough consultations with Vasyl Vytvytskyi and Tetiana Pryhorovska, Department of Engineering and Computer Graphics, Ivano-Frankivsk National Technical University of Oil and Gas. The authors thank the team of the Center for collective use of scientific instruments “Center for Electron Microscopy and X-ray Microanalysis” of the Karpenko Physico-mechanical Institute, National Academy of Sciences of Ukraine, Lviv for promptly conducting microscopic studies of PEO ceramic coatings on aluminum. The team of authors express their gratitude to the reviewers for valuable recommendations that have been taken into account to significantly improve the quality of this paper.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Cooke, K.O. Introductory Chapter: Structural Aluminum Alloys and Composites. In *Aluminium Alloys and Composites*; Cooke, K.O., Ed.; IntechOpen: London, UK, 2020; pp. 1–14. [\[CrossRef\]](#)
2. Bhatta, L.; Pesin, A.; Zhilyaev, A.P.; Tandon, P.; Kong, C.; Yu, H. Recent Development of Superplasticity in Aluminum Alloys: A Review. *Metals* **2020**, *10*, 77. [\[CrossRef\]](#)
3. Georgantzia, E.; Gkantou, M.; Kamaris, G. Aluminium alloys as structural material: A review of research. *Eng. Struct.* **2021**, *227*, 111372. [\[CrossRef\]](#)
4. Vlasii, O.; Mazurenko, V.; Ropyak, L.; Rogal, O. Improving the aluminum drill pipes stability by optimizing the shape of protector thickening. *East. Eur. J. Enterpr. Technol.* **2017**, *1*, 25–31. [\[CrossRef\]](#)
5. Varshney, D.; Kumar, K. Application and use of different aluminium alloys with respect to workability, strength and welding parameter optimization. *Ain Shams Eng. J.* **2021**, *12*, 1143–1152. [\[CrossRef\]](#)
6. Bazaluk, O.; Velychkovych, A.; Ropyak, L.; Pashechko, M.; Pryhorovska, T.; Lozynskyi, V. Influence of Heavy Weight Drill Pipe Material and Drill Bit Manufacturing Errors on Stress State of Steel Blades. *Energies* **2021**, *14*, 4198. [\[CrossRef\]](#)
7. Czerwinski, F. Thermal Stability of Aluminum Alloys. *Materials* **2020**, *13*, 3441. [\[CrossRef\]](#)
8. Timelli, G.; Fabrizi, A.; Vezzù, S.; De Mori, A. Design of Wear-Resistant Diecast AlSi₉Cu₃(Fe) Alloys for High-Temperature Components. *Metals* **2020**, *10*, 55. [\[CrossRef\]](#)
9. Udoye, N.E.; Fayomi, O.S.I.; Inegbenebor, A.O. Assessment of Wear Resistance of Aluminium Alloy in Manufacturing Industry-A Review. *Procedia Manuf.* **2019**, *35*, 1383–1386. [\[CrossRef\]](#)
10. Chokshi, A.H.; Meyers, M. The prospects for superplasticity at high strain rates: Preliminary considerations and an example. *Scr. Metall. Mater.* **1990**, *24*, 605–610. [\[CrossRef\]](#)
11. Sergueeva, A.V.; Mara, N.A.; Mukherjee, A.K. Grain Size Distribution Effect on Mechanical Behavior of Nanocrystalline Materials. *MRS Online Proc. Libr.* **2004**, *821*, 336–342. [\[CrossRef\]](#)
12. Chen, Y.; Zhao, S.; Ma, H.; Wang, H.; Hua, L.; Fu, S. Analysis of Hydrogen Embrittlement on Aluminum Alloys for Vehicle-Mounted Hydrogen Storage Tanks: A Review. *Metals* **2021**, *11*, 1303. [\[CrossRef\]](#)
13. Shatskyi, I.; Vytvytskyi, I.; Senyushkovych, M.; Velychkovych, A. Modelling and improvement of the design of hinged centralizer for casing. *IOP Conf. Ser. Mater. Sci. Eng.* **2019**, *564*, 12073. [\[CrossRef\]](#)
14. Barrak, F.N.; Li, S.; Muntane, A.M. Particle release from implantoplasty of dental implants and impact on cells. *Int. J. Implant. Dent.* **2020**, *6*, 50. [\[CrossRef\]](#) [\[PubMed\]](#)
15. Bazaluk, O.; Chuzhak, A.; Sulyma, V.; Velychkovych, A.; Ropyak, L.; Vytvytskyi, V.; Mykhailiuk, V.; Lozynskyi, V. Determining the Tightrope Tightening Force for Effective Fixation of the Tibiofibular Syndesmosis during Osteomeatal Synthesis of Fibula Injuries. *Appl. Sci.* **2022**, *12*, 4903. [\[CrossRef\]](#)

16. Pelekhan, B.; Dutkiewicz, M.; Shatskyi, I.; Velychkovych, A.; Rozhko, M.; Pelekhan, L. Analytical Modeling of the Interaction of a Four Implant-Supported Overdenture with Bone Tissue. *Materials* **2022**, *15*, 2398. [\[CrossRef\]](#) [\[PubMed\]](#)
17. Zhang, Z.; Sun, C.; Xu, X.; Liu, L. Surface quality and forming characteristics of thin-wall aluminium alloy parts manufactured by laser assisted MIG arc additive manufacturing. *Int. J. Lightweight Mater. Manuf.* **2018**, *1*, 89–95. [\[CrossRef\]](#)
18. Zinchenko, A.; Baiul, K.; Krot, P.; Khudyakov, A.; Vashchenko, S.; Banasiewicz, A.; Wróblewski, A. Materials Selection and Design Options Analysis for a Centrifugal Fan Impeller in a Horizontal Conveyor Dryer. *Materials* **2021**, *14*, 6696. [\[CrossRef\]](#)
19. Levchuk, K.G.; Moisyshyn, V.M.; Tsidylo, I.V. Influence of mechanical properties of a material on dynamics of the stuck drilling pipes. *Metallfiz. Noveishie Tekhnologii* **2016**, *38*, 1655–1668. [\[CrossRef\]](#)
20. Dean, J.; Gu, T.; Clyne, T.W. Evaluation of residual stress levels in plasma electrolytic oxidation coatings using a curvature method. *Surf. Coat. Technol.* **2015**, *269*, 47–53. [\[CrossRef\]](#)
21. Tatsiy, R.M.; Pazen, O.Y.; Vovk, S.Y.; Ropyak, L.Y.; Pryhorovska, T.O. Numerical study on heat transfer in multilayered structures of main geometric forms made of different materials. *J. Serb. Soc. Comput. Mech.* **2019**, *13*, 36–55. [\[CrossRef\]](#)
22. Tatsiy, R.; Stasiuk, M.; Pazen, O.; Vovk, S. Modeling of Boundary-Value Problems of Heat Conduction for Multilayered Hollow Cylinder. In Proceedings of the 2018 International Scientific-Practical Conference on Problems of Infocommunications Science and Technology, PIC S and T 2018, Kharkiv, Ukraine, 9–12 October 2018; pp. 21–25.
23. Shaloo, M.; Schnall, M.; Klein, T.; Huber, N.; Reitingner, B. A Review of Non-Destructive Testing (NDT) Techniques for Defect Detection: Application to Fusion Welding and Future Wire Arc Additive Manufacturing Processes. *Materials* **2022**, *15*, 3697. [\[CrossRef\]](#) [\[PubMed\]](#)
24. Bembenek, M.; Mandziy, T.; Ivasenko, I.; Berehulyak, O.; Vorobel, R.; Slobodyan, Z.; Ropyak, L. Multiclass Level-Set Segmentation of Rust and Coating Damages in Images of Metal Structures. *Sensors* **2022**, *22*, 7600. [\[CrossRef\]](#) [\[PubMed\]](#)
25. Student, M.M.; Ivasenko, I.B.; Posuvailo, V.M.; Veselivs'ka, H.H.; Pokhmurs'kyi, A.Y.; Sirak, Y.Y.; Yus'kiv, V.M. Influence of the Porosity of a Plasma-Electrolytic Coating on the Corrosion Resistance of D16 Alloy. *Mater. Sci.* **2019**, *54*, 899–906. [\[CrossRef\]](#)
26. Chen, Z.; Zhou, K.; Lu, X.; Lam, Y.C. A review on the mechanical methods for evaluating coating adhesion. *Acta Mech.* **2014**, *225*, 431–452. [\[CrossRef\]](#)
27. Abadias, G.; Chason, E.; Keckes, J.; Sebastiani, M.; Thompson, G.B.; Barthel, E.; Doll, G.L.; Murray, C.E.; Stoessel, C.H.; Martinu, L. Review Article: Stress in thin films and coatings: Current status, challenges, and prospects. *J. Vac. Sci. Technol. A* **2018**, *36*, 020801. [\[CrossRef\]](#)
28. Ropyak, L.Y.; Velychkovych, A.S.; Vytvytskyi, V.S.; Shovkopliash, M.V. Analytical study of “crosshead-slide rail” wear effect on pump rod stress state. *J. Phys. Conf. Ser.* **2021**, *1741*, 12039. [\[CrossRef\]](#)
29. Dubei, O.Y.; Tutko, T.F.; Ropyak, L.Y.; Shovkopliash, M.V. Development of Analytical Model of Threaded Connection of Tubular Parts of Chrome-Plated Metal Structures. *Metallfiz. Noveishie Tekhnologii* **2022**, *44*, 251–272. [\[CrossRef\]](#)
30. Szczepankowski, A.; Przysowa, R.; Perczyński, J.; Kułaszka, A. Health and Durability of Protective and Thermal Barrier Coatings Monitored in Service by Visual Inspection. *Coatings* **2022**, *12*, 624. [\[CrossRef\]](#)
31. Duriagina, Z.A.; Kulyk, V.V.; Filimonov, O.S.; Trostianchyn, A.M.; Sokulska, N.B. The role of stress–strain state of gas turbine engine metal parts in predicting their safe life. *Prog. Phys. Met.* **2021**, *22*, 643–677. [\[CrossRef\]](#)
32. Dolgov, N.A. Analytical Methods to Determine the Stress State in the Substrate–Coating System Under Mechanical Loads. *Strength Mater.* **2016**, *48*, 658–667. [\[CrossRef\]](#)
33. Wheeler, J.M.; Curran, J.A.; Shrestha, S. Microstructure and multi-scale mechanical behavior of hard anodized and plasma electrolytic oxidation (PEO) coatings on aluminum alloy 5052. *Surf. Coat. Technol.* **2012**, *207*, 480–488. [\[CrossRef\]](#)
34. Shi, Y.; Wang, Y.; Cheng, C. Properties and Structure of PEO Treated Aluminum Alloy. *J. Wuhan Univ. Technol. Mat. Sci. Ed.* **2021**, *36*, 424–432. [\[CrossRef\]](#)
35. Shatskyi, I.P.; Makoviichuk, M.V.; Shcherbii, A.B. Equilibrium of cracked shell with flexible coating. In *Shell Structures: Theory and Applications*; CRC Press: Leiden, The Netherlands, 2018; Volume 4, pp. 165–168. [\[CrossRef\]](#)
36. Shatskyi, I.P.; Makoviichuk, M.V.; Shcherbii, A.B. Influence of flexible coating on the limit equilibrium of a spherical shell with meridional crack. *Mater. Sci.* **2020**, *55*, 484–491. [\[CrossRef\]](#)
37. Shats'kyi, I.P.; Makoviichuk, M.V. Contact interaction of the crack edges in the case of bending of a plate with elastic support. *Mater. Sci.* **2003**, *39*, 371–376. [\[CrossRef\]](#)
38. Nobili, A.; Radi, E.; Lanzoni, L. A cracked infinite Kirchhoff plate supported by a two-parameter elastic foundation. *J. Eur. Ceram. Soc.* **2014**, *34*, 2737–2744. [\[CrossRef\]](#)
39. Shatskyi, I.P.; Ropyak, L.Y.; Makoviichuk, M.V. Strength optimization of a two-layer coating for the particular local loading conditions. *Strength Mater.* **2016**, *48*, 726–730. [\[CrossRef\]](#)
40. Ropyak, L.Y.; Makoviichuk, M.V.; Shatskyi, I.P.; Pritula, I.M.; Gryn, L.O.; Belyakovskiy, V.O. Stressed state of laminated interference-absorption filter under local loading. *Funct. Mater.* **2020**, *27*, 638–642. [\[CrossRef\]](#)
41. Bembenek, M.; Makoviichuk, M.; Shatskyi, I.; Ropyak, L.; Pritula, I.; Gryn, L.; Belyakovskiy, V. Optical and Mechanical Properties of Layered Infrared Interference Filters. *Sensors* **2022**, *22*, 8105. [\[CrossRef\]](#)
42. Shyrovkov, V.V.; Maksymuk, O.V. Analytic Methods of Calculation of the Contact Interaction of Thin-Walled Structural Elements (Review). *Mater. Sci.* **2002**, *38*, 62–73. [\[CrossRef\]](#)
43. Kul'chyts'kyi-Zhyhailo, R.; Bajkowski, A. Elastic Coating with Inhomogeneous Interlayer Under the Action of Normal and Tangential Forces. *Mater. Sci.* **2014**, *49*, 650–659. [\[CrossRef\]](#)

44. Ropyak, L.Y.; Shatskyi, I.P.; Makoviichuk, M.V. Influence of the Oxide-Layer Thickness on the Ceramic–Aluminium Coating Resistance to Indentation. *Metallfiz. Noveishie Tekhnol.* **2017**, *39*, 517–524. [\[CrossRef\]](#)
45. Kusi, Y.M.; Kuk, A.M. Investigation of the technological damageability of castings at the stage of design and technological preparation of the machine Life Cycle. *J. Phys. Conf. Ser.* **2020**, *1426*, 12034. [\[CrossRef\]](#)
46. Kusi, Y.; Onysko, O.; Kuk, A.; Solohub, B.; Kopei, V. Development of the Technique for Designing Rational Routes of the Functional Surfaces Processing of Products. In *New Technologies, Development and Application V*; Lecture Notes in Networks and Systems; Springer: Berlin/Heidelberg, Germany, 2022; Volume 472, pp. 135–143. [\[CrossRef\]](#)
47. Sathish, M.; Radhika, N.; Saleh, B. A critical review on functionally graded coatings: Methods, properties, and challenges. *Compos. Part B Eng.* **2021**, *225*, 109278. [\[CrossRef\]](#)
48. Kusi, J.; Kuk, A. Acentrifugal vibration strengthening method devised to improve technological reliability of machine parts. *East. Eur. J. Enterp. Technol.* **2015**, *1*, 41–51. [\[CrossRef\]](#)
49. Morduk, B.N.; Silberschmidt, V.V.; Prokopenko, G.I.; Nesterenko, Y.V.; Iefimov, M.O. Ti particle-reinforced surface layers in Al: Effect of particle size on microstructure, hardness and wear. *Mater. Charact.* **2010**, *61*, 1126–1134. [\[CrossRef\]](#)
50. Pokhmurs'ka, H.V.; Student, M.M.; Chervins'ka, N.R.; Smetana, K.R.; Wank, A.; Hoenig, T.; Podlesak, H. Structure and properties of aluminum alloys modified with silicon carbide by laser surface treatment. *Mater. Sci.* **2005**, *41*, 316–323. [\[CrossRef\]](#)
51. Gaponova, O.; Kundera, C.; Kirik, G.; Tarelnyk, V.; Martsynkovskyy, V.; Konoplianchenko, I.; Dovzhyk, M.; Belous, A.; Vasilenko, O. Estimating qualitative parameters of aluminized coating obtained by electric spark alloying method. In *Advances in Thin Films, Nanostructured Materials, and Coatings*; Lecture Notes in Mechanical Engineering; Springer: Berlin/Heidelberg, Germany, 2019; pp. 249–266. [\[CrossRef\]](#)
52. Hutsaylyuk, V.; Student, M.; Zadorozhna, K.; Student, O.; Veselivska, H.; Gvosdetskii, V.; Maruschak, P.; Pokhmurska, H. Improvement of wear resistance of aluminum alloy by HVOF method. *J. Mater. Res. Technol.* **2020**, *9*, 16367–16377. [\[CrossRef\]](#)
53. Peltier, F.; Thierry, D. Review of Cr-Free Coatings for the Corrosion Protection of Aluminum Aerospace Alloys. *Coatings* **2022**, *12*, 518. [\[CrossRef\]](#)
54. Student, M.M.; Pohreluk, I.M.; Hvozdetzkyi, V.M.; Veselivska, H.H.; Zadorozhna, K.R.; Mardarevych, R.S.; Dzioba, Y.V. Influence of the Composition of Electrolyte for Hard Anodizing of Aluminum on the Characteristics of Oxide Layer. *Mater. Sci.* **2021**, *57*, 240–247. [\[CrossRef\]](#)
55. Mohedano, M.; Lu, X.; Matykina, E.; Blawert, C.; Arrabal, R.; Zheludkevich, M.L. Plasma electrolytic oxidation (PEO) of metals and alloys. In *Encyclopedia of Interfacial Chemistry: Surface Science and Electrochemistry*; Wandelt, K., Ed.; Elsevier: Amsterdam, The Netherlands, 2018; pp. 423–438. [\[CrossRef\]](#)
56. Clyne, T.W.; Troughton, S.C. A review of recent work on discharge characteristics during plasma electrolytic oxidation of various metals. *Int. Mater. Rev.* **2019**, *64*, 127–162. [\[CrossRef\]](#)
57. Simchen, F.; Sieber, M.; Kopp, A.; Lampke, T. Introduction to Plasma Electrolytic Oxidation—An Overview of the Process and Applications. *Coatings* **2020**, *10*, 628. [\[CrossRef\]](#)
58. Sikdar, S.; Menezes, P.V.; Maccione, R.; Jacob, T.; Menezes, P.L. Plasma Electrolytic Oxidation (PEO) Process—Processing, Properties, and Applications. *Nanomaterials* **2021**, *11*, 1375. [\[CrossRef\]](#)
59. Qin, J.; Shi, X.; Li, H.; Zhao, R.; Li, G.; Zhang, S.; Ding, L.; Cui, X.; Zhao, Y.; Zhang, R. Performance and failure process of green recycling solutions for preparing high degradation resistance coating on biomedical magnesium alloys. *Green Chem.* **2022**, *24*, 8113–8130. [\[CrossRef\]](#)
60. Protsenko, V.S.; Bobrova, L.S.; Baskevich, A.S.; Korniy, S.A.; Danilov, F.I. Electrodeposition of chromium coatings from a choline chloride based ionic liquid with the addition of water. *J. Chem. Technol. Metall.* **2018**, *53*, 906–915.
61. Protsenko, V.S.; Bobrova, L.S.; Golubtsov, D.E.; Korniy, S.A.; Danilov, F.I. Electrolytic Deposition of Hard Chromium Coatings from Electrolyte Based on Deep Eutectic Solvent. *Russ. J. Appl. Chem.* **2018**, *91*, 1106–1111. [\[CrossRef\]](#)
62. Bazaluk, O.; Dubei, O.; Ropyak, L.; Shovkoplias, M.; Pryhorovska, T.; Lozynskyi, V. Strategy of Compatible Use of Jet and Plunger Pump with Chrome Parts in Oil Well. *Energies* **2022**, *15*, 83. [\[CrossRef\]](#)
63. Tang, Q.; Qiu, T.; Ni, P.; Zhai, D.; Shen, J. Soft Sparking Discharge Mechanism of Micro-Arc Oxidation Occurring on Titanium Alloys in Different Electrolytes. *Coatings* **2022**, *12*, 1191. [\[CrossRef\]](#)
64. Rokosz, K.; Hryniewicz, T.; Dudek, Ł. Phosphate Porous Coatings Enriched with Selected Elements via PEO Treatment on Titanium and Its Alloys: A Review. *Materials* **2020**, *13*, 2468. [\[CrossRef\]](#)
65. Shi, X.; Wang, Y.; Li, H.; Zhang, S.; Zhao, R.; Li, G.; Zhang, R.; Sheng, Y.; Cao, S.; Zhao, Y.; et al. Corrosion resistance and biocompatibility of calcium-containing coatings developed in near-neutral solutions containing phytic acid and phosphoric acid on AZ31B alloy. *J. Alloys Compd.* **2020**, *823*, 153721. [\[CrossRef\]](#)
66. Wang, Y.L.; Jiang, Z.H.; Yao, Z.P. Microstructure, bonding strength and thermal shock resistance of ceramic coatings on steels prepared by plasma electrolytic oxidation. *Appl. Surf. Sci.* **2009**, *256*, 650–656. [\[CrossRef\]](#)
67. Mahmoud, E.R.I.; Algahtani, A.; Tirth, V. Study on Microstructure Characterisation of Three Different Surface Coating Techniques on 6082-T6 Aluminum Alloy. *Met. Mater. Int.* **2021**, *27*, 4002–4013. [\[CrossRef\]](#)
68. Berladir, K.; Hovorun, T.; Gusak, O.; Reshetniak, Y.; Khudaybergenov, D. Influence of Modifiers-Ligatures on the Properties of Cast Aluminum Alloy AK5M2 for the Automotive Industry. In *Advances in Design, Simulation and Manufacturing III, DSMIE 2020*; Ivanov, V., Trojanowska, J., Pavlenko, I., Zajac, J., Peraković, D., Eds.; Lecture Notes in Mechanical Engineering; Springer: Cham, Switzerland, 2020; pp. 473–482. [\[CrossRef\]](#)

69. Pokhmurskii, V.I.; Zin, I.M.; Vynar, V.A.; Khlopyk, O.P.; Bily, L.M. Corrosive wear of aluminium alloy in presence of phosphate. *Corros. Eng. Sci. Technol.* **2012**, *47*, 182–187. [\[CrossRef\]](#)
70. Vynar, V.A.; Pokhmurs'kyi, V.I.; Zin', I.M.; Vasylyv, K.B.; Khlopyk, O.P. Determination of the Mechanism of Tribocorrosion of D16T Alloy According to the Electrode Potential. *Mater. Sci.* **2018**, *53*, 717–723. [\[CrossRef\]](#)
71. Wang, Z.J.; Nie, X.Y.; Hu, H.; Hussein, R.O. In situ fabrication of blue ceramic coatings on wrought Al alloy 2024 by plasma electrolytic oxidation. *J. Vac. Sci. Technol. A* **2012**, *30*, 021302. [\[CrossRef\]](#)
72. Melnick, A.B.; Soolshenko, V.K.; Levchuk, K.H. Thermodynamic Prediction of Phase Composition of Transition Metals High-Entropy Alloys. *Metallofiz. Noveishie Tekhnologii* **2020**, *42*, 1387–1400. [\[CrossRef\]](#)
73. Radchenko, T.M.; Tatarenko, V.A.; Zapolsky, H.; Blavette, D. Statistical-thermodynamic description of the order-disorder transformation of D0(19)-type phase in Ti-Al alloy. *J. Alloy. Compd.* **2008**, *452*, 122–126. [\[CrossRef\]](#)
74. Shihab, T.; Prysyazhnyuk, P.; Semyanyk, I.; Anrusyshyn, R.; Ivanov, O.; Troshchuk, L. Thermodynamic Approach to the Development and Selection of Hardfacing Materials in Energy Industry. *Manag. Syst. Prod. Eng.* **2020**, *28*, 84–89. [\[CrossRef\]](#)
75. Prysyazhnyuk, P.; Shlapak, L.; Semyanyk, I.; Kotsyubynsky, V.; Troshchuk, L.; Korniy, S.; Artym, V. Analysis of the effects of alloying with Si and Cr on the properties of manganese austenite based on AB INITIO modelling. *East. Eur. J. Enterpr. Technol.* **2020**, *6*, 28–36. [\[CrossRef\]](#)
76. Karnaukhov, I.M.; Levchuk, K.H. Electronic band structure of Dirac materials with Hubbard interaction. *Metallofiz. Noveishie Tekhnologii* **2022**, *5*, 565–585. [\[CrossRef\]](#)
77. Wang, S.; Liu, X.; Yin, X.; Du, N. Influence of electrolyte components on the microstructure and growth mechanism of plasma electrolytic oxidation coatings on 1060 aluminum alloy. *Surf. Coat. Technol.* **2020**, *381*, 125214. [\[CrossRef\]](#)
78. Lee, J.H.; Jung, K.H.; Kim, S.J. Characterization of ceramic oxide coatings prepared by plasma electrolytic oxidation using pulsed direct current with different duty ratio and frequency. *Appl. Surf. Sci.* **2020**, *516*, 146049. [\[CrossRef\]](#)
79. Li, X.-J.; Zhang, M.; Wen, S.; Mao, X.; Huo, W.-G.; Guo, Y.-Y.; Wang, Y.-X. Microstructure and wear resistance of micro-arc oxidation ceramic coatings prepared on 2A50 aluminum alloys. *Surf. Coat. Technol.* **2020**, *394*, 125853. [\[CrossRef\]](#)
80. Rogov, A.B.; Huang, Y.; Shore, D.; Matthews, A.; Yerokhin, A. Toward rational design of ceramic coatings generated on valve metals by plasma electrolytic oxidation: The role of cathodic polarisation. *Ceram. Int.* **2021**, *47*, 34137–34158. [\[CrossRef\]](#)
81. Mengesha, G.A.; Chu, J.P.; Lou, B.-S.; Lee, J.-W. Effects of Processing Parameters on the Corrosion Performance of Plasma Electrolytic Oxidation Grown Oxide on Commercially Pure Aluminum. *Metals* **2020**, *10*, 394. [\[CrossRef\]](#)
82. Pokhmurs'kyi, V.I.; Dovhunyk, V.M.; Student, M.M.; Klapkiv, M.D.; Posuvailo, V.M.; Kytsya, A.R. Influence of silver nanoparticles added to lubricating oil on the tribological behavior of combined metal-oxide ceramic layers. *Mater. Sci.* **2013**, *48*, 636–641. [\[CrossRef\]](#)
83. Student, M.M.; Dovhunyk, V.M.; Posuvailo, V.M.; Koval'chuk, I.V.; Hvozdet's'kyi, V.M. Friction Behavior of Iron-Carbon Alloys in Couples with Plasma-Electrolytic Oxide-Ceramic Layers Synthesized on D16T Alloy. *Mater. Sci.* **2017**, *53*, 359–367. [\[CrossRef\]](#)
84. Kotsyubynsky, V.; Shyyko, L.; Shihab, T.; Prysyazhnyuk, P.; Aulin, V.; Boichuk, V. Multilayered MoS₂/C nanospheres as high performance additives to lubricating oils. *Mater. Today Proc.* **2019**, *35*, 538–541. [\[CrossRef\]](#)
85. Hutsaylyuk, V.; Student, M.; Dovhunyk, V.; Posuvailo, V.; Student, O.; Maruschak, P.; Koval'chuk, I. Effect of Hydrogen on the Wear Resistance of Steels upon Contact with Plasma Electrolytic Oxidation Layers Synthesized on Aluminum Alloys. *Metals* **2019**, *9*, 280. [\[CrossRef\]](#)
86. Shen, X.; Nie, X.; Hu, H.; Tjong, J. Effects of coating thickness on thermal conductivities of alumina coatings and alumina/aluminum hybrid materials prepared using plasma electrolytic oxidation. *Surf. Coat. Technol.* **2012**, *207*, 96–101. [\[CrossRef\]](#)
87. Akatsu, T.; Kato, T.; Shinoda, Y.; Wakai, F. Thermal barrier coating made of porous zirconium oxide on a nickel-based single crystal superalloy formed by plasma electrolytic oxidation. *Surf. Coat. Technol.* **2013**, *223*, 47–51. [\[CrossRef\]](#)
88. Curran, J.A.; Kalkanci, H.; Magurova, Y.; Clyne, T.W. Mullite-rich plasma electrolytic oxide coatings for thermal barrier applications. *Surf. Coat. Technol.* **2006**, *201*, 8683–8687. [\[CrossRef\]](#)
89. Shirani, A.; Joy, T.; Rogov, A.; Lin, M.; Yerokhin, A.; Mogonye, J.-E.; Korenyi-Both, A.; Aouadi, S.M.; Voevodin, A.A.; Berman, D. PEO-Chameleon as a potential protective coating on cast aluminum alloys for high-temperature applications. *Surf. Coat. Technol.* **2020**, *397*, 126016. [\[CrossRef\]](#)
90. Shen, D.J.; Wang, Y.L.; Nash, P.; Xing, G.Z. Microstructure, temperature estimation and thermal shock resistance of PEO ceramic coatings on aluminum. *J. Mater. Process. Technol.* **2008**, *205*, 477–481. [\[CrossRef\]](#)
91. Dai, W.; Zhang, X.; Li, C.; Yao, G. Effect of thermal conductivity on micro-arc oxidation coatings. *Surf. Eng.* **2022**, *38*, 44–53. [\[CrossRef\]](#)
92. Pakseresht, A.H.; Saremi, M.; Omidvar, H.; Alizadeh, M. Micro-structural study and wear resistance of thermal barrier coating reinforced by alumina whisker. *Surf. Coat. Technol.* **2019**, *366*, 338–348. [\[CrossRef\]](#)
93. Kamalan Kirubakaran, A.M.; Kuppusami, P. Corrosion behavior of ceramic nanocomposite coatings at nanoscale. In *Corrosion Protection at the Nanoscale; Micro and Nano Technologies*; Rajendran, S., Nguyen, T.A., Kakooei, S., Yeganeh, M., Li, Y., Eds.; Elsevier: Amsterdam, The Netherlands, 2020; pp. 295–314. [\[CrossRef\]](#)
94. Matykina, E.; Arrabal, R.; Skeldon, P.; Thompson, G.E. Optimisation of the plasma electrolytic oxidation process efficiency on aluminium. *Surf. Interface Anal.* **2010**, *42*, 221–226. [\[CrossRef\]](#)
95. Vakili-Azghandi, M.; Fattah-alhosseini, A.; Keshavarz, M.K. Optimizing the electrolyte chemistry parameters of PEO coating on 6061 Al alloy by corrosion rate measurement: Response surface methodology. *Measurement* **2018**, *124*, 252259. [\[CrossRef\]](#)

96. Bembenek, M.; Popadyuk, O.; Shihab, T.; Ropyak, L.; Uhryński, A.; Vytvytskyi, V.; Bulbuk, O. Optimization of Technological Parameters of the Process of Forming Therapeutic Biopolymer Nanofilled Films. *Nanomaterials* **2022**, *12*, 2413. [[CrossRef](#)] [[PubMed](#)]
97. Pan, S.; Tu, X.; Yu, J.; Zhang, Y.; Miao, C.; Xu, Y.; Fu, R.; Li, J. Optimization of AZ31B Magnesium Alloy Anodizing Process in NaOH-Na₂SiO₃-Na₂B₄O₇ Environmental-Friendly Electrolyte. *Coatings* **2022**, *12*, 578. [[CrossRef](#)]
98. An, L.; Ma, Y.; Yan, X.; Wang, S.; Wang, Z. Effects of electrical parameters and their interactions on plasma electrolytic oxidation coatings on aluminum substrates. *Trans. Nonferrous Met. Soc. China* **2020**, *30*, 883–895. [[CrossRef](#)]
99. Kaseem, M.; Dikici, B. Optimization of Surface Properties of Plasma Electrolytic Oxidation Coating by Organic Additives: A Review. *Coatings* **2021**, *11*, 374. [[CrossRef](#)]
100. Songur, F.; Arslan, E.; Dikici, B. Taguchi optimization of PEO process parameters for corrosion protection of AA7075 alloy. *Surf. Coat. Technol.* **2022**, *434*, 128202. [[CrossRef](#)]
101. Hladkyi, S.I.; Palazhchenko, S.P. Development of equipment for the study of friction nodes operating in the mode of reciprocating motion. *Sci. Bull. Ivano-Frankivsk Natl. Tech. Univ. Oil Gas* **2015**, *2*, 89–100.
102. Bandura, A.; Skaskiv, O. Analog of Hayman's theorem and its application to some system of linear partial differential equations. *J. Math. Phys. Anal. Geom.* **2019**, *15*, 170–191. [[CrossRef](#)]
103. Premchand, C.; Hariprasad, S.; Saikiran, A.; Lokeshkumar, E.; Manojkumar, P.; Ravisankar, B.; Venkataraman, B.; Rameshbabu, N. Assessment of Corrosion and Scratch Resistance of Plasma Electrolytic Oxidation and Hard Anodized Coatings Fabricated on AA7075-T6. *Trans. Indian Inst. Met.* **2021**, *74*, 1991–2002. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.