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ЭВОЛЮЦИЯ НАУЧНОГО ДИСКУРСА И ИНВЕСТИЦИОННЫХ ПРИОРИТЕТОВ В ОБЛАСТИ РИСКОВ ИНТЕГРАЦИИ ВОЗОБНОВЛЯЕМЫХ ИСТОЧНИКОВ ЭНЕРГИИ: БИБЛИОМЕТРИЧЕСКИЙ АНАЛИЗ

В статье анализируется структура научного понимания рисков интеграции возобновляемых источников энергии. На основе библиометрического анализа 4823 публикаций базы данных Web of Science (2015-2025) были выявлены три устойчивых тематических кластера и продемонстрировано доминирование парадигмы системной оптимизации в условиях неопределенности. Научная новизна исследования заключается в разработке индекса релевантности системы – показателя для количественного ранжирования стратегий снижения рисков на основе топологии библиометрической сети; был выявлен разрыв между научными приоритетами и инвестиционной практикой: для ряда технологий он достигает +0,6 по нормализованной шкале. Динамический анализ публикаций за три периода времени (2015-2018; 2019-2021; 2022-2025) выявил сдвиг в программе исследований от нормативных подходов к инженерному менеджменту.

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INFLUENCE OF MICRO-ARC OXIDATION PROCESSING PARAMETERS ON THE STRUCTURE AND PROPERTIES OF ALUMINOSILICATE COATINGS FORMED ON AMG6 ALUMINUM ALLOY

Abstract: *The work presents a comprehensive study of the formation processes, structure, phase composition, and performance properties of oxide coatings produced on the AMG6 aluminum alloy by the micro-arc oxidation method. The treatment was carried out using a laboratory setup equipped with a pulsed power supply and a temperature control system, ensuring stable electrical and thermal regimes. The use of silicate-alkaline electrolytes of various compositions made it possible to purposefully control the morphology*

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and properties of the coatings. Scanning electron microscopy and energy-dispersive analysis revealed the formation of multilayer oxide coatings with a dense inner barrier layer and a well-developed porous outer layer. The coating thickness ranged from 27-33 μm. X-ray diffraction analysis confirmed the formation of crystalline modifications of aluminum oxide and the aluminosilicate phase mullite under energy-intensive processing conditions. Tribological tests demonstrated that the different MAO regimes provide distinct functional advantages. The Al-3 coating exhibited the lowest coefficient of friction (0.45-0.50), whereas the Al-1 coating showed the smallest wear area. Electrochemical measurements further demonstrated that Al-1 exhibited the highest corrosion resistance, characterized by the lowest corrosion current density among the investigated coatings. These results indicate that the optimal MAO regime should be selected according to the specific tribological and corrosion requirements of the intended application.

Key words: *micro-arc oxidation, AMG6 aluminum alloy, oxide coatings, tribological properties, corrosion resistance.*

Introduction

Improving the performance characteristics of metallic materials is an important task of modern industry, especially for components operating under high mechanical, thermal, and chemical loads. To enhance wear resistance and corrosion resistance, various surface modification methods are widely used, among which micro-arc oxidation (MAO), also known as anodic spark oxidation, is particularly effective [1, 2].

MAO is an electrochemical process that occurs in an aqueous electrolyte under the action of high-voltage pulsed current and is accompanied by the generation of micro-discharges, local melting, and rapid crystallization of the material. As a result, strong ceramic oxide coatings with a complex phase composition are formed, the properties of which are determined by the electrical parameters, electrolyte composition, and process temperature [3-6].

The stability of the MAO process and the quality of the coatings largely depend on thermal control, since the process is accompanied by intense heat generation. The use of setups with controlled heating and cooling systems makes it possible to ensure the reproducibility of processing regimes, regulate the growth and morphology of the oxide layer, and reduce the number of defects [7-11].

Despite numerous studies on the micro-arc oxidation of aluminum alloys, the influence of MAO processing parameters on the structure and properties of aluminosilicate coatings formed on AMG6 aluminum alloy remains insufficiently investigated. In particular, limited information is available regarding the combined effect of electrolyte composition and electrical processing parameters on coating formation, phase composition, tribological behavior, and corrosion resistance. The aim of this study is to investigate the influence of micro-arc oxidation processing parameters on the structure, phase composition, tribological performance, and corrosion properties of aluminosilicate coatings formed on AMG6 aluminum alloy. The scientific novelty of this work lies in the comparative analysis of different MAO regimes and in establishing their influence on the microstructure, phase composition, tribological characteristics, and corrosion resistance of aluminosilicate coatings. It should be noted that the investigated MAO regimes differ in both electrolyte composition and electrical processing parameters; therefore, this study compares complete processing regimes rather than the isolated influence of individual variables.

Materials and methods of research

The substrate material used in this study was AMG6 aluminum alloy, which is widely employed in aerospace and mechanical engineering applications due to its high specific strength and excellent corrosion resistance. Specimens with dimensions of 30 × 15 × 2 mm were prepared for the experiments. The chemical composition of the alloy is presented in Table 1. Prior to micro-arc oxidation (MAO), the specimen surfaces were mechanically ground using SiC abrasive papers up to P2000 grit. The specimens were subsequently degreased in an alkaline solution at 40–60 °C, rinsed thoroughly with tap water followed by distilled water, and dried in air.

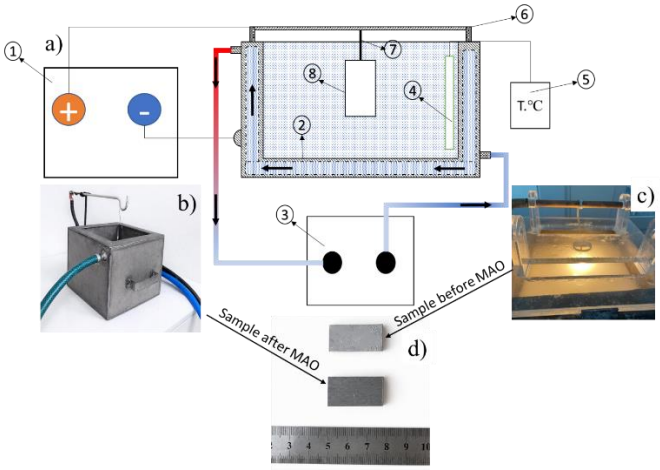
Table 1 – Chemical composition of aluminum AMG6, %

Fe	Si	Mn	Ti	Al	Cu	Be	Mg	Zn	impurities
up to 0.4	up to 0.4	0.5-0.8	0.02-0.1	91.1-93.68	up to 0.1	0.0002-0.005	5.8-6.8	up to 0.2	others, each 0.05; total 0.1

Micro-arc oxidation (MAO) was carried out using a laboratory-scale MAO system equipped with a pulsed power supply (JX-MAO, Lanzhou Jingxin Power Supply Co., Ltd., China), an electrolytic bath, an electrolyte circulation and cooling system, a heat exchanger, and a temperature controller (Figure 1). During the MAO process, the AMG6 aluminum alloy specimen served as the anode, while the stainless-steel electrolytic bath acted as the cathode. The cathode-to-anode surface area ratio was approximately 10:1, ensuring stable micro-arc discharge behavior. The specimens were mounted in a holder and fully immersed in the electrolyte to ensure uniform coating formation.

The electrolyte temperature was maintained at 25-30°C by the circulation and cooling system, while the electrolyte pH was in the range of 12-13 and the electrical conductivity was approximately 18-22 mS/cm. The power supply operated in unipolar pulse mode with a rectangular pulse shape. The pulse repetition rate was 200 Hz, with a duty cycle of 55%, corresponding to a pulse duration of 2.75 ms and a pause duration of 2.25 ms. Control was performed in current stabilization mode; the current density values for each mode are presented in Table 2. The pulsed power supply regulated the applied current throughout the oxidation process. Localized micro-arc discharges generated on the specimen surface promoted the growth of ceramic oxide coatings.

Figure 1 shows the schematic diagram of the MAO system (Figure 1a), the laboratory electrolytic bath (Figure 1b), the micro-arc oxidation process (Figure 1c), and the appearance of the AMG6 aluminum alloy specimens before and after treatment (Figure 1d). Following MAO, the specimen surface changed from metallic to light gray, indicating the formation of an oxide coating. Different MAO regimes were employed by varying both the electrolyte composition and the electrical processing parameters to investigate their effects on the microstructure and properties of the resulting coatings.



(a) basic diagram of the micro-arc oxidation installation; (b) general view of the laboratory electrolytic bath used for micro-arc oxidation of aluminum; (c) photograph of the MAO process during treatment; (d) appearance of aluminum specimens before and after MAO treatment

Figure 1 – Installation for MAO of aluminum samples:

During the treatment, a ceramic porous-sintered coating was formed. The morphology and phase composition of the coatings were studied using SEM/EDS and X-ray diffraction analysis, while the tribological and corrosion properties were evaluated using the «ball-disk» method and potentiodynamic measurements. Wear resistance was assessed using a ball-on-disk configuration on an Anton Paar TRB3 tribometer in accordance with ASTM G99 under a normal load of 6 N and a sliding speed of 3 cm/s, employing a Si_3N_4 ball with a diameter of 6 mm. The wear track radius was 6 mm. Tribological tests were conducted in a 3.5 wt.% NaCl solution at room temperature. Electrochemical corrosion tests were carried out using potentiodynamic polarization measurements in a 3.5 wt.% NaCl aqueous solution, which simulates a chloride-containing corrosive environment. The temperature of the electrolyte during the measurements was maintained at 25 ± 2°C. For comparison, the initial AMG6 alloy and three samples with MAO coatings (Al-1, Al-2 and Al-3) were investigated. All quantitative experiments were performed in triplicate (n = 3) under identical experimental conditions. The numerical results presented in the tables and graphs are reported as mean values ± standard deviation.

Results and discussion

The coatings Al-1, Al-2 and Al-3 correspond to different micro-arc oxidation regimes presented in Table 2, which allows evaluation of the influence of electrolyte composition and electrical parameters on the morphology and properties of the coatings.

Table 2 – Micro-arc oxidation regimes used for coating formation

Sample	Electrolyte composition	Voltage (V)	Frequency (Hz)	Current density (A/dm²)	Treatment time (min)	Coating thickness, μm
Al-1	20 g/L Na_2SiO_3 + 10 g/L KOH	350	200	4.75	20	33
Al-2	20 g/L Na_2SiO_3 + 10 g/L NaOH	250	200	3.25	20	27
Al-3	20 g/L Na_2SiO_3 + 10 g/L NaOH + $Na_2S_2O_3$	350	200	4.25	20	29

The investigated samples differ simultaneously in electrolyte composition and electrical parameters. Therefore, the present work compares integrated MAO processing regimes rather than evaluating the influence of a single processing parameter. Therefore, the present work compares complete MAO processing regimes rather than the isolated effect of individual variables. The selection of electrolyte compositions and micro-arc oxidation processing regimes was based on their expected influence on coating formation, discharge stability, phase composition, and functional properties. Sodium silicate (Na_2SiO_3) was used as the main electrolyte component because it provides silicon-containing species that participate in the formation of aluminosilicate phases and promote the growth of ceramic oxide coatings. KOH and NaOH were selected to create a strongly alkaline environment, increase the electrical conductivity of the electrolyte, and ensure stable micro-arc discharges during processing. The addition of $Na_2S_2O_3$ to the electrolyte for the Al-3 sample was intended to evaluate its effect on coating morphology, porosity, phase formation, and corrosion resistance.

The selected values of voltage, current density, frequency, and treatment time ensured stable micro-arc oxidation without excessive coating damage or burning. A treatment duration of 20 min was sufficient for the formation of continuous oxide coatings, while the chosen ranges of voltage and current density allowed comparison of coatings formed under different energy input conditions. Therefore, the selected electrolyte compositions and processing regimes made it possible to evaluate the relationship between processing parameters, coating structure, phase composition, tribological behavior, and corrosion resistance. As a result of micro-arc oxidation, oxide coatings with a porous-sintered morphology are formed on the surface of the AMG6 aluminum alloy. Na_2SiO_3 was selected as a silicon source for the formation of aluminosilicate phases. NaOH and KOH were used to create the required alkaline environment and to ensure stable micro-arc discharges during the oxidation process. $Na_2S_2O_3$ was added to evaluate its influence on the structure and functional properties of the coatings. This morphology is caused by the localized high-temperature effect of micro-arc discharges and the rapid crystallization of the oxide material. During the coating growth, a system of pores and discharge channels is formed.

The coating structure is heterogeneous and includes a dense inner barrier layer and a more porous outer layer, which provide protection for the aluminum substrate and determine the surface's tribological properties, respectively.

Figures 2a-c show SEM images of the cross-sections of micro-arc oxide coatings on aluminum, obtained under different processing conditions. In all specimens, the "coating-substrate" boundary is clearly defined, indicating good adhesion and the absence of interfacial defects.

The Al-1 specimen exhibits the thickest coating (33 μm) with a relatively dense structure. The Al-2 specimen has the thinnest coating (27 μm), whereas the Al-3 specimen has an intermediate thickness (29 μm) and a more developed porous outer layer.

Figure 3 presents EDS elemental maps and line-scan profiles obtained across the coating cross-sections. For all samples, oxygen is concentrated mainly within the coating layer, confirming the formation of oxide phases, whereas aluminum is predominantly detected in the substrate region. The Al-3 sample exhibits a noticeably higher silicon concentration in the coating compared to Al-1 and Al-2, indicating a more intensive incorporation of silicon-containing species from the electrolyte

into the growing oxide layer. The elemental profiles also reveal a gradual transition between the coating and substrate, suggesting good adhesion and the absence of significant interfacial discontinuities.

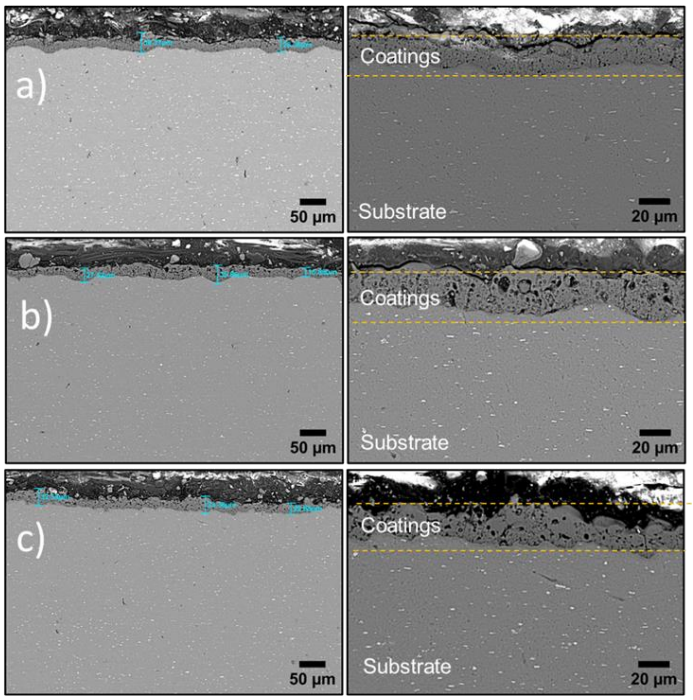


Figure 2 – Cross-sectional SEM micrographs of MAO coatings formed on AMG6 aluminum alloy: (a) Al-1, (b) Al-2, and (c) Al-3

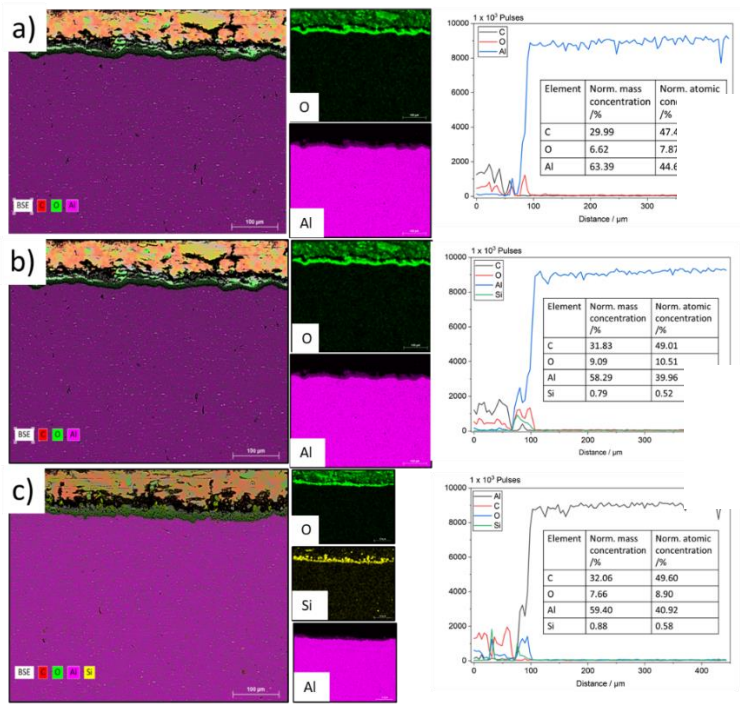


Figure 3 – Cross-sectional EDS elemental maps and line-scan profiles of MAO coatings formed on AMG6 aluminum alloy: (a) Al-1, (b) Al-2, and (c) Al-3

The quantitative EDS results for the Al-1, Al-2, and Al-3 coatings are summarized in Table 3. The elemental composition of all coatings is dominated by C, Al, and O. The Al-1 coating contains 47.47 at.% C, 7.87 at.% O, and 44.67 at.% Al. For the Al-2 and Al-3 coatings, a small amount of Si was additionally detected, reaching 0.52 and 0.58 at.%, respectively. The highest Si content was

observed in the Al-3 coating, indicating a greater incorporation of silicon-containing species from the electrolyte into the coating during the MAO process. These quantitative EDS results complement the elemental distribution presented in Figure 3 and confirm differences in the chemical composition of the coatings formed under different MAO regimes.

Table 3 – Elemental composition of MAO coatings determined by EDS analysis, at.%

Sample	C	O	Al	Si
Al-1	47.47%	7.87%	44.67%	
Al-2	49.01%	10.51%	39.96%	0.52%
Al-3	49.60%	8.90%	40.92%	0.58%

Figure 4 shows the X-ray diffractograms of micro-arc oxide coatings on the AMG6 aluminum alloy, obtained under different processing conditions. In all specimens, intense reflections of metallic aluminum are observed, resulting from the contribution of the substrate during the analysis of thin oxide layers.

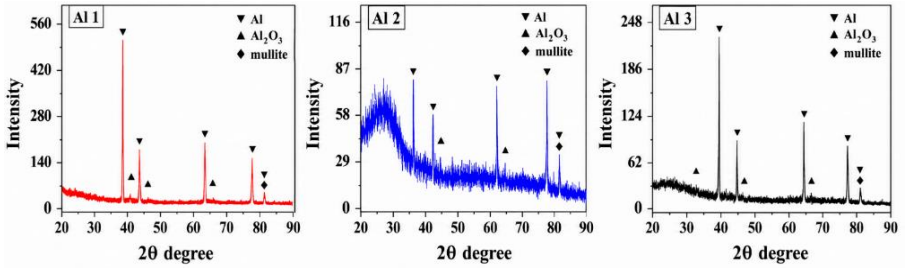


Figure 4 – X-ray diffraction patterns of MAO coatings formed on AMG6 aluminum alloy under different processing conditions

For all coatings, diffraction lines of Al_2O_3 were observed, confirming the formation of a ceramic oxide layer. The Al-1 specimen is characterized by a high degree of coating crystallinity, whereas Al-2 exhibits a partially amorphous structure, manifested by peak broadening and reduced intensity. In the diffractogram of the Al-3 specimen, additional peaks of the aluminosilicate mullite phase ($3Al_2O_3 \cdot 2SiO_2$) are detected, indicating the active involvement of silicon-containing electrolyte components under energy-intensive processing conditions.

Overall, the results of the X-ray phase analysis demonstrate the possibility of purposeful control over the phase composition and degree of crystallinity of micro-arc oxide coatings on the AMG6 aluminum alloy.

Figure 5a shows the dependence of the coefficient of friction on the sliding distance for micro-arc oxide coatings obtained under different processing conditions. All specimens exhibit a run-in stage followed by the establishment of a quasi-stationary friction regime. The Al-1 specimen demonstrates the highest and most unstable coefficient of friction (0.8-0.85). Considering that Al-1 has the greatest coating thickness (33 μm) and a relatively dense structure, its friction behavior cannot be attributed to a thinner coating and may instead be associated with differences in surface morphology, phase composition, and coating–counterbody interaction during sliding.

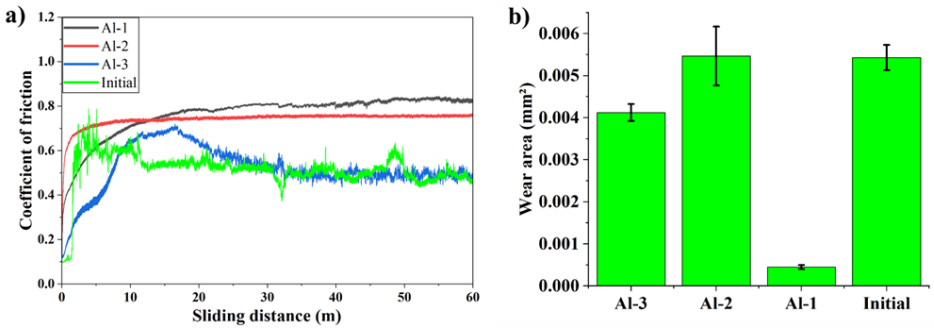


Figure 5 – Tribological characteristics of MAO coatings:
(a) coefficient of friction versus sliding distance; (b) wear area after ball-on-disk testing

For the Al-2 specimen, the coefficient of friction stabilizes rapidly and remains nearly constant, whereas the lowest values are observed for the Al-3 specimen, whose coefficient of friction stabilizes at 0.45-0.5 due to its well-developed porous structure and the presence of aluminosilicate phases.

The wear area (Figure 5b) does not strictly correlate with the friction coefficient. Although the Al-1 specimen exhibits the highest coefficient of friction, it demonstrates the smallest wear area, which can be attributed to the relatively dense structure of the coating and its higher resistance to material removal during sliding. The absence of a direct correlation between the friction coefficient and wear area indicates that wear resistance is mainly governed by the structural integrity and density of the oxide layer rather than by the friction coefficient alone.

In this work, wear resistance was evaluated based on the wear area measured after ball-on-disk testing. A decrease in the wear area corresponds to an increase in wear resistance; therefore, the reported improvement of more than two times refers to the reduction of the wear area compared with the initial alloy.

Overall, the results confirm that the micro-arc oxidation regimes significantly influence the tribological properties of the coatings. Different processing regimes provide different functional advantages depending on the intended application, owing to differences in coating morphology and phase composition.

The base AMG6 aluminum alloy has limited corrosion resistance, due to the presence of a thin and unstable natural oxide film, which is easily degraded in aggressive environments.

Potentiodynamic polarization curves (Figure 6) show that all micro-arc oxide coatings are in a passive state, confirming the formation of a protective oxide layer. The Al-1 specimen is characterized by the lowest corrosion current density and the most pronounced barrier effect, whereas Al-2 exhibits the poorest protective properties, which is associated with the increased porosity of the coating. The Al-3 specimen occupies an intermediate position and demonstrates enhanced corrosion resistance compared to Al-2 due to its denser inner layer and modified phase composition.

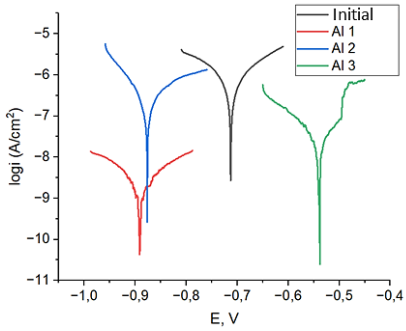


Figure 6 – Potentiodynamic polarization curves of microarc oxide coatings on aluminum alloy AMG6 for samples Al-1, Al-2 and Al-3

Overall, the results confirm that changing the micro-arc oxidation regimes allows for effective control of the coatings' corrosion-resistant properties. Among the investigated coatings, Al-1 exhibited the highest corrosion resistance, whereas Al-3 demonstrated improved corrosion performance compared with Al-2. Therefore, the selection of the optimal processing regime should be based on the required service conditions.

The corrosion current density (icorr) was calculated by normalizing the corrosion current (Icorr) to the exposed surface area of the sample. The corrosion rate (CR) was determined using the standard electrochemical relationship based on the measured current density, equivalent weight, and density of the material.

Table 4 presents the electrochemical parameters of the specimens, calculated from the results of potentiodynamic measurements, which allow for a quantitative assessment of the corrosion resistance of the micro-arc oxide coatings. The base AMG6 alloy is characterized by the highest values of corrosion current density and corrosion rate, indicating the low effectiveness of its natural passive film.

Table 4 – Electrochemical corrosion parameters of micro-arc oxide coatings on AMG6 aluminum alloy (EW – equivalent weight, g; ρ – density, g/cm³; A – exposed surface area, cm²; Icorr – corrosion current, A; icorr – corrosion current density, A/cm²; CR – corrosion rate, mm/year)

Samples	Initial	Al – 1	Al – 2	Al – 3
EW=	9	9	9	9
p=	2.7	2.7	2.7	2.7
A=	0.64	0.64	0.64	0.64
Icorr =	0.0011003	0.00010001	0.0007216	0.00027907
icorr =	0.001719219	0.000156266	0.0011275	0.000436047
CR=	1.87395E-05	1.7033E-06	1.22898E-05	4.75291E-06

The minimum values of these parameters are observed for the Al-1 specimen, indicating the most pronounced barrier properties of the coating and a slowdown of electrochemical processes. The Al-2 specimen exhibits increased corrosion activity, associated with the well-developed porosity of the coating and reduced protective capability. The Al-3 specimen occupies an intermediate position, showing higher corrosion resistance compared to Al-2 due to the optimal combination of a dense inner layer and a functional outer layer.

Overall, the data in the table confirm that the micro-arc oxidation regimes significantly affect the corrosion resistance of the AMG6 aluminum alloy and the effectiveness of the protective coatings.

Conclusions

The obtained results indicate that different micro-arc oxidation processing regimes provide different functional advantages. The Al-3 coating exhibited the lowest coefficient of friction, whereas the Al-1 coating demonstrated the smallest wear area and the highest corrosion resistance. Therefore, the selection of the optimal coating formation regime should be based on the specific service conditions and the required combination of tribological and corrosion properties.

X-ray phase analysis revealed the formation of Al_2O_3 phases in all coatings, whereas the Al-3 sample additionally exhibited the presence of the aluminosilicate mullite phase ($3Al_2O_3 \cdot 2SiO_2$).

Tribological tests demonstrated a reduction in the coefficient of friction after micro-arc oxidation treatment. The lowest values were observed for the Al-3 sample (0.45-0.50), whereas the coefficient of friction for Al-1 ranged from 0.80 to 0.85. In addition, the wear area decreased by more than two times compared with the untreated alloy.

Electrochemical measurements revealed a significant improvement in corrosion resistance after micro-arc oxidation treatment. The lowest corrosion current density was obtained for the Al-1 coating (1.56×10^{-4} A/cm²), compared with 1.72×10^{-3} A/cm² for the untreated alloy.

It was established that the electrolyte composition and processing parameters significantly influence the morphology, phase composition, tribological behavior, and corrosion resistance of the coatings. Different processing regimes provided different functional advantages, indicating that the optimal coating should be selected according to the specific service requirements.

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АМГ6 АЛЮМИНИЙ ҚОРЫТПАСЫНДА ҚАЛЫПТАСҚАН АЛЮМОСИЛИКАТТЫ ЖАБЫНДАРДЫҢ ҚҰРЫЛЫМЫ МЕН ҚАСИЕТТЕРІНЕ МИКРОДОҒАЛЫҚ ОКСИДТЕУ ПАРАМЕТРЛЕРІНІҢ ӘСЕРІ

Бұл жұмыста микродоғалық оксидтеу әдісімен АМГ6 алюминий қорытпасы бетінде алынған оксидті жабындардың қалыптасу процестері, құрылымы, фазалық құрамы және пайдалану қасиеттері кешенді түрде зерттелді. Өңдеу электрлік және жылулық режимдердің тұрақтылығын қамтамасыз ететін импульстік қорек көзі мен температураны бақылау жүйесі бар зертханалық қондырғыда жүргізілді. Құрамы әртүрлі силикатты-сілтілі электролиттерді қолдану жабындардың морфологиясы мен қасиеттерін мақсатты түрде басқаруға мүмкіндік берді. Растрлық электрондық микроскопия және энергодисперсиялық талдау әдістері тығыз ішкі тосқауылдық қабаты және дамыған кеуекті сыртқы қабаты бар көпқабатты оксидті жабындардың қалыптасуын көрсетті. Жабындардың қалыңдығы 27-33 μm аралығында болды. Рентгенфазалық талдау энергиясы жоғары өңдеу режимдерінде алюминий оксидінің кристалдық модификациялары мен алюмосиликатты муллит фазасының түзілетінін растады. Трибологиялық сынақтар микродоғалық оксидтеудің әртүрлі режимдері әртүрлі функционалдық артықшылықтарды қамтамасыз ететінін көрсетті. Al-3 жабыны үйкеліс коэффициентінің ең төмен мәнімен (0,45-0,50) сипатталса, Al-1 жабыны ең аз тозу ауданын көрсетті. Электрохимиялық өлшеулер Al-1 жабынының зерттелген жабындар арасында коррозиялық ток тығыздығының ең төмен мәнімен сипатталып, ең жоғары коррозияға төзімділікке ие екенін де көрсетті. Алынған нәтижелер микродоғалық оксидтеудің оңтайлы режимін болжанатын пайдалану жағдайларына қойылатын нақты трибологиялық және коррозиялық талаптарды ескере отырып таңдау қажеттігін көрсетеді.

Түйін сөздер: *микродоғалық оксидтеу; АМГ6 алюминий қорытпасы; оксидті жабындар; трибологиялық қасиеттер; коррозияға төзімділік.*

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ВЛИЯНИЕ ПАРАМЕТРОВ МИКРОДУГОВОГО ОКСИДИРОВАНИЯ НА СТРУКТУРУ И СВОЙСТВА АЛЮМОСИЛИКАТНЫХ ПОКРЫТИЙ, СФОРМИРОВАННЫХ НА АЛЮМИНИЕВОМ СПЛАВЕ АМГ6

В работе выполнено комплексное исследование процессов формирования, структуры, фазового состава и эксплуатационных свойств оксидных покрытий, полученных на алюминиевом сплаве АМГ6 методом микродугового оксидирования. Обработка проводилась на лабораторной установке с импульсным источником питания и системой температурного контроля, обеспечивавшей стабильность электрических и тепловых режимов. Использование силикатно-щелочных электролитов различного состава позволило целенаправленно управлять морфологией и свойствами покрытий. Методами растровой электронной микроскопии и энергодисперсионного анализа установлено формирование многослойных оксидных покрытий с плотным внутренним барьерным слоем и развитым пористым внешним слоем. Толщина покрытий составляла 27-33 μm. Рентгенофазовый анализ подтвердил образование кристаллических модификаций оксида алюминия и алюмосиликатной фазы муллита при энергонасыщенных режимах обработки. Трибологические испытания показали, что различные режимы микродугового оксидирования обеспечивают разные функциональные преимущества. Покрытие Al-3 характеризовалось наименьшим коэффициентом трения (0,45–0,50), тогда как покрытие Al-1 продемонстрировало наименьшую площадь износа. Электрохимические измерения также показали, что покрытие Al-1 обладает наибольшей коррозионной стойкостью и характеризуется наименьшей плотностью коррозионного тока среди исследованных покрытий. Полученные результаты свидетельствуют о том, что оптимальный режим микродугового оксидирования следует выбирать с учетом конкретных требований к трибологическим и коррозионным свойствам для предполагаемых условий эксплуатации.

Ключевые слова: *микродуговое оксидирование; алюминиевый сплав АМГ6; оксидные покрытия; трибологические свойства; коррозионная стойкость.*

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ГИДРОДИНАМИЧЕСКИЕ И ТЕПЛОФИЗИЧЕСКИЕ АСПЕКТЫ ОПТИМИЗАЦИИ ОРОСИТЕЛЬНЫХ УСТРОЙСТВ В ТЕХНИЧЕСКИХ СИСТЕМАХ РАСПЫЛЕНИЯ: ОБЗОР

Аннотация: *В статье представлен обзор современных исследований, посвящённых гидродинамическим и теплофизическим аспектам работы оросительных и распылительных устройств в технических системах. Цель работы заключается в систематизации научных представлений о влиянии конструктивных, режимных и теплофизических параметров сопел на формирование распылённого потока, равномерность орошения и эффективность тепло- и массообмена. Рассмотрены основные типы оросительных устройств, включая струйные, веерные, конусные, центробежные и пневматические распылители. Проанализировано влияние рабочего давления, расхода жидкости, геометрии проточной части, размера и скорости капель, угла раскрытия факела, плотности орошения и свойств рабочей среды на структуру капельного потока. Показано, что эффективность оросительных устройств определяется не только расходной характеристикой и давлением, но и рациональным сочетанием дисперсности распыла, устойчивости факела, равномерности распределения жидкости и условий взаимодействия капель с газовой средой, насадкой или теплообменной поверхностью. Особое внимание уделено распылительному охлаждению, где ключевое значение имеют капельный спектр, положение сопла, состояние поверхности, режим кипения и критический тепловой поток. Для градирен и испарительных систем выделена роль равномерного водораспределения как одного из определяющих факторов эффективности тепло- и массообмена. Рассмотрены возможности CFD-моделирования для анализа внутреннего течения в соплах, закручивания потока, формирования жидкой плёнки и структуры факела распыла. Сделан вывод о необходимости комплексного учёта гидродинамических, теплофизических и эксплуатационных параметров при проектировании и оптимизации оросительных устройств для градирен, испарительных охладителей, аппаратов газоочистки и установок распылительного охлаждения.*

Ключевые слова: *оросительные устройства; атомизация жидкости; тепло- и массообмен; распылительное охлаждение; CFD-моделирование.*

Введение

Оросительные и распылительные устройства широко применяются в технических системах, где требуется обеспечить эффективный контакт жидкости с газовой средой, нагретой поверхностью или зоной тепло- и массообмена. К таким системам относятся

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