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Tribological properties of MAO coatings on aluminum alloy AL25

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The tribological properties of the oxide coatings were studied on the aluminum alloy AL25. The coatings were formed by microarc oxidation (MAO) in an alkaline-silicate electrolyte under cathodic-anodic conditions. The structure of the working layer of MAO coatings, their phase composition, and hardness were studied. The coatings were tested in friction pairs with cast iron SCh20 and alloy AL25 under oil lubrication. The friction coefficient was determined on the SMC-2 friction machine according to the 'disc-pad' scheme, the load varied from 0.2 to 2 kN, the nominal pressure – from 1 to 11 MPa. It was found that the MAO coating has a crystal structure with a phase composition including mullite ($3Al_2O_3{\cdot}2SiO_2$) and high-temperature modifications of aluminum oxide (α-Al_2O_3 and γ-Al_2O_3); hardness ~ 10-12 GPa, and total porosity of 10-15 %. The friction coefficient of the pairs 'grey cast iron - MAO coating' and 'MAO coating - MAO coating' reaches 0.04 and 0.007 when lubricated with oil. The friction coefficient in the pair 'MAO coating - MAO coating' is characterized by the absence of tribochemical interaction of the contacting surfaces. The low sliding friction coefficient and high mechanical properties of the coatings make it possible to use MAO technology to increase the service life of tribotechnical parts (pistons, shafts, plain bearings, etc.).

Keywords: aluminum alloy AL25, cast iron, steel, micro-arc treatment, coating, phase composition, crystal structure, aluminum oxides, coating thickness, coating hardness, friction coefficient, tribological properties.

Трибологічні властивості МДО-покриттів на алюмінієвому сплаві АЛ25. *В.В. Субботіна, В.В. Білозеров, О.В. Субботін, О.О. Волков, С.А. Князев, В.А. Рябоштан, В.М. Баранніков, В.І. Бобров, І.А. Калініченко, С.О. Фесюков*

Трибологічні властивості оксидних покриттів були досліджені на ливарному алюмінієвому сплаві АЛ25. Покриття були сформовані методом мікродугового оксидування (МДО) в лужно-силікатному електроліті при катодно-анодному режимі. Вивчено структуру робочого шару МДО-покриттів їх фазовий склад та твердість. Покриття випробовували в парах тертя з чавуном СЧ20 та сплавом АЛ25 в умовах змащування мастилом. Визначено коефіцієнт тертя на машині тертя СМЦ-2 за схемою «диск–колодка», навантаження змінювалось від 0,2 до 2 кН, номінальний тиск – від 1 до 11 МПа. З'ясовано, що МДО-покриття має кристалічну структуру з фазовим складом, що включає муліт ($3Al_2O_3{\cdot}2SiO_2$) та високотемпературні модифікації оксиду алюмінію (α-Al_2O_3 і γ-Al_2O_3), твердість ~ 10 – 12 ГПа, загальна пористість складає 10 – 15 %. Коефіцієнт тертя для пар 'сірий чавун – МДО покриття' та 'МДО покриття – МДО покриття' досягає значень 0,04 та 0,007 в умовах змащування мастилом. Коефіцієнт тертя в парі 'МДО покриття – МДО покриття' визначається відсутністю трибохімічної взаємодії контактуючих поверхонь. Низький коефіцієнт тертя ковзання і високі механічні властивості покриттів дають змогу застосовувати МДО-технологію для підвищення ресурсу деталей триботехнічного призначення (поршні, вали, підшипники ковзання тощо).

1. Introduction

When equipment is operated at high speeds and loads, the problem of increasing the wear resistance of machine parts is a pressing one. Ceramic coatings with high resistance to intensive wear and aggressive environments are promising for such working conditions. These requirements are met by ceramic composites based on aluminum oxide, which have good physical and mechanical properties and are also an inexpensive and abundant material.

Aluminum alloys are widely used in the manufacture of many parts and components in the engineering industry. Parts made of aluminum alloys are 25-30% lighter than parts made of, for example, cast iron. At the same time, the thermal conductivity of aluminum alloys is 3-4 times higher than that of steel and cast iron, which makes it possible to reduce the temperature of parts operating under high heat stress [1, 2]. The advantage of aluminum alloys is their good mechanical properties, comparable to those of steel and cast iron [3]. The disadvantages of aluminum alloys are their high coefficient of linear expansion and low wear resistance [4, 5]. To increase the wear resistance of aluminum alloy parts, various coatings and surface modification methods are commonly used [5].

At present, the micro-arc oxidation (MAO) method, which belongs to the surface modification methods, is being developed and is becoming widespread [6]. Today, microarc oxidation (MAO) is one of the most promising technological methods for surface hardening of parts made of Al, Mg, Ti, Ta, Nb, Zr, Be and their alloys [7-9]. This technology is used to create multifunctional coatings on aluminum alloys: wear-resistant, dielectric, heat-resistant, decorative and corrosion-resistant. The essence of the MAO method is the use of microarc discharges to form a high-strength ceramic layer (MAO layer) consisting mainly of mullite ($3Al_2O_3 \cdot 2SiO_2$) and aluminum oxides (α-Al_2O_3 (corundum) and γ-Al_2O_3) on the surface of a part [7, 10]. The MAO method makes it possible to obtain coatings with a thickness of up to 400 μm and a high microhardness of up to 24 GPa [7, 11, 12]. There is limited information on the antifriction properties of aluminum oxide coatings.

In connection with the above, the purpose of this study is to determine the friction coefficient of MAO coatings on AL25 alloy in combination with cast iron and in combination with MAO coating on AL25 alloy under oil lubrication; the feasibility of using MAO technology in tribotechnical units of hydraulic and steam turbines, generators and pumps, where requirements are imposed to reduce friction and increase wear resistance of parts, as well as for friction units of engines, the structural elements of which operate under conditions of high temperatures and loads (Fig. 1), will also be determined.

Fig. 1. Parts with micro-arc coating

2. Experimental

Aluminum alloy AL25 (AK12M2MgN: 11 - 13 % Si, 1.5 - 3 % Cu, 0.8 - 1.3 % Mg, 0.8 - 1.3 % Ni, HB = 900 MPa) used for casting piston engine parts, was studied.

«Pads» and «discs» made of AL25 aluminum alloy were subjected to microarc oxidation in an alkaline-silicate electrolyte (1 g/l KOH + 6 g/l Na_2SiO_3) in an anode-cathode mode at a current density of 20 A/dm^2 and an electrolysis duration of 180 minutes. It should be noted that the formed coating has a two-layer structure (Fig. 2): a technological layer and a working layer [13]. During microarc oxidation, the total thickness did not exceed 160 μm. After removing the technological layer by grinding, the thickness of the working layer was 80-90 μm.

Tribological tests were performed on a SMC-2 friction machine, with and without lubricant in accordance with DSTU 2823-94 [14], using various schemes. The principle of operation of the machine is that the samples are subjected to a relative displacement under a given load. At the same time, the friction moment is measured. The machine does not provide direct measurement of wear during the test [15].

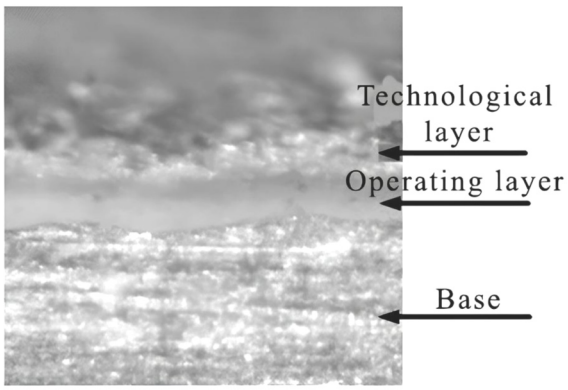

Fig. 2. Microstructure of the alloy cross-section after MAO treatment (x 100)

The tribological properties of the coatings were evaluated by the friction coefficient under step loading. The test was carried out according to the "disk-pad" scheme. A step load was applied in the range of 0.2-2 kN with a step of 0.2 kN, which corresponded to specific stresses from 1 to 11 MPa. The test time at each load stage was 10 minutes; sliding speed was 1.3 m/s; lubrication was carried out by the immersion method; lubricant was diesel oil.

The discs (∅ 50 mm) were made of grey cast iron (HB 340) and aluminum casting alloy AL25, the working surfaces were ground to a roughness of Ra = 0.3-0.4 μm. The pads were made of aluminum alloy AL25. A KSP-4 recorder was used for continuous recording of the dynamics

The presence of phases, as well as their relative content in the working layer with the MAO coating, were determined by the X-ray phase analysis on a DRON-3 X-ray diffractometer with Bragg-Brentano focusing in Cu-*K*α radiation [15].

The thickness of the MAO coatings was measured using a VT-10NC eddy current meter, which allows measuring the thickness of dielectric coatings on non-ferromagnetic metal samples. The microhardness of the working layer of the coatings was measured using a PMT-3 device with a load of 200 g.

3. Results and discussion

The force interaction of friction contact surfaces is explained by the adhesion-strain theory developed by Kragelsky I.V. [17], Bowden F.P. and Tabor D [18], and developed in the works of the outstanding domestic tribologist Kostetsky B.I. and his school [19, 20]; according to this theory, the boundary layer is considered as a "third body", and the friction coefficient is the sum of the adhesive and deformation components.

The adhesive component is caused by the adhesive force between the atoms or molecules of the two surfaces. When two surfaces come into contact, a microscopic bond is formed between them through intermolecular or interatomic interactions. These adhesive forces contribute to an increase in resistance to movement, which increases the friction coefficient.

The deformation component is caused by the deformations that occur on the surfaces during friction. Since real surfaces have microscopic irregularities, these irregularities press against each other during friction, resulting in plastic or elastic deformation. Additional forces must be applied to produce these deformations, which also affect the coefficient of friction.

MAO coatings (materials with a dispersed-oxide structure) are known for their high hardness, which reduces the deformation of surfaces during friction. The harder the material, the less it is subject to deformation under pressure, which leads to a reduction in the deformation component of friction. However, even with high hardness, if the surface remains rough, micro-irregularities can increase the friction force due to their interaction, causing microplastic deformation and increased resistance to movement.

Surface roughness has a negative effect on friction, since a rougher surface leads to stronger adhesion of micro-irregularities and increases both the deformation and adhesion components. This means that while a hard coating reduces deformation, roughness can increase resistance to movement due to adhesion. Liquid lubricants significantly reduce the adhesive component of friction. They create a film between the surfaces that prevents molecules and atoms from coming into direct contact, which reduces the adhesion between the surfaces. This can significantly reduce the friction coefficient, since the liquid phase reduces both sliding friction and possible wear of the surfaces.

The results of the study allow us to note the following points.

X-ray diffraction phase-structure analysis showed that the hardened layer has a crystalline structure (Fig. 3). Phase composition of the MAO coating: 14 % α-Al_2O_3, 34 % γ-Al_2O_3, 52 % mullite ($3Al_2O_3 \cdot 2SiO_2$); microhardness ~ 12 GPa. Thus, the structure of the coating is three-phase, with mullite (HV0.2 ~ 10 GPa) as the base and harder phases γ-Al_2O_3 (HV0.2 ~ 14 GPa) and α-Al_2O_3 (HV0.2 ~ 25 GPa), which corresponds to the structure of antifriction \materials.

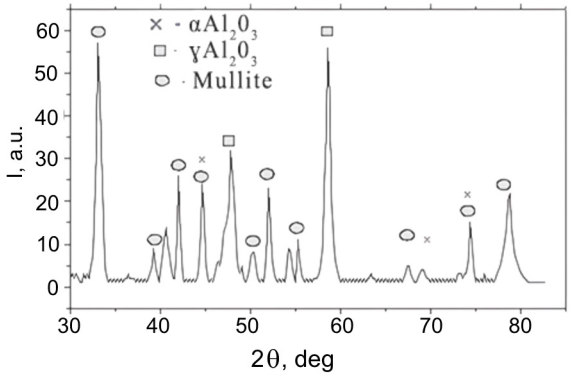

Fig. 3. Fragment of the X-ray diffraction spectrum of a MAO coating on AL25 alloy, obtained in the electrolyte 1 g/l KOH + 6 g/l Na_2SiO_3 (τ = 180 min, Kα-Cu radiation)

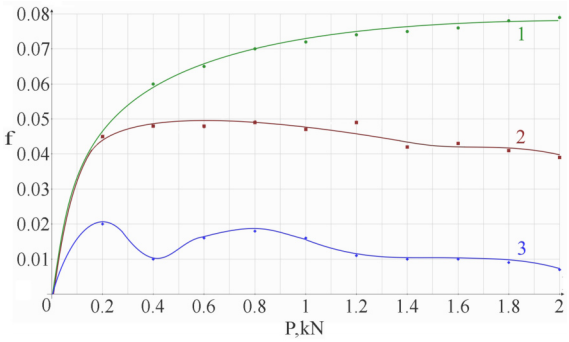

Fig. 4. Dependence of friction coefficient on load: 1 - pair 'cast iron SCh20 - alloy AL25'; 2 - pair 'cast iron SCh20 - alloy AL25 with MAO coating'; 3 - pair 'alloy AL25 with MAO coating - alloy AL25 with MAO coating'

Table1. Dependence of friction coefficient on load

Disc material	Pads material	Value of the coefficient of friction under load P, κN									
		0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
cast iron	AL25	0.045	0.06	0.065	0.07	0.072	0.074	0.075	0.076	0.078	0.079
cast iron	AL25 with MAO coating	0.045	0.048	0.048	0.049	0.047	0.049	0.042	0.043	0.041	0.039
AL25 with MAO coating	AL25 with MAO coating	0.02	0.01	0.016	0.018	0.016	0.011	0.010	0.010	0.009	0.007

It should be noted that the total porosity of the coating is 10-15 %. This factor should contribute to the antifriction performance of coatings under sliding friction with liquid lubrication.

The results of measuring the friction coefficient under different loads are shown in Table 1 and Fig. 4. As can be seen from Fig. 4, that in the absence of a MAO coating on the alloy (curve 1), there is a continuous increase in the friction coefficient with increasing load. This is due to the adhesion of the plastic material of the alloy to the counterbody. The presence of a MAO coating on the surface (with a hardness of 14 GPa) leads to a change in the type of the curve of the friction coefficient versus load. In the entire load range, the friction coefficient is almost constant and equal to 0.045 (Fig. 4, curve 2).

The results of the friction coefficient study are shown in Table 1.

The analysis of the results shows that the friction pairs 'cast iron − coating' with oil lubrication can be classified as antifriction, since their friction coefficient does not exceed 0.045. The 'coating-coating' friction pairs are also classified as antifriction when oil lubrication is used.

The tribological characteristics of the oxide coatings, assessed by the friction coefficient showed that the coatings have a high level of antifriction properties over the entire load range. Thus, the presence of MAO coatings with a composition of 14 % α-Al_2O_3, 34 % γ-Al_2O_3, and 52 % mullite $3Al_2O_3{\cdot}2SiO_2$ significantly reduces the sliding friction coefficient in a pair with grey cast iron. A significant decrease in the friction coefficient was found in the pair 'coating-coating' (Fig. 3, curve 3). This result can be explained by the absence of tribochemical interaction between the contacting surfaces.

4. Conclusions

1. The coefficient of sliding friction of MAO coating on AL25 alloy in combination with cast iron (f = 0.045) and MAO coating (f = 0.007) was determined during friction with lubrication.

2. It has been established that MAO coatings with a structure consisting of a mullite base with the inclusions of aluminum oxides α-Al_2O_3 (corundum) and γ- Al_2O_3 and a porosity of 10-15% exhibit antifriction properties in friction pairs with both cast iron and MAO coatings under lubricated conditions.

3. The expediency of using MAO technology to increase the service life of tribotechnical parts is shown, since the low friction coefficient and high coating hardness (10-12 GPa) should increase the wear resistance of the surface of AL25 aluminum alloy parts with MAO coating.

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References

1. S.S. Dyachenko, I.V. Doschechkina, I.V. Ponomarenko, S.I. Bondarenko, Materials for various purposes, their processing and properties: a textbook. Kh.: KhNADU, 348 (2016).
2. L.G. Bodrova, G.M. Kramar, Y.O. Kovalchuk. Technology of structural materials and materials science, section Materials science I.V., Textbook,157 (2023).
3. E.G. Aftandilianets, O.V. Zazymko, K.G. Lopatko, Materials Science: Textbook, Higher Education, Kyiv, 548 (2012)
4. E.S. Gevorkian, L.A. Timofeeva, V.P. Nerubatsky, O.M. Melnyk Integrated technologies of materials processing: textbook. Kharkiv: UkrDUZT, 238 (2016),
5. A.G. Fesenko, K.V. Bechke, S.V. Manzhalievskyi. Methods of surface hardening in the process of manufacturing machine parts: a textbook. Dnipro: RVV DNU, 104 (2015).
6. Li, W.J., Li, H.X., R.G. Song, Ji Z., *Materials science and technology,* **28**, 5, 567 (2012)
7. D. Asquith, A. Yerokhin, N. James, J. Yates. *Physical Metallurgy and Materials Science,* **44**, 10, 4464 (2013)
8. D. Shen, J. Cai, C. Guo, P. Liu. *Chinese Journal of Mechanical Engineering*, **26**, 6, 11–1151 (2013).
9. J. Dean, T. Gu, T.W. Clyne. *Surface and Coatings Technology*, **269**, 53 (2015)
10. V.M. Volchuk, D.B. Hlushkova. *Functional Materials*, **31**(2), 206 (2024),
11. E. Matykina, R. Arrabal, M. Mohedano, B., Mingo. *Transactions of Nonferrous Metals Society of China,* **27**, 1440 (2017)
12. M. Javidi, H. Fadaee. *Applied Surface Science,* **286**, 215 (2013)
13. P.X. Lv, G.X. Chi, D.B. Wei, S.C. Di. *Advanced Materials Research,* **189**, 1296 (2011)
14. DSTU 2823-94 "Wear resistance of products. Friction, wear and lubrication. Terms and definitions".
15. Y.O. Kharlamov, O.V. Romanchenko, V.I. Sokolov, O.S. Krol. Tribotechnics and machine reliability: a textbook, 184 (2021),
16. S.I. Mudryi, Y.O. Kulyk, A.S. Yakymovych. X-ray diffraction analysis in materials science: a textbook, 227 (2017).
17. I.V. Kragelsky, Friction and wear. M., Mashinostroenie, 487 (1968.
18. F.P. Bowden, D. Tabor. Friction and lubrication of solids. M., Mashinostroenie, 544 (1968)
19. Kostetsky, I.G. Nosovsky. Wear resistance and antifriction of machine parts. Kiev, Tehnika, 205 (1965).
20. B.I. Kostetsky, M.E. Natanson, L.I. Bershadsky. Mechano-chemical processes at boundary friction. M., Nauka, (1972) .