Research of the AK4-1 alloy microarc oxidation modes effect on the composite ceramic coatings erosion resistance

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Abstract. The article presents the results of the coatings erosion resistance experimental studies obtained by microarc oxidation using the AK4-1 aluminum alloy. The coatings formation modes by MAO varied in relation to the electrolytic components KOH, Na$_2$SiO$_3$ (gr/l concentration); current density $j$ (A/dm$^2$) and the cathode/anode ($I_c/I_a$) currents ratio. The MAO coatings erosion resistance was determined from the ablation rate while the sample was blown with Al$_2$O$_3$ powder.

1. Introduction
The use of aluminum alloys in mechanical engineering is due to their high manufacturability, low cost and low specific weight. On the other hand, their use in machines loaded elements and mechanisms is limited due to its relatively low strength and low resistance to various wear types: abrasive, adhesive, erosion etc. The main consumer of aluminum alloys is the aerospace industry, where structural elements low specific weight plays an important role. For example, cladding airframes, launch vehicles, pylons, engine nacelle components, housing units of various support systems, gas turbine engines air intake elements and fan blades are made of aluminum alloys.

Erosion is a wear process associated with the material fatigue-abrasive destruction in the surface layer, due to the periodic particles effects (gas or hydroabrasive erosion) or shock waves (cavitation erosion). The material destruction leads to the loss of strength, reduced endurance and other consequences. To protect the working surfaces, various types of erosion-resistant coatings are used, mainly obtained by gas-thermal or ion-plasma methods [1].

The most acceptable technological method to protect aluminum elements from wear is the formation of composite ceramic coatings by the microarc oxidation method (plasma electrolytic oxidation). The coatings obtained in this way have high adhesion to the substrate, high hardness, sufficient thickness and corrosion resistance – all this allows to achieve excellent performance indicators, increase the service life and reliability of parts [2–4].

2. Materials and methods
MAO coatings were formed on Ø35 mm and 5 mm thick samples, made of AK4-1 heat-resistant aluminum alloy with a pre-polished surface to a roughness of $Ra \leq 1.2$ μm. Before installing the samples in the electrolytic bath, they were cleaned with isopropyl alcohol in an ultrasonic bath.

For the formation of MAO coatings, an automated MAI-2 20 kW power source and an alkali silicate electrolyte (KOH and Na$_2$SiO$_3$) were used. The electrolyte was mixed by compressed air. To study the effect of treatment modes on the erosion resistance of coatings, the electrolyte composition,
current density \((j, \text{A/dm}^2)\) and the cathode/anode current ratio were varied using a ballast resistance \((I_c/I_a)\) (table 1). The process time for all samples was limited to the moment when the amount of electricity passed through the circuit reached 100 kC/dm\(^2\).

| Sample | C (KOH), g/l | C (Na\(_2\)SiO\(_3\)), g/l | Current density, A/dm\(^2\) | Current ratio \((I_c/I_a)\) | Time, min |
|--------|--------------|----------------|------------------|------------------|---------|
| 1      | 1            | 4             | 6                | 1                | 276     |
| 2      | 2            | 4             | 12               | 1.1              | 139     |
| 3      | 1            | 12            | 18               | 1                | 93      |
| 4      | 2            | 12            | 12               | 1.1              | 139     |

Table 1. MAO coatings formation modes on samples from AK4-1 alloy.

To study the coatings morphology, an EVO-40 Carl Zeiss scanning electron microscope was used. The coatings thicknesses and layers measurement was carried out on transverse thin sections. The coatings microhardness was measured by the Vickers pyramid under a 200 g load on a PMT-3M microhardness tester. The erosion resistance was determined on a special erosion plant. The plant consists of a high-precision dispenser for TWIN10V abrasive powder, a compressed air supply and control system, which includes: a compressor, a gearbox, a rotameter, a fine adjustment valve and an erosion device (figure 1). The coating erosion wear was carried out with the sample being blown with an abrasive powder (Al\(_2\)O\(_3\)) with particle sizes from 20 \(\mu\)m to 50 \(\mu\)m. The cleaning and sieving of the powder was carried out on fine-mesh sieves, and the separation of the powder to the required fraction 20...50 \(\mu\)m from dust (fine fraction) was carried out in an ultrasonic bath. Before loading the powder into the dispenser, it was dried in a vacuum oven at a temperature of 1500 °C for three hours. The coatings erosion resistance was determined by the gravimetric method on the ViBRA HT-220CE scales.

![Figure 1. Erosion device with sample holder.](image_url)

Table 2. MAO coatings formation modes on samples from AK4-1 alloy.

| Sample | Specific weight gain, gr/dm\(^2\) | Total thickness, \(\mu\)m | Technological layer thickness, \(\mu\)m | HV\(_{200}\), GPa |
|--------|----------------------------------|--------------------------|---------------------------------------|-----------------|
| 1      | 1,033                           | 67.7                     | 26.7                                  | 20.9            |
| 2      | 1,051                           | 74.9                     | 30.3                                  | 21.3            |
| 3      | 1,599                           | 106.5                    | 51.2                                  | 18.6            |
| 4      | 1,405                           | 86.5                     | 36.4                                  | 21.4            |

When comparing the MAO coatings formation mode for samples 1 and 3, which have a difference in liquid glass content and current density of up to 3 times respectively, it is clear that the total thickness of the coatings differs by about 40%, while the proportion of the technological layer is approximately the same and is equal to ~45%. However, the microhardness of the sample base layer 1 is higher compared to sample 3 by 2.3 GPa, which can be attributed to the increased porosity of the latter due to the high current density of 18 A/dm\(^2\), which is clearly seen in the SEM image (figure 2(a)).
Figure 2. Image of the MAO coatings cross-section samples 1 (a), 2 (b), 3 (c) and 4 (d), obtained using a scanning electron microscope.

For samples 2 and 4, the formation modes were almost identical, except for the 3-times increase in the liquid glass content respectively. In addition, compared to previous samples, the alkali content was increased to 2 g/l, and the current density was maintained at an average level of 12 A/dm². This formation mode, on the one hand with greater liquid glass content, allowed increasing the thickness by 12 μm for the sample 4 while maintaining the thickness proportion of the technological layer with the main layer, and on the other hand, the microhardness remained at the same level, which was higher compared to all the samples. However, the sample 4 technological layer porosity was greater (figure 2(b), (d)) compared to sample 2 because of the higher liquid glass content.

Figure 3 shows a graph of the coating massive ablation rate reduced to the thickness for all samples. As can be seen, samples 1 and 2 showed the coating lowest ablation rate while samples 3 and 4 showed the highest ablation rate. It should be mentioned that with samples 2 and 4 coatings similar characteristics their resistance to erosion differs by 2 times, which speaks of the liquid glass effect (table 1) contributing to the formation of a more porous structure, which in a decisive way affects the coating resistance to erosion. This fact is indirectly confirmed by the fact that the sample 3 coating, formed with a maximum current density of 18 A/dm² and the same liquid glass content as sample 4, showed the lowest resistance to erosion. In addition, the coating that showed the best resistance to erosion was the one obtained in the most "soft" mode with a current density of 6 A/dm², which implies that a more "soft" MAO mode contributes to the formation of a coating with a lower porosity.
3. Conclusions

Thus, the study showed that the greatest influence on the erosion resistance during the MAO coatings formation is due to the electrolyte content of Na$_2$SiO$_3$ and the current density value. At the same time, to achieve maximum resistance to the coating erosion, it is necessary to create a solid structure with low porosity.

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