Influence and calculation of the cathode form in the formation of uniform thickness MAO-coatings

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Abstract. The paper presents the results of using the methods of numerical simulation of the cathode shapes for the formation of a uniform thickness of the MAO coatings over the entire surface of the part. The data obtained by numerical simulation were tested on samples with a coating obtained according to the traditional scheme and in a scheme with a new cathode form.

1. Introduction

A characteristic feature of the microarc oxidation (MAO) process is the formation of the coating crystal structure in the mode of electrical discharges, the places of origin, development and attenuation of which are determined by a large number of factors. The voltage drop during the formation of MAO coating in alkaline electrolytes due to their high dissipative capacity does not exceed 1...5 % of the initial voltage, and the entire voltage drop then concentrates between the coating boundary, called the quasi-cathode, and the metal part. This contributes, in the opinion of a number of authors [1–3], to the discharges uniform migration over the part’s surface and to obtain a uniform thickness coating on the parts surface of any geometric shape.

This assumption, in our opinion, is most legitimate at the initial stage of the MAO process – the stage of spark discharges, when during the breakdown of a very thin oxide film, the electric field exceeds several hundred kV/mm and the number of simultaneously burning discharges is calculated by hundreds and thousands. In this case, a voltage difference distribution over the surface of a few volts may not appear.

A different picture is observed with an increase in the coating thickness (> 1 μm), when the realization of the breakdown of gas or vapor-gas interlayers between the electrolyte and the base metal begins, i.e. the stage of microarc discharges. The number of discharges decreases, the current density in them increases, and a voltage difference of even 1 V can lead to a voltages change of hundreds and thousands of V/mm, facilitating the binding of discharges to such zones. Local heating of the coating at the binding points of the microarc discharges increases the conductivity, thereby determining their predominant burning zones during the entire subsequent MAO process.

When oxidizing flat samples and using an electrolytic bath as a cathode, the minimum thickness of the coating is always observed in the center of the sample, and the maximum on the edges, where in accordance with the electrostatics laws, there is a tension field concentration. One of the methods to eliminate this disadvantage in the self-regulating MAO process is to set additional cathodes, the fields of which, overlapping each other, ensure its uniformity on the surface.
2. Experimental procedure
The configuration of the additional cathode can be determined by the method of mathematical modeling using finite element analysis. For this purpose, a simplified mathematical model was developed with initial and boundary conditions describing a flat axisymmetric disk made of aluminum alloy with an MAO coating of 100 μm and a radius of curvature at the edge of 0.1 mm. The electrolyte is an alkaline medium with a specific resistance of 2.0 ohm-m. The voltage applied to the sample (anode), stationary.

The finite element mesh was a flat element formed by 4 nodes, with one degree of freedom (voltage) in each and the only material property – resistance.

The calculations were performed using ANSYS software for various cathode and anode configurations. At the same time, the selection of the form of an additional cathode, which ensures the alignment of the electric field strength over the entire surface of the sample (part) to its values at the edges, was carried out due to consecutive iterations of the calculation.

Experimental verification of the calculation results was carried out on the example of microarc oxidation of aluminum alloy AL9 with the following operational parameters of capacitor power supply (figure 1): electrolyte – KOH (1 g/l), Na₂SO₄ (6 g/l); current density – 15 A/dm²; process duration – 210 min.

![Figure 1. Scheme of power supply.](image)

Two samples with an area of 0.6 dm² were oxidized: one with a cathode bath, the second with an additional spherical cathode with a radius of 24 mm located at a calculated distance of 10 mm from the center of the sample (figure 2). An optical measuring microscope METAM RV-21 was used to measure the thickness distribution along the substrate of the coatings.

![Figure 2. Scheme of sample installation.](image)

3. Results and discussions
Figure 3(a) shows the distribution of the electric field strength on a flat cylindrical sample with a cathode – an electrolytic bath, where the failure of the electric field strength in the center of the sample and its significant increase at the edge are clearly visible. And in figure 3(b) it is shown the distribution for the additional cathode configuration obtained as a result of the calculation, which demonstrates the almost complete absence of the “edge” effect.
Figure 3. Distribution of the electric field strengths in the electrolytic: (a) – cathode – bath; (b) – cathode – sphere.

The distribution of the MAO coating thickness of these samples, measured on cross sections is shown in figure 4. And if the use of an electrolytic bath body as a cathode leads to a decrease in the thickness of the coating in the center of the sample by more than 30 %, then the installation of an additional electrode in a sphere form made it possible to obtain a coating close to equal thickness.

Figure 4. Distribution of the MAO coating thickness.

Similar calculations and experiments were carried out for other configurations of samples and cathodes. So, on a flat sample with a size of 100×100 mm it was necessary to apply a coating of equal thickness in the form of an annular track of 22.5 mm wide. In accordance with the calculations, an additional electrode of 2 mm in diameter had the shape of a torus, and was located at a distance of 20 mm from the sample. Comparison of the experimental results for the cathode-bath and the cathode-torus also showed the effectiveness of using mathematical modeling to ensure equal thickness of the MAO coating.

However, it should be kept in mind that the use of the developed mathematical model provides only a qualitative picture of the distribution of the MAO coating and does not quantify its thickness, and also requires quite laborious work on the development of a finite element mesh, selection of initial and boundary conditions and calculations for each surface configuration of the parts.

In case of carrying out the MAO process on alternating current, the influence of the non-uniformity of the electric field should be less significant, since the cathode discharges burn at lower voltages (due to high electronic conductivity), and have a temperature much higher than the anode ones, thus creating conditions (heating) for the migration of anode discharges, called "bit chains" [4]. However, even in alternating current, the irregularity of the MAO coating application with the cathode bath is manifested.

To reduce this effect during the MAO process, the voltage stability in the anodic (or cathodic) half-period was reached with appropriate changes in the ratio of the current cathodic component to the anodic one – $I_k/I_a$. 
Figure 5. Thickness of the MAO coating obtained at $U_a = \text{const}$ due to $I_k/I_a = \text{var}$.

Figure 5 shows the results of the coating thickness distribution in the cross section of a sample of D16T alloy oxidized in silicate-alkaline electrolyte – KOH (1 g/l), Na$_2$SO$_4$ (10 g/l) in two stages. During the first 15 min, the oxidation was carried out at a current density of 15 A/dm$^2$ and an $I_k/I_a$ ratio = 0.95 in order to create conditions for the formation of microarc discharges. At the second stage, due to the change in the ratio $I_k/I_a$ in the range from 0.8 to 1.26, the voltage in the anode half-period was kept constant and equal to 595 ± 5 V. The duration of the entire MAO process was limited to a total amount of electricity of 75 000 C/dm$^2$ and a total of 84 minutes.

As can be seen in the graph, the unevenness of the coating thickness in the cross section does not exceed 20 %, both for the entire coating and for the base layer. The comparison of the obtained coatings characteristics (figure 6) definitely indicated a significant improvement in the efficiency of the MAO process while maintaining a constant voltage $U_a$ and $U_k$, rather than maintaining a constant current density of $j = \text{const.}$ [5].

4. Conclusions
Conducted research has shown that the use of numerical modeling in the design of the cathode can improve the uniformity of the thickness of the MAO coating over the entire part. It should be noted that the data obtained are valid for the simple form of the cathodes. For more complex forms of the cathode and its effect on the uniformity of the coating, additional research is needed.

References
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