Control of the plasma electrolytic oxidation process

Denis Lazarev[1*], *Azamat* Fatkullin[1], *Evgeny* Parfenov[1,2], *Arkady* Shevtsov[1], *Ivan* Silin[1], and *Vadim* Abdurahmanov[1]

[1]Ufa University of Science and Technology, Ufa, 450076, Russia
[2]Academy of Sciences of Republic of Bashkortostan, Ufa, 450008, Russia

Abstract. The article is devoted to solving the problem of controlling the plasma electrolytic oxidation process used for applying protective coatings on aluminum alloys in the potentiostatic mode. The problem of measuring the unobservable parameters of the surface layer was solved by using indirect identification of the state system by informative statistical characteristics of the population of microdischarges. The automated control system structure is developed and the operation algorithm is proposed.

1 Introduction

The technological process of plasma electrolytic oxidation makes it possible to effectively apply protective coatings with high performance properties on the surface of parts made of light alloys [1]. The high quality of coatings obtained by this method determines the expansion of their use in aviation, automobile, shipbuilding and other industries. That's why there is a need to automate the PEO process to increase efficiency, improve the quality of processing, reduce energy consumption, as well as reduce the number of defective products [2]. However, when automating this process, it must be taken into account that it is carried out at high voltages (400-700 V) [1]. Plasma electrolytic oxidation is a complex and nonlinear process operating under conditions of uncertainty in terms of the parameters of the initial surface preparation and the state of the electrolyte [3-4].

Modern automated control systems for the technological processes of the formation of oxide coatings on aluminum alloys are aimed not only at software control of current density and stabilization of technological parameters, but also at diagnosing the properties of the surface layer, and completing the process when a given coating thickness is reached [1].

2 Formulation of the problem

Automated control systems are needed for the formation of PEO coatings with the required characteristics, that will provide current control of the parameters of the state of the surface layer. In this regard, there is a need to create feedback loops that will provide a current

---

* Corresponding author: denis_rb84@mail.ru

assessment of the parameters of the surface state based on the results of registration and analysis of informative characteristics.

It is known that during plasma electrolytic oxidation, numerous microdischarges occur on the treated surface [4]. Microdischarges have a significant effect on the oxide layer and the alloy material, and look like luminous areas with a diameter of 0.1 to 1 mm visible to the naked eye [5]. During the PEO process, the movement of microdischarges along the surface of the part, the change in the spectrum of their luminescence, the apparent size and density of distribution, depending on the processing conditions and, consequently, on the thickness of the coating, is noted [6]. Thus, a significant amount of information about the state of the surface layer and the mechanism of the PEO process as a control object can be extracted when processing, for example, photographs of a population of microdischarges. In the work [7], an algorithm has been developed for processing photos of a population of microdischarges, which allows calculating the density of the distribution of microdischarges N and the average visible size of the microdischarge S. The dynamics of changes in the distribution density and the average visible size of microdischarges during the PEO process under various processing conditions and exposure durations are analyzed. Based on the results of correlation analysis, a method for identifying the PEO process is proposed based on convolution of the distribution density and the average visible size of microdischarges into an integral informative parameter P, which is strongly correlated with the coating thickness. The square of the coefficient of paired correlation of the integral informative parameter with the coating thickness was at least 0.95.

In this way, the aim of the study is to develop an automated control system for the process of plasma electrolytic oxidation in a potentiostatic mode based on the control of the coating thickness according to the characteristics of microdischarges.

3 Automated process control system PEO

3.1 Structure of the automated control system

Figure 1 shows a block diagram of an automated control system for the PEO process based on the control of the coating thickness by an integral informative parameter. The developed system contains a control computer, an electrolyte temperature stabilization system, a DC power supply and an electrolyzer for PEO.

The control computer contains a master device, a photo processing unit, a unit for calculating the parameters of microdischarges, an integration unit, a unit for calculating the thickness according to parameter P, a comparison unit and an alarm unit. The setting device is designed to manually set the operator of the target value of the coating thickness h_t. This device programmatically calculates the required values of the voltage of the power supply U^* and the temperature of the electrolyte $T°^*$ according to the set value of h_t. A digital camera photographs the surface of the part during the PEO process. The photo processing unit, during the PEO process, converts the original color image of microdischarges represented by the array X_2 into a binary image represented by the array Y. The binary image in the form of an array Y is fed to the input of the microdischarge parameter calculation unit, which calculates the density of the distribution of microdischarges N and the average visible size of microdischarges S. The calculated values of N and S are fed to the input of the integration unit, which calculates the value of the integral informative parameter P from the input parameters. The value of the integral parameter P enters the input of the thickness calculation unit, which calculates the current value of the coating thickness according to the formula $h_c = k \cdot P$. The calculated value of h_c enters the input of the comparison unit, which compares the target and current values of the coating thickness. If $h_c = h_t$, then a mismatch signal ε is generated at the output of the comparison unit, which enters the input of the alarm unit, which gives the operator a signal about the need to stop the process.

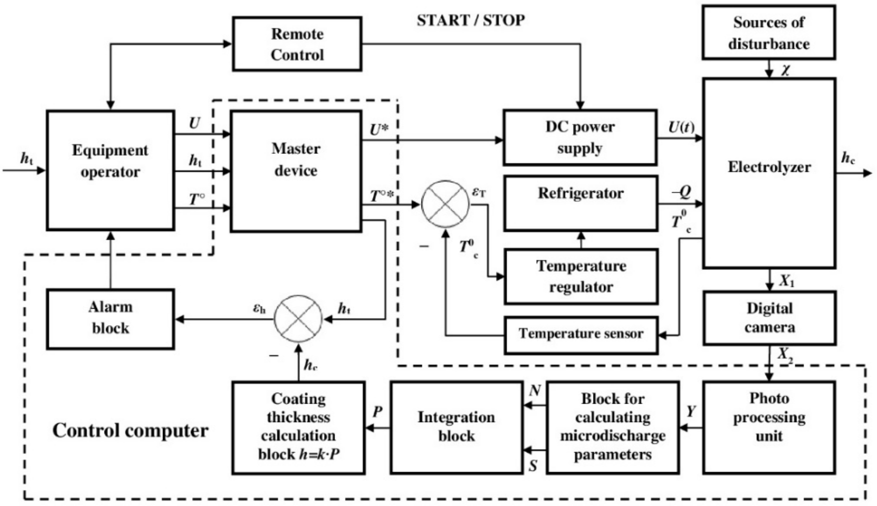

Fig. 1. Structure of an automated control system for the PEO process.

The temperature stabilization system contains a temperature sensor, a temperature controller and a refrigerator. This system ensures the stabilization of the electrolyte temperature $T°$ in the electrolyzer. The electrolyzer is a bath filled with electrolyte, into which the workpiece is placed. A DC power supply is connected to the electrolyzer. The DC power supply is an actuating device of the system designed to directly control the coating thickness of the part h during the PEO process due to the electric voltage $U(t)$ with a constant value U. As a result of the action of an electric voltage $U(t)$, the modification of the surface of the part, followed by the formation of a coating, occurs due to the energy introduced into the channel of the microarc discharge, the energy going to the Joule heating of the near-electrode region and the energy consumed for electrochemical reactions.

A PEO installation operating under conditions of uncertainty is affected by disturbances χ. The most typical disturbances are random deviations of the supply voltage parameters from the passport ones. The uncertainty lies in incomplete information about the technological heredity of the surface condition and about the parameters of electrolyte production.

So, the developed structure of the control system, through the use of a coating thickness control circuit according to an integral informative parameter, provides control of the duration of the PEO process carried out at a constant processing voltage U, and its completion when the coating thickness reaches the target value h_t.

3.2 Process PEO control algorithm

As a result of the analysis of the method for controlling the thickness of the coating using the informative characteristics of the population of microdischarges [8], a method for controlling the duration of the PEO process based on measuring the thickness of the coating by the integral informative parameter P. This method consists in photographing the surface of the part in real time, measuring and analyzing the informative parameters of the population of microdischarges, and «convolving» them into an integral informative parameter P. According to the value of the integral informative parameter P, the current coating thickness

h_c is indirectly measured and when $h_t = h_c$ is reached, the power supply is disconnected from the electrolyzer. The algorithm of the proposed control method is presented in the block diagram (Figure 2).

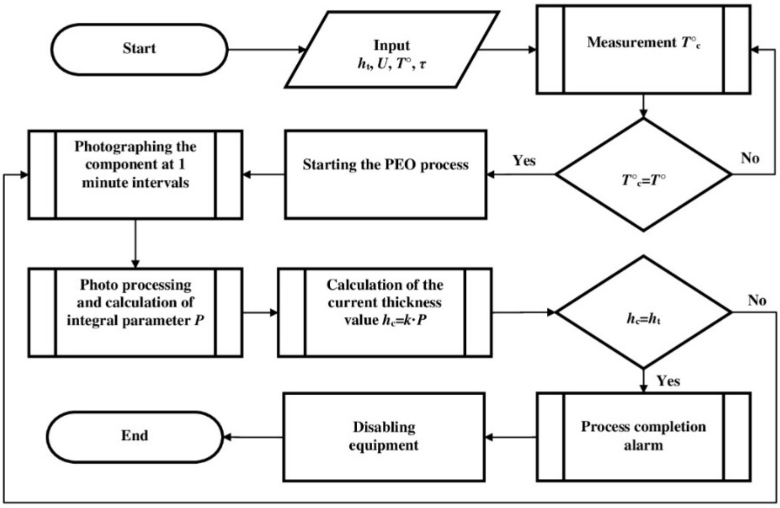

Fig. 2. Algorithm of the PEO duration control.

At the first stage, the operator enters the target value of the coating thickness h_t, the exposure duration τ, the required values of the constant processing voltage U and the electrolyte temperature $T°$. After reaching the set temperature of the electrolyte, the operator receives permission from the control computer to start the installation.

At the second stage, the operator manually starts the PEO process. During the PEO process, the surface of the part is photographed every Δt=1 min. A photograph of the surface of the part is transmitted to the control computer. The control computer, using the algorithm of the photo processing program [8], measures the current values of the density of the distribution of microdischarges N and the average size of the microdischarge S. Further, according to the method [8], the control computer calculates the current value of the integral informative parameter P by the values of N and S.

Then, the control computer calculates the current thickness of the h_c coating by the integral informative parameter P, which is strongly correlated with the thickness of the coating. After calculating the h_c, it is compared with the h_t. If $h_t = h_c$, then the operator is given a recommendation to complete the PEO process. If $h_t \neq h_c$, the coating thickness measurement cycle repeats and functions until the condition $h_t = h_c$ is met or an equipment error occurs.

4 Evaluation the accuracy of the control method

We used PEO equipment (UUST, Russia) in the potenciostatic mode for the approbation of the developed control system.

The accuracy of the method for controlling the PEO process was evaluated during the formation of a coating on rectangular samples with a size of 20x25x5 mm made of aluminum alloys BS6082 and AA2024. The samples were treated by plasma electrolytic oxidation in a solution containing 1 g/l KOH, 2 g/l $Na_4P_2O_7 \cdot 10H_2O$ and 2 g/l Na_2SiO_3 at a temperature of

20 °C for 5...20 minutes at constant voltages of 450 V, 500 V, 550 V and 600 V. The surface of the samples was photographed with a digital camera at time intervals $\Delta t = 1$ min.

Figure 3 shows photographs of microdischarges on the surface of samples recorded with an exposure duration of $\tau = 1/2$ s with the developed automated control system, in the process of PEO in a potentiostatic mode at voltages of 500 V and 550 V. The photographs (Figure 3) show microdischarges that appear in the pores of the forming oxide coating and lead to its intensive growth. In the photos (Figure 3) it can be seen that with an increase in the duration of processing with an increase in the thickness of the coating, the density of the distribution of microdischarges decreases, and the image area of the microdischarge as a whole increases. Such changes in the characteristics of microdischarges are explained by the connection between the patterns of coating growth during plasma electrolytic oxidation at constant voltage and the properties of a set of microdischarges that are channels of current flow through the barrier oxide layer.

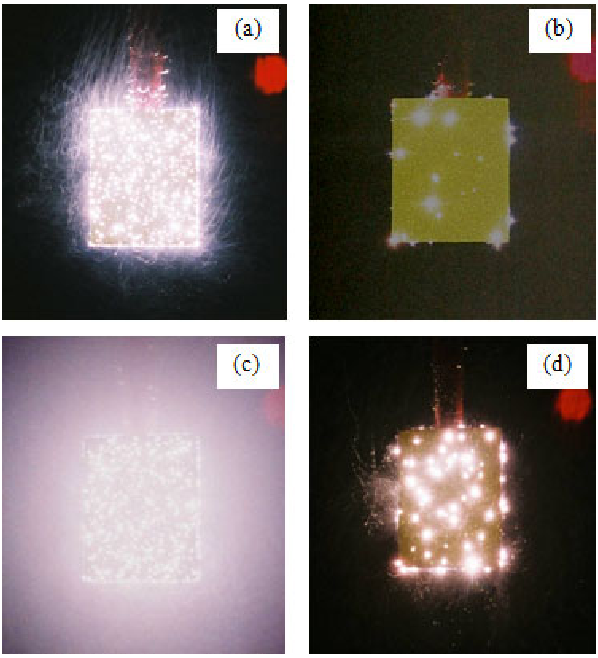

Fig. 3. Photographs of microdischarges on the surface of samples at different voltage U and treatment time t: (a) – $U = 500$ V, $t = 1$ min; (b) – $U = 500$ V, $t = 20$ min; (c) – $U = 550$ V, $t = 1$ min; (d) – $U = 550$ V, $t = 20$ min.

The duration of the PEO process at constant voltage was controlled on the basis of measuring the current value of the coating thickness h using the integral informative parameter P according to the equation:

$$h = k \cdot P \tag{1}$$

where k – an empirical coefficient depending on the nature of the processed material and the composition of the electrolyte.

The PEO process was stopped when the coating thickness h reached the target value. After plasma electrolytic oxidation, the thickness of the coating on the samples was also measured with an eddy current thickness gauge Defelsko Positector 6000 and the data was averaged over 10 measurements.

The results of evaluating the accuracy of the PEO process control method are shown in Table 1. Figure 4 shows the calibration curves for BS6082 and AA2024 alloys.

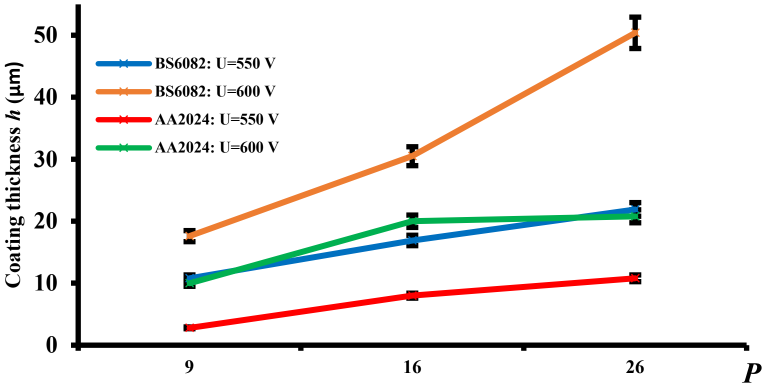

Fig. 4. Calibration curves for alloys BS6082 and AA2024.

Table 1. Results of evaluation the accuracy of the PEO process control method.

Alloy *BS*6082 **Alloy AA2024**	**Voltage (V)**			
	450	**500**	**550**	**600**
Coating thickness *h* (µm)	**Treatment time *t* = 5 min**			
h_1[a]	1.2±0.3 2.3±0.3	4.0±1.0 2.6±1.0	10.3±1.3 2.6±1.3	20.8±1.9 11.0±1.9
h_2[b]	1.5±0.5 1.9±0.2	4.1±0.7 2.7±0.4	10.8±0.9 2.8±0.7	17.6±2.1 10.0±1.2
	Treatment time *t* = 10 min			
h_1[a]	1.6±0.3 2.5±0.3	5.3±0.9 4.9±0.9	15.2±1.3 8.4±1.3	32.1±1.6 21.0±1.6
h_2[b]	2.0±0.5 2.7±0.3	5.8±0.7 4.8±0.5	16.9±0.9 8.0±0.7	30.5±2.2 20.0±1.5
	Treatment time *t* = 20 min			
h_1[a]	1.5±0.4 2.7±0.4	6.2±1.2 5.4±1.2	22.2±1.5 11.0±1.5	48.5±2.3 22.0±2.3
h_2[b]	2.0±0.5 2.6±0.4	6.4±0.8 5.7±0.7	21.9±0.9 10.8±0.9	50.4±2.3 20.8±1.7

[a] Coating thickness, measured by eddy current thickness gauge.
[b] Coating thickness, determined in accordance with the developed method.

A joint analysis of Figure 4 and Table 1 shows that the coating thickness determined during the plasma electrolytic oxidation process using the developed method, within the margin of error, coincides with the thickness determined by independent measurements after processing. At the same time, the relative error of measuring the thickness of the coating according to the developed method does not exceed 10% for both alloys.

The differences in the calibration curves (Figure 4) are due to differences in the mechanisms of coating formation on BS6082 and AA2024 alloys. The differences in the mechanisms of coating formation are due to differences in the chemical composition of alloys, the percentage of pure aluminum to impurities, as well as in the methods of manufacturing and pretreatment of alloys.

Thus, the developed control method is operable in a wide range of processing conditions, both when applying thick-layer and thin-layer coatings.

5 Conclusion

An automated control system for the plasma electrolytic oxidation process in a potentiostatic mode based on the control of the coating thickness according to the characteristics of microdischarges has been developed and implemented. The control system provides an increase in the accuracy of coating formation by timely stopping the process when the target coating thickness is reached. The proposed approach to the automation of the PEO process will allow in the future to develop systems for optimal control of this process, taking into account unobservable variables characterizing the state of the surface layer.

References

1. E. Matykina, A. Berkani, P. Skeldon, G.E. Thompson, Electrochim. Acta **53(4)**, 1987-1994 (2007).
2. V.M. Cassidy, Modern Metals **50**, 4-7 (1994).
3. A.R. Fatkullin, E.V. Parfenov, A. Yerokhin, D.M. Lazarev, A. Matthews, Surf. Coat. Technol. **284**, 427-437 (2015).
4. J. Jovović, S. Stojadinović, N.M. Šišović, N. Konjević, Journal of Quantitative Spectroscopy and Radiative Transfer **113(15),** 1928-1937 (2012).
5. F. Jaspard-Mecuson, T. Czerwiec, G. Henrion, T. Belmonte, L. Dujardin, A. Viola, J. Beauvir, Surf. Coat. Technol. **201(21)**, 8677-8682 (2007).
6. S. Stojadinovic, R. Vasilic, I. Belca, M. Petkovic, B. Kasalica, Z. Nedic, Lj. Zekovic, Corrosion Science **52(10),** 3258-3265 (2010).
7. M. Tański, J. Podliński, A. Berendt, J. Mizeraczyk, Applied Sciences **14(24)**, 11596 (2024).
8. Z. Donkó, S. Hamaguchi, T. Gans, Plasma Sources Sci. Technol. **27,** 054001 (2018).