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Modeling of the dynamic current-voltage characteristic of micro-arc oxidation

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Abstract. The dynamic current-voltage characteristics of the micro-arc oxidation process were modeled by approximating the experimental curves. The hypothesis about the possibility of approximation of the anode ascending and cathode incident branches by exponential functions due to the presence of a valve effect in the metal-oxide-electrolyte system is confirmed. The selection of approximating curves for sections of micro-discharges is performed. The correctness of the approximating functions choice was evaluated by determining the approximation error at the experimental points. It is shown that it is expedient to use a polynomial function for approximating sections of anodic microdischarges, and an exponential function or a hyperbolic sine for sections of cathode ones. The limitations of the approach used in this work, which are associated with the approximate nature of the approximating functions, as well as with insufficient research into the mechanism of micro-arc oxide coatings formation are revealed. The simulation results can be used to develop a digital twin of the micro-arc oxidation process.

Keywords: micro-arc oxidation, digital twin, current-voltage curves, mathematical modelling

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Материалы конференции
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Моделирование динамической вольтамперной характеристики микродугового оксидирования

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Аннотация. Выполнено моделирование динамических вольтамперных характеристик процесса микродугового оксидирования путем аппроксимации экспериментальных кривых функциями различного вида. Подтверждена гипотеза о возможности аппроксимации анодной восходящей и катодной падающей ветви экспоненциальными функциями, что обусловлено вентильным эффектом в системе «металл-оксид-электролит».

Правильность выбора аппроксимирующих функций определялась в виде относительной погрешности аппроксимации. Результаты моделирования могут быть использованы при разработке цифрового двойника процесса микродугового оксидирования.

Ключевые слова: микродуговое оксидирование, цифровой двойник, вольтамперные характеристики, математическое моделирование

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Introduction

Currently, digital twins, which include mathematical models that reflect the operation of each node in the technological chain are increasingly used for process control [1, 2]. For traditional industries (for example, engineering), such models are well known [3, 4]. For new technological processes, the task of developing digital twins is much more difficult, since there is no mathematical description of their “components”. Thus, the micro-arc oxidation process (MAO) is distinguished by the interdisciplinary nature of the occurring phenomena, as a result of which the fundamental theory of this process has not yet been developed (the existing mathematical models describe only certain classes of phenomena) [5, 6]. Therefore, modeling of the external characteristics of this process, which can be measured in practice, is of great practical importance. Thus, a large number of works are devoted to the study of the forming curve (the dependence of the maximum voltage on the processing time), which reflects the mechanism of oxide coating growth on a valve metal substrate [7]. At the same time, much less attention is undeservedly paid to the study of dynamic current-voltage characteristics (CVCs), which are also informative [8]. In particular, dynamic current-voltage characteristics make it possible to determine the electrical resistance and, consequently, the thickness of the formed coatings, as well as to study the electrical characteristics of microdischarges, which is one of the unsolved problems of the MAO process. Thus, modeling the dynamic current-voltage characteristics of the MAO process is an urgent scientific problem.

Materials and Methods

Oxide coatings samples in the amount of 10 pieces were obtained on AD31T1 aluminum alloy substrates 23×15×1.5 mm in size. MAO processing was carried out on an automated laboratory setup in the anode-cathode mode at a sinusoidal current with a frequency of 50 Hz at current density of 10.88 A/dm^2 in an electrolyte containing 0.5 g/l NaOH and 80 g/l Na_2SiO_3. The processing time was 60 s for all samples. At time 60 s by synchronization signal the current and voltage oscillograms in the galvanic cell (two periods) were measured, after which the obtained data were averaged over all samples, as well as between two periods. As a result, idealized current and voltage oscillograms were obtained for one period of the process current, on the basis of which the dynamic CVCs were built. Approximation of the anodic and cathodic ascending and falling CVC branches was performed by functions of various types (Table 1) in order to determine the best form of the approximating curve (its smallest deviation from the experimental dependence). The approximation error $\delta I(u_m)$ of the experimental dependences was determined in the relative form:

$$\delta I\left(u_m\right)=\frac{I_a\left(u_m\right)-I_m\left(u_m\right)}{I_a\left(u_m\right)}\cdot 100\%, \quad (1)$$

where $I_a(u_m)$ and $I_m(u_m)$ – are the values of the approximating function and the experimental dependence taken at the point um, where the measurement was performed. A similar approach was previously used in the study of hysteresis loops of ferroelectrics [9] and was chosen because the dynamic CVC characteristics also exhibit hysteresis due to an increase in the resistance of the oxide coating with time.

Table 1

The forms of the approximating functions

No	Type of function	Equation
1	Exponential	$I = a_1 \cdot \exp(a_2 \cdot U) + a_3$
2	Double exponential	$I = a_1 \cdot \exp(a_2 \cdot U) + a_3 \cdot \exp(a_4 \cdot U) + a_5$
3	n^{th} degree polynomial	$I = a_0 \cdot U^n + a_1 \cdot U^{n-1} + \ldots + a_n$
4	Hyperbolic sine	$I = a_1 \cdot \mathrm{sh}(a_2 \cdot U + a_3) + a_4$

Notations: a_0, a_1 ... a_n are the empirical coefficients, *I* and *U* are current and voltage respectively.

Results and Discussion

The obtained oscillograms of current and voltage, as well as the corresponding current-voltage characteristic of the metal-oxide-electrolyte system, are shown in Fig. 1. On the graph of the current-voltage characteristic, characteristic points, the physical meaning of which is indicated in Table 2 can be distinguished.

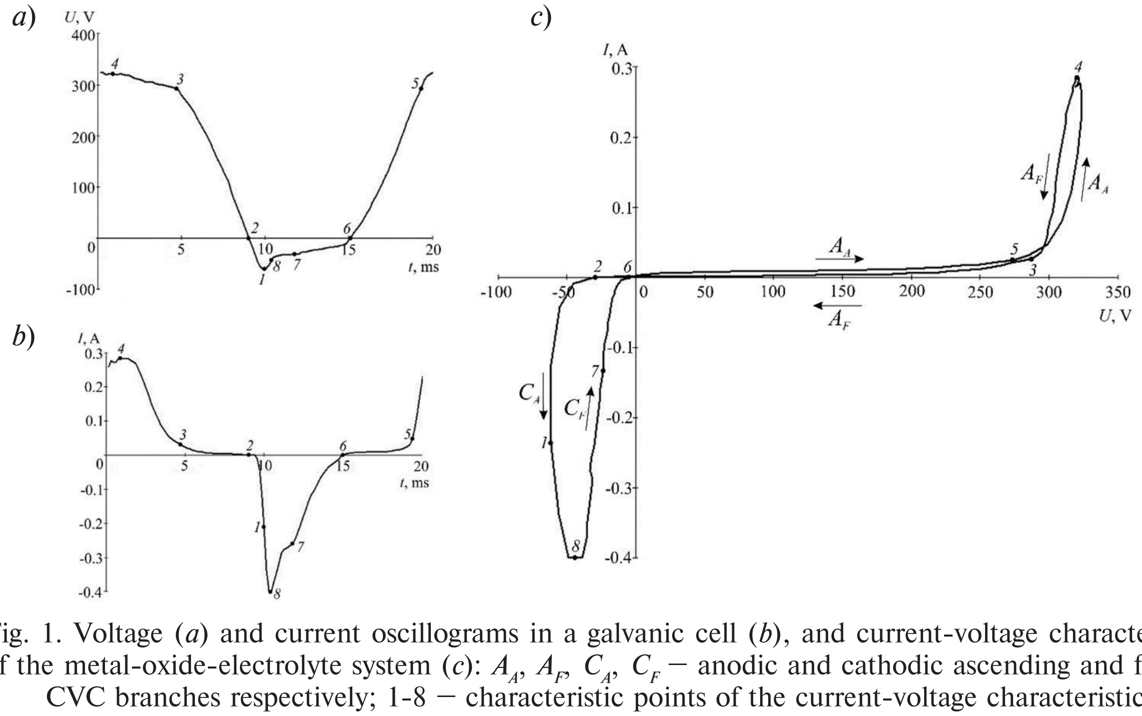

Fig. 1. Voltage (*a*) and current oscillograms in a galvanic cell (*b*), and current-voltage characteristic of the metal-oxide-electrolyte system (*c*): A_A, A_F, C_A, C_F – anodic and cathodic ascending and falling CVC branches respectively; 1-8 – characteristic points of the current-voltage characteristic

Table 2

Characteristic points of the current-voltage characteristic

Point	Physical meaning
1	Minimum voltage
2 and 6	Zero voltage and current
3	Microdischarge quenching voltage (knee point)
4	Maximum current
5	Microdischarge ignition voltage (knee point)
8	Minimum current

Several sections are distinguished on the dynamic CVC characteristic. The middle part of the CVC (regions 1-2-3 and 5-6-7 in Fig. 1, *c*) looks like an inverted CVC of a semiconductor diode (sections 1-2 and 6-7 correspond to the "forward branch" of the diode CVC, and sections 2-3 and 5-6 – "reverse"). This kind of CVC is quite reasonable due to the presence of the valve effect in the metal-oxide-electrolyte system. Sections 3-4 and 4-5 correspond to the microdischarges appearance on the sample surface. Sections 7-3 and 3-8 correspond to some transient electrochemical processes, and, possibly, "cathodic microdischarges" [10].

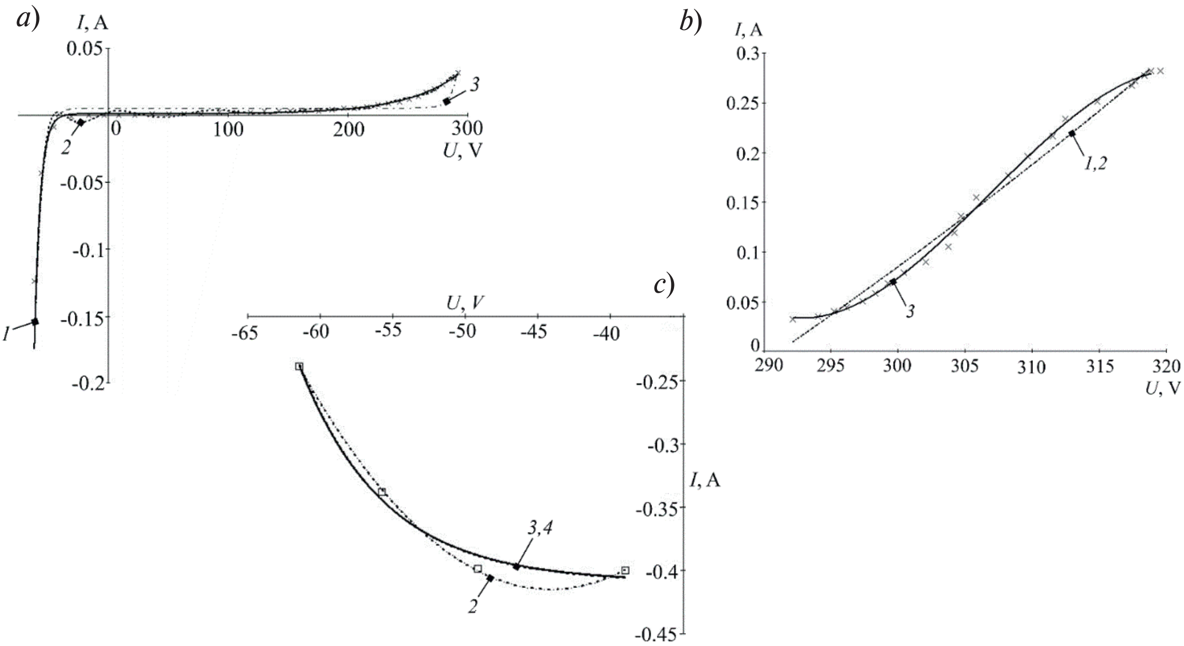

Fig. 2. Graphs of the approximating functions of the dynamic CVC characteristics sections: 1-2-3 (*a*), 3-4 (*b*), 8-1 (*c*) (in sections 5-6-7, 4-5, 7-8 similarly); *1* – double exponential function; *2* – polynomial of the nth degree; *3* – hyperbolic sine; *4* – exponential function

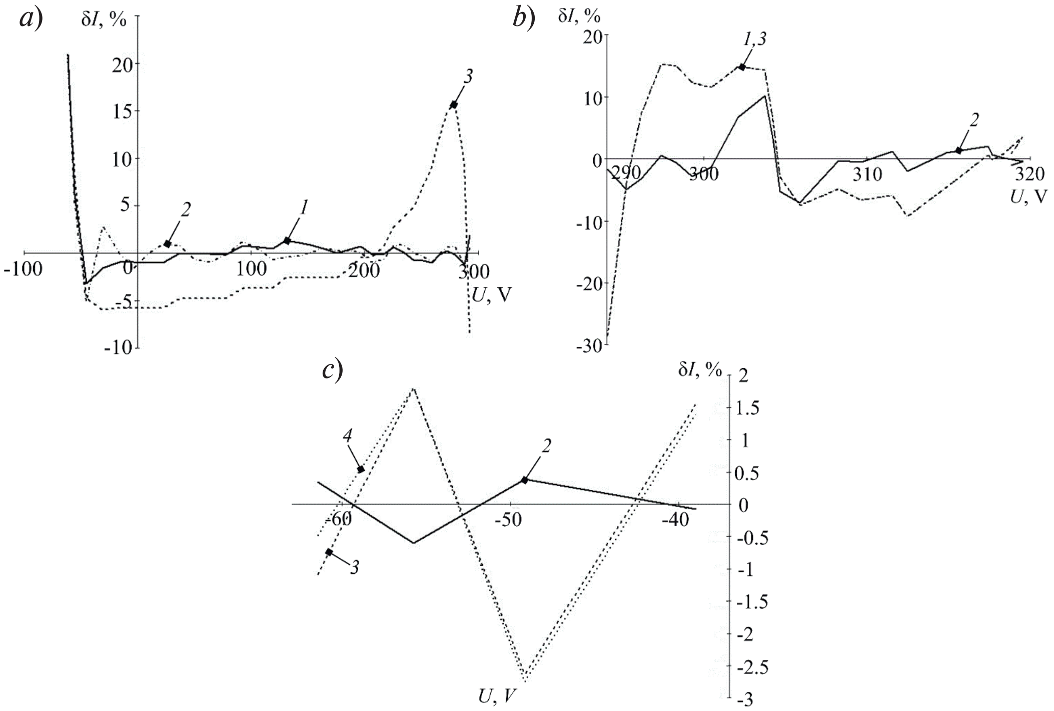

Fig. 3. Graphs of the approximation error: section 1-2-3 (*a*), section 3-4 (*b*), section 8-1 (*c*); *1* – double exponential function; *2* – polynomial of the nth degree; *3* – hyperbolic sine; *4* – exponential function

Graphs of the approximating functions of the dynamic CVC characteristics sections and approximation errors are presented in Fig. 2 and Fig. 3 respectively. It can be seen that in sections 1-2-3 and 5-6-7 the best approximation of the experimental data is given by the double exponential function, as expected. The hyperbolic sine can also be used to approximate this section, but in this case there is a strong discrepancy with the experiment near point 3 of the CVC. Approximation of this section by a polynomial function does not make sense due to the high order of the approximating polynomial. In the microdischarges sections (3-4 and 4-5), on the contrary, the polynomial of the 3rd degree has the smallest approximation error. In sections 8-1 and 7-8, the exponential function and the hyperbolic sine have the best convergence with the experiment.

Conclusion

The obtained approximating functions make it possible to determine the dependences of the coating resistance, ignition and quenching voltage of microdischarges and can be used in the development of mathematical models that form the basis of the digital twin of the micro-arc oxidation process.

The proposed approach has limitations. Firstly, the obtained approximating functions allow to determine only an approximate form of functional dependencies. Secondly, there is no generally accepted mechanism and exact mathematical description of some physical processes, such as the microdischarges combustion, which does not guarantee the correct choice of the approximating function type. To eliminate the identified shortcomings in the development of a mathematical model, it is necessary to take into account the physicochemical laws of the oxide layers growth and microplasma phenomena.

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