2021 International Seminar on Electron Devices Design and Production (SED)

Methodology for Choosing a Method and Instruments of Measuring Technological Modes and Parameters of Synthesized Coatings According to Technical and Economic Indicators

Ekaterina A. Pecherskaya
dept. «Information-measuring equipment and metrology»
Penza State University
Penza, Russia
pea1@list.ru

Pavel E. Golubkov
dept. «Information-measuring equipment and metrology»
Penza State University
Penza, Russia
golpavpnz@yandex.ru

Vladimir V. Antipenko
dept. «Information-measuring equipment and metrology»
Penza State University
Penza, Russia
v.antipenko7@yandex.ru

Artem V. Volik
dept. «Information-measuring equipment and metrology»
Penza State University
Penza, Russia
Minor401@gmail.com

Gennadiy V. Kozlov
Polytechnic Institute
Penza State University
Penza, Russia
gvk17@yandex.ru

Timur O. Zinchenko
dept. «Information-measuring equipment and metrology»
Penza State University
Penza, Russia
scar0243@gmail.com

***Abstract*— It has been shown that in order to obtain oxide coatings with desired properties, in the process of their synthesis, it is necessary to measure and control the technological parameters and properties of the coatings. The authors proposed an automated system for the synthesis and study of coating parameters by the micro-arc oxidation method. An algorithm for the selection of methods and instruments for measuring technological modes and parameters of synthesized coatings according to technical and economic indicators and a method for choosing the optimal means for measuring technological parameters of the micro-arc oxidation process according to technical and economic indicators based on the average gain criterion have been developed. The analyzed technical indicators include metrological characteristics of measuring instruments. The technique was implemented in the selection of optimal measuring instruments for coating parameters in the process of micro-arc oxidation, which confirmed the relevance of the development of an automated system for the synthesis of coatings with specified properties, with a relative measurement error of the parameters not exceeding ±0.5 % by micro-arc oxidation.**

Keywords*— *micro-arc oxidation, parameter measurement, automated system, measurement error, average gain criterion, measuring instrument

I. Introduction

An important direction in the development of micro-arc oxidation (MAO) is the development of new technological and research equipment [1–3], which makes it possible to obtain coatings with the required properties depending on the field of application. For example, in [4], a mechanism for the formation of coatings used in biomedical products is proposed; in [5], the results of tests of MAO coatings for microhardness and wear resistance are presented; in [6] the morphology of the surface, cross-section using scanning electron microscopy, X-ray diffraction are investigated; in [7] the results of studies of the structure, phase and elemental composition of MAO coatings of diesel engines pistons are presented. Regardless of the field of application of oxide coatings, the control of the technological process requires the choice of methods and instruments for measuring technological parameters and properties of coatings in real time that meet the technical and economic requirements.

The authors of this study proposed an automated system for the synthesis and study of MAO coatings [8 - 10], which has the technical and metrological characteristics indicated in Table 1.

TABLE I. Metrological Characteristics of the Automated System for the Synthesis and Study of MAO Coatings

Parameter	Parameter value
Sample voltage range	from –200 to 600 V
Range of average current through the sample	from 0.25 to 1.75 A
Test signal frequency range	from 5 Hz to 10 kHz
AC signal amplitude range	from 0.1 to 1 V
Measurement limits for capacitance	0.1 and 1 μF
Basic error of capacitance measurement	no more than ±0.5 %
Current measurement limits	0.5 and 3 A
Voltage measurement limit	600 V
Basic error of voltage and current measurement	no more than ±0.5 %
Resistance measurement range	up to 20 kOhm
Basic error of resistance measurement	no more than ±0.5 %
Temperature measurement range	from 0 to 100 ^{0}C
Basic temperature measurement error	no more than ±0.5 %

To estimate the errors of measuring channels of measuring instruments (MI), the methodology of metrological analysis is used, for example, given in various studies [11 - 13].

The reported study was funded by RFBR according to the research project № 19-08-00425.

978-1-6654-3941-1 @2021 IEEE

To compare instruments for measuring technological parameters of the micro-arc oxidation process and selecting their optimal ones in terms of technical and economic indicators, the authors proposed an algorithm and a technique based on the methodology of system analysis, theoretical metrology.

II. Algorithm for Selecting the Method and Measurement Tools of Technological Modes and Parameters of Synthesized Coatings

The decision-making is based on the expert methodology for choosing instruments for measuring the parameters of materials according to technical and economic indicators, which implements the algorithm (Fig. 1).

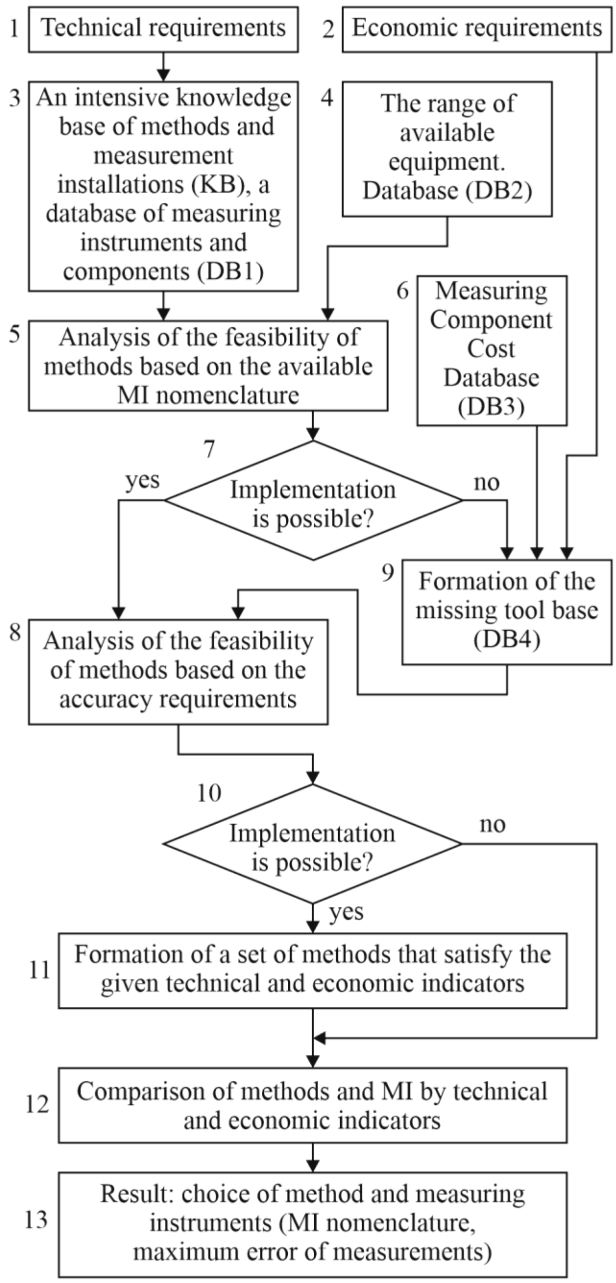

Fig. 1. Algorithm for choosing a method and instruments of measuring technological modes and parameters of synthesized coatings according to technical and economic indicators

Technical and economic requirements (blocks 1 and 2, see Fig. 1) form respectively two data arrays, the elements of which contain information listed in more detail in the blocks in Fig. 1. The intellectual system is based on the intensive knowledge base (KB) of methods for measuring the properties of active dielectrics and their instrumental implementations (Fig. 1, block 3), containing for each measurement method:

- diagrams of measuring installations,
- functional and metrological models (respectively, formulas for the indirect determination of measured quantities and formulas for evaluating the limiting values of errors in the results of indirect measurements).

In addition, a database (DB1) of measuring instruments and components of electronic equipment, containing the metrological characteristics (MC) of the nomenclature of elements that is presented in the intensive knowledge base (KB) is created. The open database DB2 (block 4, Fig. 1) contains the metrological characteristics of the available equipment from the nomenclature, which is also presented in the KB. In block 5 (Fig. 1), the values of metrological characteristics from DB2 are substituted into the formulas of the functional models of the KB. As a result, the analysis of the feasibility of the methods, based on the available nomenclature of measuring components (block 5) is carried out, and if such an implementation is possible (output "yes" of block 7), then in block 8 the calculation of the limiting values of measurement results errors using metrological models of the KB is realized.

If, as a result of block 5, it is concluded that it is impossible to implement the method using only the available equipment (DB2), then, guided by economic requirements (block 2), in block 9, a database of the missing instrumental base (DB4) is formed. For these purposes, an open database (DB3, block 6), containing information on the nomenclature, technical characteristics and cost of measuring components (in the case of their purchase, lease, etc.) from third-party organizations (suppliers) with which it is installed cooperation. In fact, the information of an economic nature contained in DB4 supplements DB1 (contains the technical characteristics of the components), and therefore these DBs can be combined, taking into account the fact that the unique information of DB4 must be updated according to the changes of the supplier organizations.

The metrological characteristics of the measuring components from the output of block 9 are fed to the input of block 8, where the analysis of the feasibility of the methods, taking into account the accuracy requirements is again performed.

In block 10, the calculated errors are compared with the specified values according to the technical requirements (specified in block 1).

Thus, at the output of block 11, a variety of methods that satisfy the given technical and economic indicators are formed. The following is a comparison of methods and measuring installations for the specified indicators. As a result, the method that has the lowest cost and at the same time provides a measurement error that is within the range of acceptable values is selected. If the methods have the same cost, for example, if they are implemented using existing equipment, then the criterion of measurement accuracy is decisive. In this case, the choice of measurement methods can be carried out using the procedure for making a managerial decision by comparing methods and instruments for measuring the coatings properties, depending on the metrological characteristics. Comparison of methods of indirect measurements in terms of metrological indicators can be carried out in two directions, depending on whether the problem is solved directly or inversely:

- a direct task is to compare methods at the stage of their development;
- an inverse problem is a metrological analysis of already developed methods.

Since, as a rule, when setting the problem in the initial data, the required measurement accuracy, which should be ensured by the methods under consideration (or measuring installations implemented with various MI combinations) is specified, then the solution of problem (a), in addition to developing methods, should contain their analysis, and problems (b) - development. In the latter case, the question of the need to continue the development is decided on the basis of comparing the metrological characteristics obtained as a result of the analysis with those indicated in the initial data. Consequently, the process of comparing methods by metrological indicators always contains feedback, which is illustrated in the form of a structure (Fig. 2, a, b).

Below is the process of comparison and decision making based on methods of system analysis of complex systems.

III. Methodology for Choosing Optimal Measurements of Technological Parameters of the Micro-Arc Oxidation Process by Technical Indicators Based on the Average Gain Criterion

Let us consider the application of the average gain criterion to select the optimal measuring installation by technical indicators, and then use the aggregation function in the form of the accuracy indicators ratio (identified with the target effect) to the indicators of costs for achieving this effect.

A. Formulation of the problem

There are alternative measuring instruments a_l, each of which is designed to measure N of physical quantities (the ordinal number of a physical quantity is denoted by i, $i = 1, ..., N$).

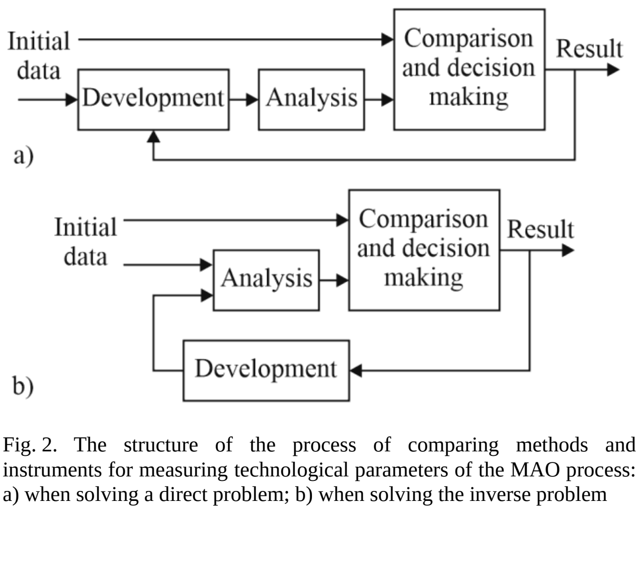

Fig. 2. The structure of the process of comparing methods and instruments for measuring technological parameters of the MAO process: a) when solving a direct problem; b) when solving the inverse problem

In this case, AC voltage, current, capacitance, resistance, temperature, that is, $N = 5$, are subject to measurement. Known indicators of accuracy x_{il} characterizing the target effect when measuring the i-th of physical quantity l-th measuring installation. It is necessary to choose the optimal method (measuring instruments) with the maximum value of efficiency.

B. Methodology for choosing the best measuring instruments by technical and economic indicators

1. Drawing up a matrix of the effectiveness of measuring instruments for the example considered above (Table 2), which also contains the values of the corresponding cost indicators g_l. In this case, $1/x_{il}$ is the modulus of the ratio of the maximum permissible relative measurement error of the i-th value to the maximum relative measurement error of the measuring instrument a_l, where $l = 1, 2 ... 5$ according to the numbering adopted in Table 2 (in column 1). For $i = 1$, AC voltage measurement is considered, for $i = 2$ - AC current measurement, for $i = 3$ - resistance measurement, $i = 4$ corresponds to capacitance measurement, $i = 5$ corresponds to temperature measurement. The numerical values indicated in Table 2 correspond to specific measuring instruments of the listed parameters, which are considered as alternatives. The average gain criterion assumes setting the probability p_i of the so-called onset of the situation associated with the measurement of the i-th physical quantity.

2. Evaluation of the probabilities of occurrence of events associated with the measurement of physical quantities. The function of probability can be performed by a weighting coefficient that takes into account the rank of the factors under consideration, depending on the prioritization of ensuring accuracy in measuring physical quantities. In this paper, it is proposed to use the ratio of the measurements number of one physical quantity to the total number of measurements over a certain time interval equal to the duration of the measurement experiment. Then, an event related to the measurement of the most demanded physical quantity is considered as the highest priority. In a particular case, if all physical quantities are measured often equally (which is the case when measuring the parameters of the MAO process), then the probabilities are equal to each other:

$$p_1 = ... = p_i = ... = p_N = \frac{1}{N}, \quad (1)$$

and the average gain criterion degenerates into the Laplace criterion.

3. Evaluation of the measuring instruments effectiveness (sets of measuring instruments) when measuring all physical quantities. For each alternative measuring instrument (or their combination with $l = 4$) a_l, it is necessary to calculate the efficiency $K(a_l)$ using the formula:

$$K(a_l) = \sum_{i=1}^{N} p_i \frac{1}{x_{il}}, \; l = 1, ..., L. \quad (2)$$

TABLE II. Matrix of the Effectiveness and Costs of Measuring Instrument

a_l	$1/x_{il}$					g_l
	$1/x_{1l}$	$1/x_{2l}$	$1/x_{3l}$	$1/x_{4l}$	$1/x_{5l}$	

a_l	$1/x_{il}$					g_l
	$1/x_{1l}$	$1/x_{2l}$	$1/x_{3l}$	$1/x_{4l}$	$1/x_{5l}$	
a_1	0.714	0.625	1.667	0.555	5.000	1.78
a_2	0.714	0.625	1.667	0.555	0.500	1.25
a_3	0.385	0.250	1.250	0.250	0.500	1.10
a_4	0.167	0.333	5.000	5.000	0.500	1.18
a_5	1.000	1.000	1.000	1.000	1.000	1.00

When measuring the parameters of the MAO process, $p_1 = p_2 = p_3 = p_4 = p_5 = 1/5$, the efficiency values are as follows:

$K(a_1) = 1.712$; $K(a_2) = 0.8122$; $K(a_3) = 0.527$; $K(a_4) = 2.2$; $K(a_5) = 1$.

4. Determination of the optimal measuring instrument for the target effect, which has an efficiency K_{opt} that satisfies the expression:

$$K_{opt} = \max_l \sum_{i=1}^{N} p_i \frac{1}{x_{il}}, \; l = 1, ..., L. \quad (3)$$

In our case, $K_{opt} = K(a_4) = 2.2$, therefore, according to the technical parameters (according to the target effect), the set of measuring instruments a_4 is taken to be optimal.

5. Taking into account the influence of the cost factor g_l. The data required to calculate the aggregation function that takes into account the target effect and the cost factor are summarized in Table 3.

TABLE III. VALUES OF EFFICIENCIES AND COST FACTORS OF MEASURING INSTALLATIONS

a_l	$K(a_l)$	g_l
a_1	1.712	1.78
a_2	0.812	1.25
a_3	0.527	1.10
a_4	2.2	1.18
a_5	1	1

The aggregating function $K(a_l, g_l)$ is defined as the ratio of efficiency $K(a_l)$ to cost factor g_l:

$$K(a_l, g_l) = \frac{K(a_l)}{g_l}. \quad (4)$$

In our case, $K(a_1, g_1) = 0.95$; $K(a_2, g_2) = 0.65$; $K(a_3, g_3) = 0.48$; $K(a_4, g_4) = 1.86$; $K(a_5, g_5) = 1$.

7. Determination of the optimal measuring instrument for the target effect and cost factor, which has $K(a_l, g_l)_{opt}$:

$$K(a_l, g_l)_{opt} = \max_l \frac{K(a_l)}{g_l}. \quad (5)$$

In our case, since the set of measuring instruments a_4 does not satisfy the requirements for automation of measurements and processing of results, the intelligent system under development, designated a_5, is recognized as optimal.

IV. CONCLUSION

In order to compare methods and measuring instruments, as well as to select the optimal ones in terms of technical and economic indicators, the authors proposed:

- an original algorithm for choosing methods and instruments for measuring technological modes and parameters of synthesized coatings in terms of technical and economic indicators;
- a technique for choosing the optimal measuring instruments for the technological parameters of the micro-arc oxidation process according to technical and economic indicators based on the average gain criterion.

Metrological characteristics (limiting basic relative measurement errors of voltage, current, capacitance, resistance, temperature) are considered as technical indicators. The methodology implies the development of a matrix of efficiency and costs of measuring instruments; evaluating the effectiveness of measuring instruments (or their aggregates) when measuring all physical quantities; determination of the optimal measuring instrument for the target effect; analysis of possible limitations inherent in the selected measuring instrument and affecting the possibility of using the indicated measuring instrument in specific conditions of the technological process (the possibility of automation and implementation of nondestructive control of parameters directly in the process of micro-arc oxidation); calculation of the aggregation function in the form of the accuracy indicators ratio (identified with the target effect) to the cost indicators for achieving this effect.

The technique has been tested in relation to the selection of optimal instruments for measuring the parameters of oxide coatings in the process of micro-arc oxidation, which confirmed the relevance of the development of an automated system for the synthesis of coatings with specified properties, with a relative measurement error of parameters not exceeding ±0.5 %, by the method of micro-arc oxidation.

REFERENCES

[1] L. Hongyang, Y. Wei, H. Jiye, and Y. Shiyan, "Method of micro-arc oxidation load characteristics measurement," Digests IEEE 11th Int. Conf. on Electronic Measurement & Instruments, Harbin, pp. 722-725, 2013.

[2] Z. Feng, and X. Dai "Study on Factors Affecting the Properties of Micro-arc Oxidation Film on Magnesium Alloys Based on Phosphate Electrolyte," ACM Int. Conf. Proc. Series, pp. 589-594, 2020.

[3] S. S. Arbuzova, P. I. Butyagin, A. V. Bol'shanin, A. I. Kondratenko, and A. V. Vorob'ev, "Microarc Oxidation of Metal Surfaces: Coating Properties and Applications," Russ. Phys. J., vol. 62, pp. 2086–2091, 2020.

[4] X. Zhang, Zh. Peng, X. Lu, Y. Lv, G. Cai, L. Yang, and Z. Dong, "Microstructural evolution and biological performance of Cu-incorporated TiO2 coating fabricated through one-step micro-arc oxidation," Appl. Surf. Sci., vol. 508, 144766, 2020.

[5] X. Qi, H. Shang, B. Ma, R. Zhang, L. Guo, and B. Su, "Microstructure and Wear Properties of Micro Arc Oxidation Ceramic Coatings," Materials, vol 13(4), no. 970, pp. 1-10, 2020.

[6] Y. Wang, B. Jiang, T. Lei, and L. Guo, "Dependence of growth features of microarc oxidation coatings of titanium alloy on control modes of alternate pulse," Mater. Letters, vol. 58(12-13), pp. 1907-1911, 2004.

[7] Ch. Ma, J. Liu, X. Zhu, Zh. Yan, D. Cheng, W. Xue, J. Fu, and Shenglin Ma, "Optimization of surface texture fabricated by three-step microarc oxidation for self-lubricating composite coating of diesel engine piston skirts," Wear, vol. 466–467, 203557, 2021.

[8] P. Golubkov, E. Pecherskaya, O. Karpanin, M. Safronov, J. Shepeleva, and A. Bibarsova, "Intelligent automated system of controlled synthesis of MAO-coatings of MAO-coatings," Digests Conf. of Open Innovation Association, FRUCT, no. 8711874, pp. 96-103, April 2019.

[9] D. V. Artamonov, V. A. Baranov, E. A. Pecherskaya, A. V. Pushkareva, B. V. Tsypin, and A. V. Fimin, "Application of a Hyper-Complex Impedance Model for Indirect Measurements of Materials Parameters of Functional Electronics," Digests Int. Conf. of Young Specialists on Micro/Nanotechnologies and Electron Devices, EDM, no. 8823442, pp. 760-764, June 2019.

[10] P. E. Golubkov, E. A. Pecherskaya, Y. V. Shepeleva, A. V. Martynov, T. O. Zinchenko, and D. V. Artamonov, "Methods of applying the reliability theory for the analysis of micro-arc oxidation process," J. of Phys.: Conf. Ser., vol. 1124(8), 081014, 2018.

[11] L. A. A. Souza, E. De Barros, R. T. Vasconcellos, A. C. S. De Lima, and M. B. Martins, "Metrological analysis of voltage transducers under multi-harmonic signals," Digests Conf. on Precision Electromagnetic Measurements, CPEM, 91918672020, August 2020.

[12] R. Y. Kurnosov, T. I. Chernyshova, N. V. Chernyshov and M. A. Kamenskaya, "Metrological Analysis of Analog-To-Digital Conversion Measurement Procedure in Information-Measuring and Control Systems," Digests 2nd Int. Conf. on Control Systems, Mathematical Modeling, Automation and Energy Efficiency (SUMMA), Lipetsk, pp. 61-64, 2020.

[13] E. A. Pecherskaya, D. V. Artamonov, V. I. Kondrashin, P. E. Golubkov, O. V. Karpanin, and T. O. Zinchenko, "Software - Hardware Complex for Measurement and Control of Ferroelectrics Parameters," IOP Conf. Ser.: Mater. Sci. and Eng., vol. 225(1), 012254, 2017.