Intelligent Automated System of Controlled Synthesis of MAO-Coatings

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Abstract—**An intelligent automated system that allows the controlled synthesis of protective oxide coatings using micro-arc oxidation has been developed. The hardware and software structure and knowledge bank, the information exchange principles between the component parts of the device, as well as the software operation algorithm are given. The considered system allows to establish the relationship between the technological process parameters of the micro-arc oxidation and the properties of the formed coatings. This intelligent system can be used both for scientific research and for production in order to optimize the technological modes of micro-arc treatment.**

I. Introduction

Currently, micro-arc oxidation (MAO) – the direction of plasma-chemical processing of parts from valve metals and alloys is actively developing. Coatings obtained by micro-arc oxidation are used in the automotive industry, aerospace industry, shipbuilding, railway engineering, medicine and many other industries [1-3]. More than 10 major enterprises in the world that successfully manufacture products with hardening coatings, made using this technology, are widely known. This is Keronite in the UK, Plasma Technology Ltd. and GERE in China, Progress Industrial Systems SA in Switzerland, LLC “Russian Profile”, CJSC “Manel”, LLC “Sibspark”, JSC “NII STT”, LLC “NPP Magnetic-Don”, LLC “NPTs Titan” in Russia and other.

However, the MAO process is not fully studied, in particular, the problem of its controllability still remains unsolved, the solution of which is devoted to a large number of theoretical and experimental works [4–12]. The main difficulty that scientists face in it is a large number of factors that collectively affect the MAO coatings properties, and, as a result, the quality parameters of manufactured products.

This problem confronts scientists for a long time, a large number of attempts have been made to automate the MAO process [13–19], but only recently works have begun to appear in which intelligent algorithms, for example, neural networks [20–23], are being used to solve this problem. However, in these works, the entire set of influencing factors was not used, and there was no feedback between the technological parameters and the properties of the MAO coating.

In this regard, the authors proposed an intelligent automated system of controlled synthesis of MAO coatings, designed to establish the relationship between the parameters of the MAO process and the properties of oxide coatings and implements controlled production of these coatings with the required properties based on intelligent algorithms.

II. Theoretical information about MAO process

Detailed theoretical information about the MAO process can be found in [24–25], below are those that are necessary for understanding the operation of an intelligent system.

MAO is a regular development of anodizing technology and is a plasma-chemical method of hardening samples of valve metals with unipolar conductivity in the metal-oxide-electrolyte system, such as aluminum, magnesium or titanium. MAO coatings synthesized by this method are an oxide layer consisting of high-temperature crystalline modifications of alumina, mainly corundum. This coating has a high micro-hardness (up to 25 GPa), wear resistance, corrosion resistance, electrical strength and heat resistance (withstands short-term thermal shock up to 1500° C) [26], as well as good biocompatibility [27]. To obtain MAO coatings, a galvanic cell – an electroplating bath in which two electrodes are immersed – the anode (a piece of valve metal) and a cathode made of stainless steel is used. The most popular electrolyte is silicate-alkaline, consisting of sodium silicate Na_2SiO_3 and potassium hydroxide (KOH). A technological current source is connected to the anode and cathode.

The coating is formed during high-voltage impulse action on the part, and different processes occur in the positive (anodic) and negative (cathodic) half-period. In the anodic half-period, the growth of the oxide film is observed, in the cathode one – its partial dissolution and surface preparation for the subsequent formation of a new oxide layer.

There are four stages of the MAO process, which are clearly visible on the forming curve (the dependence of the forming voltage on the processing time): the anodizing stage, the spark, micro-arc, and arc discharges. The anodizing stage is the shortest (lasts a few minutes), while the total MAO treatment time varies from 30 minutes to 2.5 hours. The arc discharge stage is undesirable because it leads to the destruction of the coating. The main beneficial effect occurs at the stage of micro-arc discharges, in which the phase transformation of amorphous allotropic modifications of alumina to high-temperature crystalline ones occurs.

ISSN 2305-7254

The properties of an MAO coating are affected by many factors systematized in [28], [29]:

- Technological parameters: current density, processing time, the ratio of the anodic and cathodic currents, the frequency of technological current source pulses, forming voltage.
- The parameters of the workpiece: the composition of the original alloy, surface roughness.
- Electrolyte parameters: composition, temperature, turbidity and development.

In the course of serial production, with the long-term use of the same electrolyte, its development occurs – depletion of ions, which become part of the coating. As a result, the electrolyte loses its useful properties, which leads to burnout of the coating and waste of the product. In this regard, strict control and periodic adjustment of the electrolyte composition in the MAO process is necessary.

During MAO treatment in the electrolyte, sludge, which is formed from the coating particles discharged by micro-discharges, which, with stirring, gives the electrolyte undesirable turbidity and makes it difficult to measure the brightness of the micro-discharges also forms.

III. STRUCTURE OF THE INTELLIGENT SYSTEM

The intelligent automated system of controlled synthesis of MAO coatings consists of three main parts: hardware, software and information support (Fig. 1).

The hardware is a set of technical means necessary for obtaining MAO-coatings, measuring their properties and process parameters in real time, as well as for processing the results of experiments. In this case, this is the MAO installation and a computer.

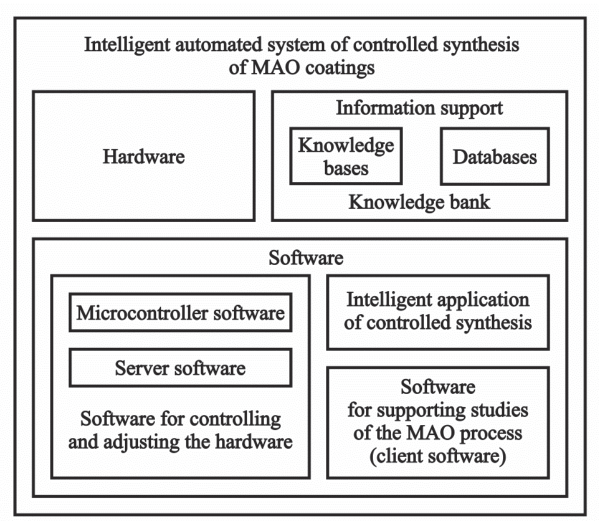

Fig. 1. The structure of the intelligent automated system of controlled synthesis

Software includes: software for controlling and adjusting the hardware, intelligent application of controlled synthesis, and software for supporting studies of the MAO process (client software). The software for controlling and adjusting includes the microcontroller software, which provides signals for controlling the MAO installation and performing measurements, and the server software, which is responsible for setting up the system. Intelligent application of controlled synthesis combines software algorithms that implement the techniques of controlled synthesis of MAO coatings developed by the authors.

Software for supporting studies of the MAO process includes software tools that implement the processing of experimental results and display data in a form that is convenient for users to understand. In particular, the "Experiment Planning" program interface should be presented in the form of a directed graph displaying the relationship "technological parameter – property of MAO-coating – quality parameter". At the same time, it is possible to select properties that must be controlled according to the specified requirements in the MAO process. An exemplary view of the graph interface and a view of the property selection window are presented in Fig. 2.

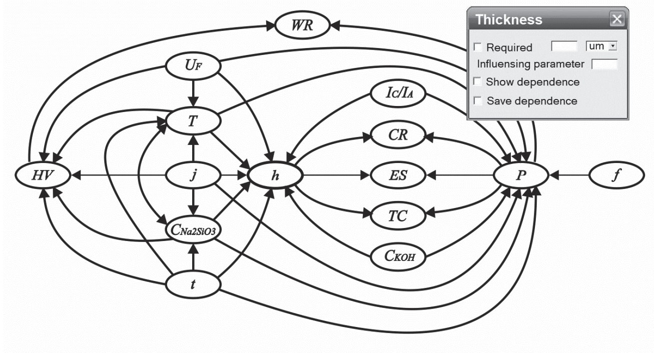

Fig. 2. Graph interface: HV – micro-hardness, WR – wear resistance, CR – corrosion resistance, ES – electrical strength, TC – thermal conductivity, h and P – thickness and porosity of MAO coating respectively, j – current density, t – time of the MAO treatment, T, $C_{Na2SiO3}$, C_{KOH} – temperature and concentration of electrolyte components, respectively, I_C/I_A – ratio of anodic and cathodic currents, U_F – forming voltage, f – frequency of technological current pulses

Information support implies the existence of a knowledge bank in the system containing the following knowledge bases and databases:

- Knowledge base of the MAO coatings properties.
- Database of technological parameters of MAO process.
- Knowledge base of theoretical methods for studying MAO coatings (physicochemical regularities, equivalent electrical circuits, etc.).
- Knowledge base of mathematical models of the relationship between technological parameters, properties and quality parameters of MAO coatings.
- Knowledge base of the MAO process modes.
- Knowledge base of methods for measuring technological parameters and properties of coatings.
- Database of measuring instruments and their metrological characteristics.
- Reference knowledge base about MAO mechanism.

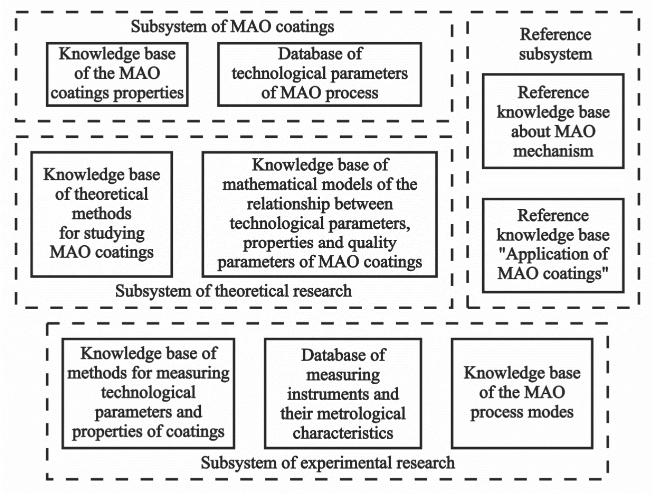

Fig. 3. Knowledge bank structure

- Reference knowledge base "Application of MAO coatings" (includes approximate values of the MAO coatings properties for various applications).

The structure of information support is shown on Fig. 3.

IV. Structure of the Hardware of the Intelligent System

The hardware of the intelligent system of controlled synthesis of MAO coatings includes a technological current source, a measuring circuit, a microprocessor module, a galvanic cell, an electrolyte cooling and mixing system, and a power supply unit of low-voltage circuits (Fig. 4).

The technological current source is a high-voltage (600 V) transistor current source, built on a bridge circuit and operating according to the pulse-width modulation principle.

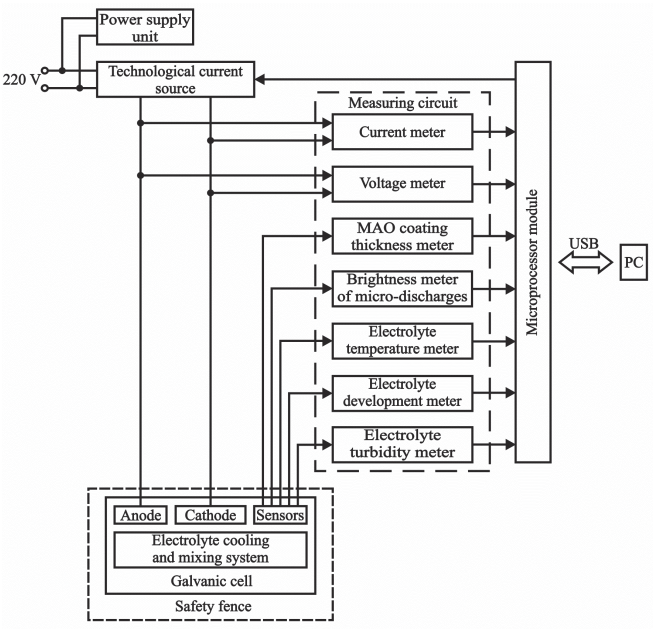

Fig. 4. The hardware structure of the intelligent system

At its output, a pulsed signal of the technological current (impact) with variable polarity (anodic pulses, cathode pulses, anodic-cathodic pulses) and a form (sinusoidal, rectangular, triangular, trapezoidal), which is applied to the sample in a galvanic cell, is formed.

The measuring circuit is a set of transducers that allow real-time measurement of the technological parameters of the MAO process (current, voltage, brightness of micro-discharges, temperature, turbidity and electrolyte development) and the properties of the growing MAO coating (thickness). Measuring transducers perform a double function: firstly, they are used to collect experimental data, as well as the completion of the knowledge base; secondly, measuring transducers are an feedback element between a technological current source and an intelligent application. It will establish the relationship of the process parameters and properties of MAO coatings and makes it possible to carry out controlled synthesis of high-quality oxide layers.

The microprocessor module is designed to generate control signals for the process current source and measuring transducers. The microprocessor module includes a microcontroller that has an analog-digital and digital-analog converter, an 8-channel multiplexer and a UART port; digital signal synthesizer, USB-to-UART interface converter based on FT232RL microcircuit and galvanic isolation node. By means of galvanic isolation of the USB port, communication with a PC is organized to meet safety requirements.

The galvanic cell is a stainless steel tank filled with electrolyte, in which two electrodes are immersed – the anode and cathode, as well as temperature sensors and the electrolyte development and the thickness of the MAO coating. A micro-discharge brightness sensor, which is an IR photodiode, is mounted in the cover of the galvanic cell. The turbidity sensor of the electrolyte is placed in a separate cell located on the pipe of the flow-through cooling system.

The electrolyte mixing system combined with galvanic cell (Fig. 5) makes it possible to significantly reduce the electrolyte turbidity by localizing sludge particles in the galvanic cell sludge trap using a rotating vortex – cyclone.

The electrolyte 1 with sludge particles 2 is pumped through by pump 3 through the galvanic cell from the bottom up. In this case, the jet of contaminated electrolyte undergoes turbulence between the wall of the electroplating bath 4 and the galvanic cell housing 5, gets into the cone 6 and accelerates there, dragging the sludge particles into the lower opening of the cone. After passing through the hole, the flow rate of the electrolyte decreases due to an increase in the volume in which the liquid is located, and the sludge particles settle to the bottom under the action of gravity. After the initial cleaning, the electrolyte is pumped up through a hole in the cone, passes through a filter 7, in which it undergoes additional cleaning. After several such iterations, the electrolyte is practically freed from sludge.

The electrolyte cooling system is flow-through, with electrolyte rather than water circulating through the pipes. Since the electrolyte is a highly dilute aqueous solution of alkali, the pipes can be made of polypropylene. Passing through a copper or aluminum ribbed radiator 11 blown by fans 12, the warm electrolyte is cooled.

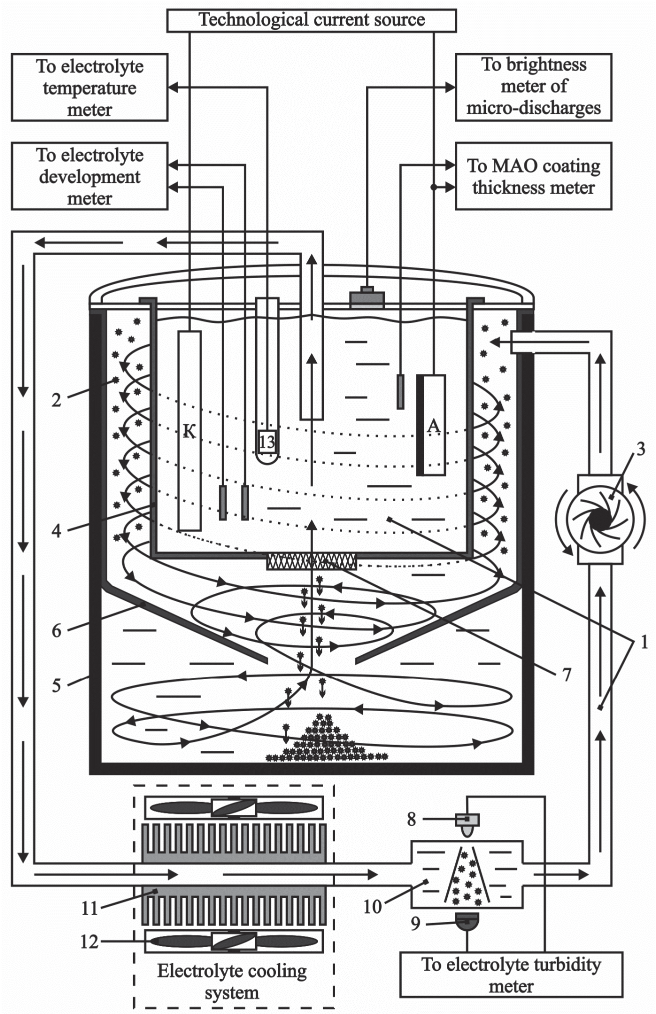

Fig. 5. Construction of the galvanic cell: 1 – electrolyte, 2 – sludge particle, 3 – pump, 4 – electroplating bath, 5 – housing, 6 – cone, 7 – filter, 8 – light emitting diode, 9 – photodetector, 10 – cell, 11 – radiator, 12 – fan, 13 – temperature sensor

The power supply of the intelligent system is carried out from the 220 V network, and a separate power supply unit is allocated for low-voltage equipment (measuring circuit, microprocessor module, fans, etc.). The system also provides a safety fence in the form of a limit switch, which is triggered when the galvanic cell is opened.

V. The algorithm of the software work of the intelligent system

The model of hardware and software interaction is shown in Fig. 6. During the operation of the system, client software, intelligent application of controlled synthesis, server software and microcontroller software exchange data packets. The software of the microcontroller controls the operation of technological current source via analog signals, and receives signals from measurement transducers, which, after analog-digital conversion and transmission via the USB interface, become available to the intelligent application of controlled synthesis. Intelligent application analyzes the obtained data on the technological parameters and properties of the synthesized coating, and if they deviate from the required optimal values identified earlier, it performs the adjustment of the technological mode, controlling the microcontroller (Fig. 6, a). This behavior is similar to the presence of feedback between the measuring transducers, intelligent application of controlled synthesis and technological current source (Fig. 6, b), which ensures the maintenance of the optimal technological parameters of the MAO process throughout the entire processing time.

The general algorithm of the intelligent system's software functioning is presented in Fig. 7. At the beginning of work, the operator needs to specify the type of work to be performed: experimental studies (option 1) or production of MAO coatings with specified properties (option 2). If option 1 is chosen, the operator will be offered the choice of the interrelation "technological parameter of the MAO process – a property of MAO coating" on the graph interface. The choice is made by highlighting the graph arc with the mouse.

In this case, the MAO process will be carried out according to the technological parameters specified by the user, which, in general, are not optimal, and serve only to refine the mathematical models of the MAO process.

If option 2 is selected, an intelligent application based on the data analysis available in the knowledge bank will offer

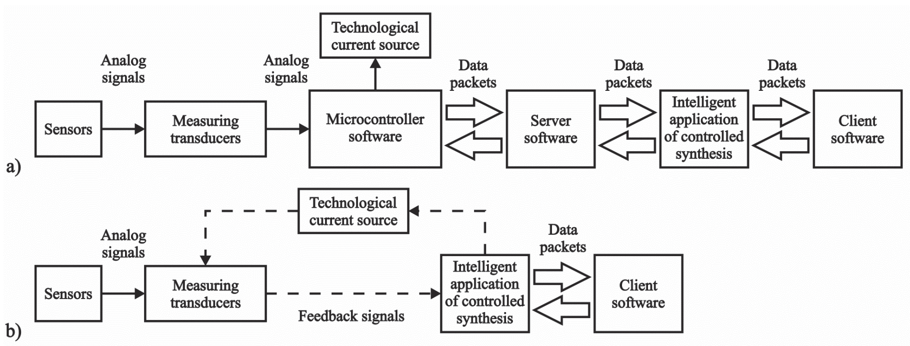

Fig. 6. The model of hardware and software interaction of the intelligent system: a) actual, b) with the feedback

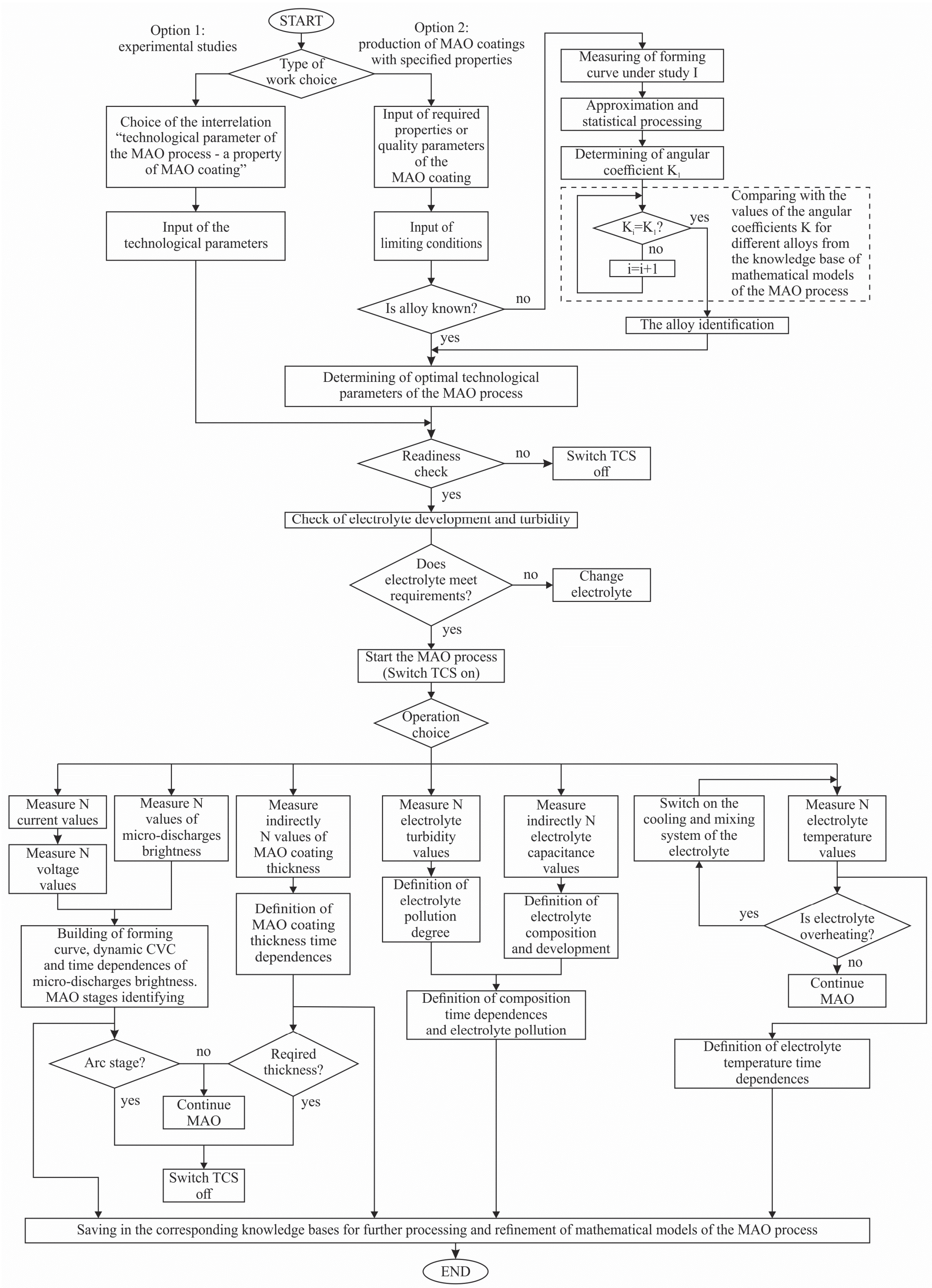

Fig. 7. Algorithm of the intelligent system software functioning

the operator several optimal processing modes, based on the design-technological and technical-economic requirements.

Next, the system prompts the operator to enter the necessary parameters of the process (current density, processing time, the ratio of anodic and cathodic currents, technological current source pulse frequency, forming voltage, temperature and initial electrolyte composition) (for option 1), or required properties (thickness, microhardness, porosity) or quality parameters of the coating (wear resistance, corrosion resistance, electrical strength, thermal resistance), part characteristics (area surface, alloy name (if known), or at least its main component, surface roughness (if known).

Coating requirements for option 2 can also be entered using limiting conditions. For example, if you want to obtain a corrosion-resistant coating, you must explicitly set the value of corrosion resistance and thickness, and the porosity should be as low as possible. The specified surface area of the part implicitly limits the minimum allowable current density, below which the MAO process is practically not performed. Limiting conditions can also be technical and economic indicators. For example, the parameter “number of machined parts per shift” limits the maximum processing time of 1 dm^2 of the workpiece surface, and the cost of 1 dm^2 of coating limits the power consumption (in kWh) during the processing time of 1 part.

Let us consider an algorithm for obtaining the optimal technological parameters of an MAO process by an intelligent application of controlled synthesis using the example of a specific problem of the synthesis of a corrosion-resistant MAO coating. We have the following initial data:

- Corrosion resistance $CR = CR_1$.
- MAO coating thickness $h = h_1$.
- The initial composition of the electrolyte. Denote the concentration of the first component (for example, Na_2SiO_3) C_1, and the second component (KOH) – C_2. The composition of the electrolyte can be determined automatically by measuring the electrolyte development.
- The surface roughness of the part S (determined by the design and technological requirements for the workpiece and machine parameters).
- The composition of the alloy (or its main component).

In addition, we have the following limiting conditions (j_{min}, j_{max}, T_{min}, T_{max} – the minimum and maximum allowable values of the process parameters):

- Minimum porosity condition.
- The condition of the minimum processing time.
- Current density range $j \in [j_{min}; j_{max}]$.
- The temperature range of the electrolyte $T \in [T_{min}; T_{max}]$.

If the exact alloy composition is unknown, and only its main component is known (for example, aluminum, titanium alloy), the alloy identification algorithm is launched. Its work is based on the fact that the dependence of the forming voltage U on the MAO treatment time t (forming curve) has different angular coefficients for different alloys (Fig. 8) (each stage of

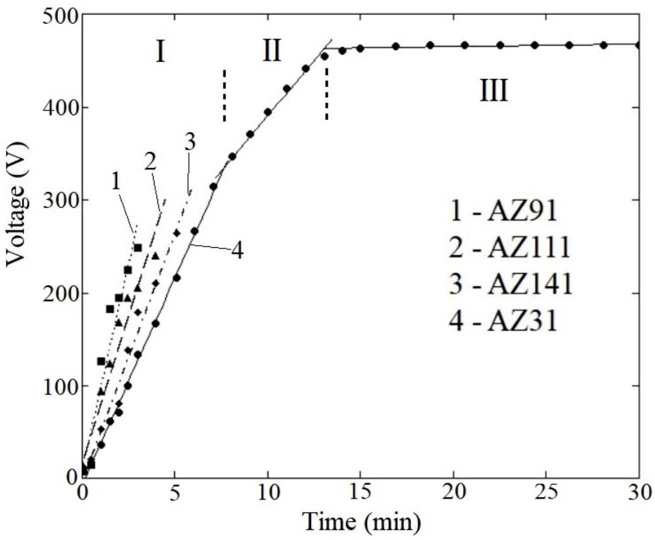

Fig. 8. Slope of forming curves at the anodizing stage (area I) for different magnesium alloys

the MAO process on forming curve can be approximated by straight lines) [4].

Thus, to identify the alloy, it is enough to measure the forming curve of the sample under study at the minimum permissible current density at the anodizing stage (area I in Fig. 8), lasting a few minutes, approximate it by the least squares method and determine the angular coefficient of the resulting straight line through the derivative:

$$k = \frac{\partial U}{\partial t} \quad (1)$$

Then the obtained angular coefficient is compared with the values of the angular coefficients for different alloys from the knowledge base of mathematical models of the MAO process taking into account the measurement error, and if these coefficients are equal, the corresponding alloy is determined.

Then, using the developed algorithms of controlled synthesis, the optimal technological parameters of the MAO process for this alloy are determined from the available initial data and taking into account the limiting conditions using the information contained in the knowledge bank. As a result of the work of the subprogram of controlled synthesis, we obtain the set of values of technological parameters at which the required thickness h_1 is achieved (different methods of coating obtaining):

$$\begin{aligned} &Way\ 1: j_1, t_1, T_1, (I_C/I_A)_1, U_{F_1}, f_1, p_M, C_1, C_2 \\ &Way\ 2: j_2, t_2, T_2, (I_C/I_A)_2, U_{F_2}, f_2, p_M, C_1, C_2 \\ &Way\ i: j_i, t_i, T_i, (I_C/I_A)_i, U_{F_i}, f_i, p_M, C_1, C_2 \\ &Way\ n: j_n, t_n, T_n, (I_C/I_A)_n, U_{F_n}, f_n, p_M, C_1, C_2 \end{aligned} \quad (2)$$

where C_1, C_2 are the temperature and concentration of electrolyte components, respectively, p_M is the percentage of main component in the original alloy, and the index 1, 2, i, n –

the number of a set of process parameters, other designations correspond to those adopted in Fig. 2.

Then these expressions are displayed in a convenient form, on the computer screen, and the operator, based on his preferences, selects one of the coating methods and starts the MAO process.

After that, the obtained data on the selected optimal processing mode is transferred to the server software and the microcontroller software, which controls the process equipment. After entering parameters it is necessary to check the system readiness according to the state of the end switch of the safety fence. If this fence is open, technological current source is disabled, and a corresponding message is displayed on the screen, and the program will continue to work only when the safety fence is closed.

Next, the electrolyte state is checked by measuring the electrolyte development, and if the electrolyte does not meet the requirements, a message about its replacement is displayed.

After the preparatory procedures, the MAO process itself begins. At the same time it is possible to perform several independent tasks:

- MAO-treatment.
- Current measurement.
- Voltage measurement.
- Measurement of the thickness of the MAO coating.
- Measurement of brightness of micro-discharges.
- Measurement of electrolyte temperature.
- Measurement of electrolyte development.
- Measurement of electrolyte turbidity.

In this case, the main task is MAO-treatment, since it involves technological current source, and all other tasks are performed simultaneously with it. This number of tasks indicates the need for developing a microcontroller own operating system, and the task number will be set by the intelligent application of controlled synthesis.

Measuring the current and voltage on the sample allows you to build the forming curves of the MAO process and dynamic current-voltage characteristics of the metal-oxide-electrolyte system (voltage dependencies on current over one period of the technological current source signal), and also determine the stage of the MAO process, ignition and quenching voltage of the micro-discharge. Moreover, if the MAO process has reached the beginning of the arc stage, the technological current source is turned off and a message about the end of the MAO treatment is displayed on the computer screen. It is also possible to determine the staging of the MAO process on the basis of measuring the micro-discharges brightness.

Measuring the thickness of MAO coatings in real time makes it possible to build its time dependences and, on their basis, derive mathematical models of the MAO process, thus adding to the knowledge bank. The thickness of the MAO coatings is determined by measuring the capacity of the MAO coating using a frequency integrating scanning converter of the original design [30].

Measuring the time dependences of electrolyte development will determine its service life, as well as develop recommendations for adjusting the electrolyte composition as it is depleted in ions. Electrolyte development is determined by measuring the capacitance of a capacitor with an electrolyte as a dielectric with the help of the second frequency integrating scanning converter. It should be noted that before each MAO treatment, the intelligent application of controlled synthesis corrects data on the electrolyte composition, measuring its development.

The electrolyte temperature is measured by an LM35 type integrated diode sensor and is maintained at the optimal level by the intelligent application of controlled synthesis, which also controls the cooling and mixing system of the electrolyte. If it is necessary to obtain the time dependences of the electrolyte temperature or the temperature dependences of the MAO coating properties, the cooling and mixing system of the electrolyte should be turned off or the temperature should change discretely with a small step, respectively.

Measuring the electrolyte turbidity makes it possible to establish the dependence of the intensity of sludge secretion on the micro-discharges power, as well as to evaluate the efficiency of the cooling and mixing system of the electrolyte.

After the MAO process completion, all the obtained dependences and processing modes are stored in the corresponding knowledge bases for further processing and refinement of mathematical models of the MAO process.

It should be noted that since the developed intelligent automated system is intended for scientific researches, it has a limitation associated with a small area of the workpiece (up to 10 cm2). In addition, the proposed design of the galvanic cell does not guarantee the absolute cleaning of the electrolyte from sludge, particles of which sometimes have a very small size and can penetrate through the pores of the filter.

VI. Conclusion

The intelligent automated system proposed in this work makes it possible to obtain high-quality MAO coatings at the lowest cost of electricity and time for their production through the use of algorithms of controlled synthesis and the control of technological parameters of the micro-arc oxidation process in real time. The presence of an automated selection of technological modes facilitates the work of the operator with this system and allows to optimize the technological process of coatings production.

The developed intelligent system can be applied at the enterprises of the aerospace industry, mechanical engineering, instrument making and transport, in medicine and the production of household and special-purpose goods, as well as in scientific research.

The proposed intelligent automated system of controlled synthesis will solve one of the significant problems of fundamental science – establishing the relationship between the technological parameters of the MAO process and the properties of MAO coatings, and contributes to the controllability of micro-arc oxidation technology, which will lead to an increase in the quality and competitiveness of MAO coatings produced in Russia worldwide the market.

ACKNOWLEDGMENT

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

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