Automation of the micro-arc oxidation process

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Abstract. At present the significantly increased interest in micro-arc oxidation (MAO) encourages scientists to look for the solution of the problem of this technological process controllability. To solve this problem an automated technological installation MAO was developed, its structure and control principles are presented in this article. This device will allow to provide the controlled synthesis of MAO coatings and to identify MAO process patterns which contributes to commercialization of this technology.

1. Introduction

Micro-arc oxidation (MAO) is a perspective technological process, demanded in many sectors of industry: automobile, aircraft and aerospace manufacturing, electronics, medicine, photonics and nanotechnology. Its essence lies in the surface treatment of parts made of valve metals and alloys, in particular aluminum, to impart them unique properties: high micro-hardness, wear resistance and corrosion resistance (increase the reliability and durability of machine parts); high thermal conductivity (allows us to produce smaller radiators with the same power dissipation); good biocompatibility (used in prosthetics); ordered pores structure of the top layer of the MAO coating (allows to grow arrays of nanowires in a matrix of aluminum oxide, for example, to obtain metamaterials).

However, the complexity and multifactorial of MAO process prevents the commercial implementation of this technology, because the mode of equipment operation for each application has its own characteristics. To resolve this problem, it is necessary to install the relationship between MAO technological process parameters and properties of obtained coatings.

Works of this kind have already been held in Russia [1] and abroad [2] – [5], but they could not provide enough information for a full and comprehensive analysis of the MAO process (the effect of only one or a group of parameters of MAO process on one or some more coating properties was studied and other factors were not considered). In addition, in these works the investigation of the MAO coatings properties was carried out only after receiving them. It was not possible to change the conditions for obtaining or control of coatings properties during the manufacturing process.

2. Problem definition

The purpose of the study is to establish the laws of micro-arc oxidation process and to develop the controlled synthesis of MAO coatings technology. For this an automated process installation of micro-arc oxidation with the ability to select the optimum mode of operation for each type and scope MAO coating was developed. It allows you to automate the process and contributes to its commercialization.

3. Structure of automated installation MAO

The structure of the automated installation of MAO is shown in Figure 1.
**Figure 1.** The structure of the automated installation of MAO.

The device consists of a technological current source (TCS), a power supply unit, a supply switch, a protective guard, measuring transducers, a microprocessor module and a galvanic cell.

The technological current source is built on the principle of width pulse modulation (WPM) and is designed to generate current pulses of oxidation of particular shape in a galvanic cell, which provide the MAO process flow. The managing WPM signal goes to the TCS from the microcontroller, which is a part of the microprocessor module that allows you programmatically to set any current pulse form, including arbitrary.

Galvanic cell (GC) is a bath with electrolyte, in which two electrodes are immersed – an anode and a cathode, where the anode is a workpiece from a valve metal or alloy. To GC are connected sensors (temperature, pressure, turbidity, production of electrolyte, etc.) generating a signal for the respective transmitters. The electrolyte is typically a mixture of NaOH or KOH and technological waterglass Na₂SiO₃, but in order to study the influence of the electrolyte parameters on the MAO process other similar electrolytes can be applied. GC is equipped with an electrolyte stirring system which can act as a magnetic stirrer and a cooling system (it is better to use a water one) as the electrolyte in a bath may reach a high temperature.

Microprocessor module (MPM) is used to process signals from the measuring transducers and to control MAO process. The structure of the microprocessor module is shown in Figure 2. The microprocessor module includes a microcontroller, having in his part an analog-to-digital (ADC) and a digital-to-analog converter (DAC), a multiplexer connecting the different measuring channels to the ADC, a digital signal synthesizer, a digital potentiometer, a galvanic isolation assembly and a USB-controller. By means of a galvanically isolated USB-port the communication with a PC is arranged. It
meets the requirements of safety. Assign remaining elements of MPM will be discussed further in the description of the measuring transducers.

**Figure 2.** Structure of the microprocessor module.

Measuring transducers are used to convert signals from sensors and to transmit them to the MPM for the subsequent processing. The number of transducers include voltage meter in GC, current meter, impedance meter, discharge optical parameters meter, electrolyte turbidity meter, electrolyte temperature meter, electrolyte development meter, MAO coating porosity meter.

Voltage and current meters are used to construct the mold curves and dynamic current-voltage characteristics of the MAO process. The signal from the voltage meter is a voltage drop across the sample in GC. The signal from the current meter is proportional to the current of TCS flowing through the sample.

Impedance meter is a capacitor voltage divider where one capacitor is a sample in GC and the other is a reference and is used to set the reference voltage. The capacity of the reference capacitor can be changed by switching limits of the impedance measurement. Impedance measurement requires a test signal of a certain frequency coming from MPM signal synthesizer. This signal is applied to the sample, and the voltage is measured on the sample. In this case the current flowing through the sample using a current-voltage converter is converted into a voltage. The impedance can be calculated from Ohm’s law.

The switch is designed to switch GC between TCS and the impedance meter.

Discharge optical parameters meter is designed to measure the radiation intensity and the general level of illumination. As you know, during the MAO micro-discharges on the sample surface change its color depending on the capacity. Thus, measuring the radiation intensity you can judge the MAO process stage. Taking into account the fact that MAO is usually conducted with natural lighting, to correct the first photo-sensor readings we need to know the general level of illumination, for that the second photo-sensor can be used outside of GC. The signal from these sensors is supplied to the current-voltage converter and then transmitted to the ADC of the microcontroller.

Measuring the electrolyte turbidity the later is illuminated by LED, and the transmitted or reflected light is recorded by a photo-detector. This signal is supplied to the LED with the frequency 1 kHz from the synthesizer. This transmitter can be operated in two modes: “transmission” and “reflection” depending on the location of the sensors (in front of and perpendicular to each other, respectively). To eliminate the influence of external factors on the turbidity measurement Fourier software transform is used.

Electrolyte temperature meter is presented in the form of a temperature sensor and an amplifier, which output signal is supplied to the ADC of the microcontroller. Metrological analysis of a measuring channel may be conducted in a similar manner as described in article [6].

For MAO process such parameter is important as electrolyte development. It is related to the fact that during the MAO processing a part of electrolyte anions is built into the coating, and the electrolyte, respectively, is depleted. Over time this leads to the fact that the electrolyte becomes unable to provide the desired amount of ions inflow to the coating and must be replaced, or the coating quality is severely degraded and the item is rejected. To make timely replacement of the electrolyte, an
electrolyte output meter has been developed, which is based on measurement of electrical conductivity. A variant of this converter design is based on a Wheatstone bridge. At the same time as an unknown resistance an electrolyte in GC acts, a comparator is connected to the bridge diagonal and one of the resistors is a digital potentiometer which is controlled by the microcontroller. By varying the resistance of the digital potentiometer the balancing bridge is achieved which is shown by the signal from the comparator output and then measure the resistance. The unknown resistance in this case is calculated by the formula:

$$R_x = \frac{R_2 R_3}{R_4},$$

where $R_x$ - electrolyte resistance, $R_2$, $R_3$, $R_4$ are resistances included in the arms of a Wheatstone bridge. For the measurement of electrolyte production the placement of two additional electrodes in GC may be required.

The device is powered by a three-phase 220 V (basically it is necessary for TCS, which forms the technological current pulses with a voltage of 600 V). Also an additional power supply that provides power to control electronics and measuring transducers is available.

In the construction of this installation a protective guard must be provided to ensure the safety requirements working with high voltage. It can be organized as a limit switch on the lid of GC, which disconnects the unit when the cover is opened during the MAO process.

4. MAO process automation

MAO process automation includes the development of the overall structure of the software (SW) and MAO installation governance. The SW of this automated system is based on the "client-server" technology and consists of microcontroller software, client and server software. The general information exchange scheme between the constituent parts is shown in Figure 3.

![Figure 3. Information exchange between the components of the installation software.](image)

As it was shown, the microprocessor receives an analog signal from the measuring transducers, converts it into digital form and transmits it to the server in the form of a data packet. Server software carries out the processing of incoming information from the microcontroller, displays it on the screen in the form of schedules and manages MAO modes by the user signal or automatically. Client software is used to create a user-friendly interface.

In general, the operation algorithm of the installation is shown in Figure 4. At first MAO mode is set by a user: current value and forms (both anode and cathode). At the same time there is a choice of both standard forms of current pulses (sinusoidal, rectangular, saw-tooth, etc.) and an arbitrary one when the user defines the form of the current curve (so-called "technological current designer") himself on the computer screen. Next the device readiness is checked. If the GC cover is opened, the message about the lack of readiness appears on the screen. It should be noted that the protective guard can interrupt the MAO process at any time, as it operates independently of the program.

Before the MAO process, turbidity and electrolyte development monitoring are carried out and if the electrolyte does not meet the technical standard the message about its replacement is displayed. The electrolyte production measurement can also be used to obtain information about its composition during the MAO process as it is possible to determine the concentration of the electrolyte components by the results of conductivity measurements.

It should be noted that the measurement channels of turbidity, electrolyte development, temperature and porosity are independent on the MAO process, while it is advisable to carry the measurement of
current, voltage, optical parameters of discharges during the MAO. As the anode and the cathode in GC are used by the TCS and the impedance meter, measurement processes and detail processing ones simultaneously can be not implemented. At the same time it is necessary to carry out the impedance measurement during the detail processing to control this process better. Therefore, it was decided to alternate between the MAO-processing and impedance measurement using the switch. Thus the impedance meter is virtually independent on the MAO process, but it is used during this process.

After all the preparatory measures (readiness check and electrolyte production) you can proceed directly to the MAO process. This microcontroller includes TCS and passes the control WPM signal, the current form of which corresponds to the MAO mode selected by the user. TCS amplifies and averages this signal and generates a technological impact applied to the sample.

At this time the measurement of several values of the current flowing through the sample, the voltage drop across it as well as the intensity of micro-discharges radiation are performed. Further, the switch commutes and indirect impedance measurement take place, and then the MAO process goes again. If it is necessary you measure the turbidity, conductivity and the electrolyte temperature. All these measurements occur cyclically to provide current information about the properties of the coating directly during its formation.

Data obtained from measurements are transmitted to the server and then are appropriately treated. With the help of voltage and current through a sample forming curves and dynamic current-voltage characteristics (CVC) of the system metal-oxide-electrolyte are constructed. Forming curves as well as the dependence of the intensity of micro-discharges radiation from the time allow to determine the MAO process stage at any given time. These relationships are of great practical importance since the arc stage characterized by high power micro-discharges damages the coating and makes it unsuitable for practical use. Therefore, the installation provides the automatic completion of MAO process (TCS shutdown) at the transition to the arc stage.
From the values of the impedance of the test sample obtained by measuring the MAO coating thickness and its dependence on time are calculated. This makes possible to interrupt the MAO process when the desired thickness of the coating is reached, which is critical for some applications (such as nanotechnology and photonics).

From the measured values of the electrolyte conductivity you can judge its structure, as with a known conductivity you can determine the concentration of the electrolyte components and the turbidity measurement gives the information about its contamination (in MAO process as a result of micro-discharges fine particles can enter the electrolyte coating). Thus, the time dependences of conductivity and electrolyte turbidity constructed from the measured data enable us to determine the degree of electrolyte development.

Electrolyte temperature measurement is necessary for the investigation of its effect on the MAO process and also to prevent overheating. In addition, you can indirectly determine the MAO process stage as the micro-discharges capacity on the sample surface influence on the electrolyte temperature. According to the porosity measurements the porosity dependences on the MAO process time are built. It allows not only to determine the effect of process parameters on the coating porosity but also to create a nanoporous matrix by stopping the MAO process in the early stages.

After the MAO completion it is possible to store information about technological modes and the results of measurements into a database for the further study or use in the industrial production.

5. Conclusion

Thus, the application of the proposed installation will allow not only to identify patterns of the micro-arc oxidation process and carry out the controlled synthesis of MAO coatings with different properties but also to increase efficiency of this process on technical-and-economic indexes due to its automation.

References

[1] Kazantsev I A, Rosen A E, Krivenkov A O and Chugunov S N 2007 News from higher educational institutions. Volga region 3 138–42
[2] Dehnavi V, Luan B L, Shoesmith D W, Liu X Y and Rohani S 2013 Surf. & Coat. Technol. 226 100–07
[3] Dehnavi V, Liu X Y, Luan B L, Shoesmith D W and Rohani S 2014 Surf. & Coat. Technol. 251 106–14
[4] Dehnavi V, Luan B L, Liu X Y, Shoesmith D W and Rohani S 2015 Surf. & Coat. Technol. 269 91–9
[5] Dehnavi V, Shoesmith D W, Luan B L, Yari M, Liu X Y and Rohani S 2015 Materials Chemistry and Physics 161 49–58
[6] Ryabov D V, Pecherskaya E A, Shepeleva J V and Pecherskaya R M 2014 J. of Phys.: Conf. Series. 541 012012.