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Analysis of technological indicators in electrochemical machining (ECM) of details with deep holes

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Abstract

Machining of deep holes with a special configuration in parts subjected to intensive wear is realized mainly by electrochemical methods.

The operational, technological and economic parameters of the parts are increased after wear-resistant coatings are deposition them. Electrochemical coatings on parts of aluminum alloys are formed by anodizing, and on steel parts by chrome plating. The presence of coating leads to an increase in the technical resource, reliability parameters - faultlessness, durability, repairability and keeping, corrosion resistance, as well as the main indicators hardness, wear resistance, heat resistance and thermal conductivity. Anodized and chromed coatings are characterized by low levels of residual stresses, high adhesion to the base material and a low coefficient of friction.

The relevance of the issues discussed in the article is determined by the need to create new or more efficient technologies for manufacturing of details with higher durability and wear resistance, operating in conditions of extreme, intensive, cyclic thermodynamic loading. The competitive environment, combined with the exceptional dynamics of the market for products, which include parts with a similar configuration and purpose worldwide, require the improvement of mechanical, thermal, dynamic and tribological indicators to be realized in conditions of constantly increasing productivity and decreasing technological cost while complying with the requirements for preservation, and in a number of cases for improving the geometrical and physico-mechanical qualities of the treated surfaces.

Keywords: Electrochemical machining (ECM), electrochemical anodic machining (ECAM), dimensional electrochemical machining (DECM), hard anodizing (HA), electrochemical cathodic deposition (ECCD), CAD system

1. Introduction

Electrochemical Machining (ECM) of materials are characterized by direct use of high density controlled energy impacts obtained as a result of electrical and physico-chemical phenomena occurring in the working area.

Methods are applied to machining of hard, difficult-to-process materials, complex and inaccessible surfaces and surfaces with very small dimensions, where traditional processing methods are unworkable or low-performance. Processing productivity and energy consumption practically do not depend on the physical and mechanical properties of the processed material. The technological processes for machining of the details can be built entirely on physico-chemical processing methods or these methods can be included as separate operations in the technological route.

2. Deep holes with a special configuration-geometry

One of the priority and most intensively developing directions in electrochemical machining methods is related to the production of deep holes with a special configuration in details subjected to intensive wear fig 1 a.

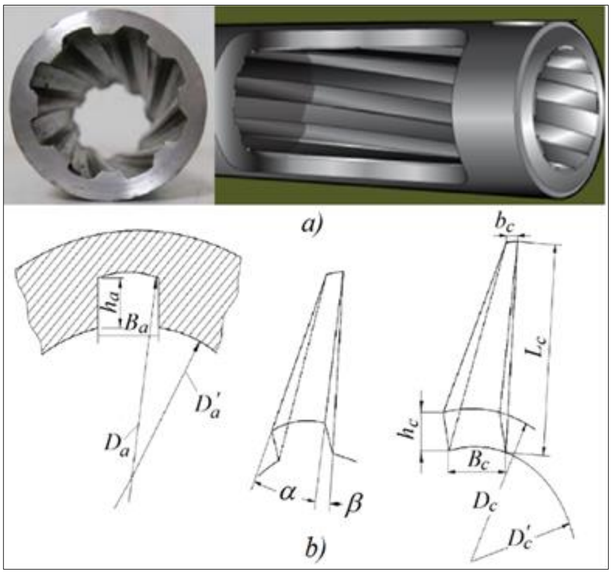

Fig 1: Parameters of deep holes with a special configuration [1, 2, 3, 4]: a) model, b) parameters.

Fig. 1, a, b show such details. They have the form of screw keyways [3, 5] with parameters:

- Ba: The width of cannon rifle,
- Ha: The depth of cannon rifle,
- Bc: The width of the big tooth,
- Bc: The width of the small tooth,
- Lc: The length of the work tooth,
- Δc: The gaps between rifle and cathode flank,
- Δ0: The gaps between rifle and cathode crest,
- α: Half-angle of the cathode tooth,
- β: Half-taper angle of the cathode tooth,
- H: Length of the rifle zone of the part,
- θ: Helix angle,
- $\varphi_{1:}$ Working angle of the cathode profile, the resultant angle obtained as a result of the movement of the cathode.

1. They are made by designing a tool–Fig. 2, a, d. After design, only one of the channels is simulated – Fig. 2, b. As a consequence of this simulation, it is often necessary to secondarily optimize the parameters and only then to design a real tool–Fig. 2c [3].

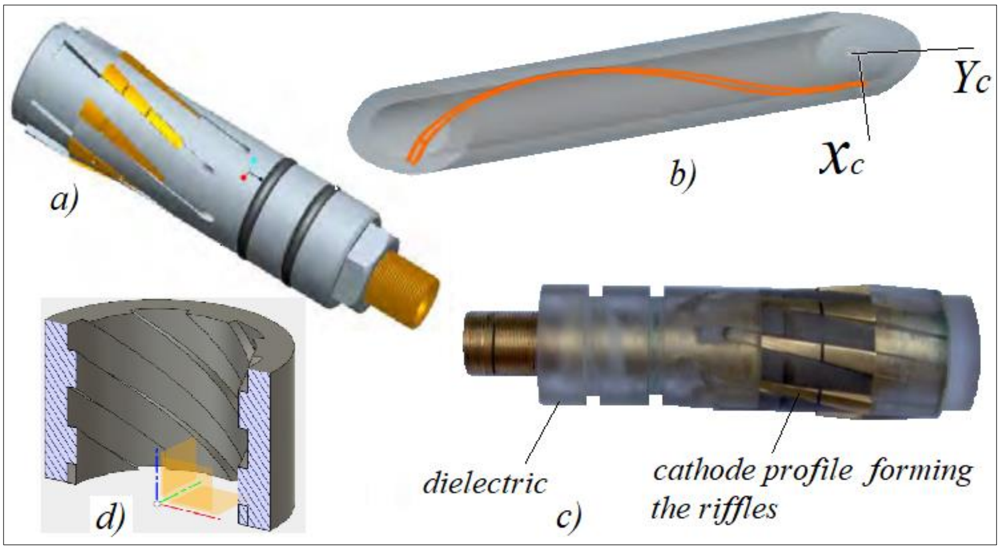

Fig 2: Design of a tool - cathode [1, 2, 3, 4]: a) 3D tool model b) path simulation c) real tool d) model building

3. Electrochemical technologies

3.1 Varieties of Electrochemical anodic Machining (ECAM) and Electrochemical cathodic deposition (ECCD)

Electrochemical anodic Machining (ECAM) includes various technological operations. Depending on the size of the layer of metal removed from the surface of the workpiece, the values of the controlled technological parameters and the quality of the obtained surfaces, the following varieties differ [6, 7, 8].

- **Finishing ECAM:** Aimed at improving the properties of the surface layer of the metal.
- Preparation ECAM, which is mainly used for primary shaping and separation operations of parts from rod or sheet material or for cutting profile material into individual blanks [9, 10].
- Dimensional electrochemical machining (DECM), in which the external or internal surface of the part is formed by means of electrochemical dissolution - anode, by copying the profile of the cathode tool - drilling [11,12], broaching [13,14], volume forming [3,15], etc.

Electrochemical molding or dimensional electrochemical machining (DECM), as a manufacturing method, was proposed by researchers V.N. Gusev and L.A. Rozhkov in 1929. The patented characteristic features of the process have been preserved even in the modern stage of its development.

Electrochemical molding is a method of achieving a set shape, dimensions and surface quality of a work piece with a complex shape, by means of zone local removal of metal from the surface of the work piece, by means of an electrochemical dissolution process - fig.3. The cathode tool is profiled. The kinematic scheme of a dimensional electrochemical machining (DECM) requires that it moves with a set linear (feed f, mm/min) or angular velocity in the direction of realization of the electrochemical dissolution process [16]. The quality of the obtained surfaces is determined by the degree of accuracy with which the shape of the tool - cathode is copied on the surface of the work piece - anode.

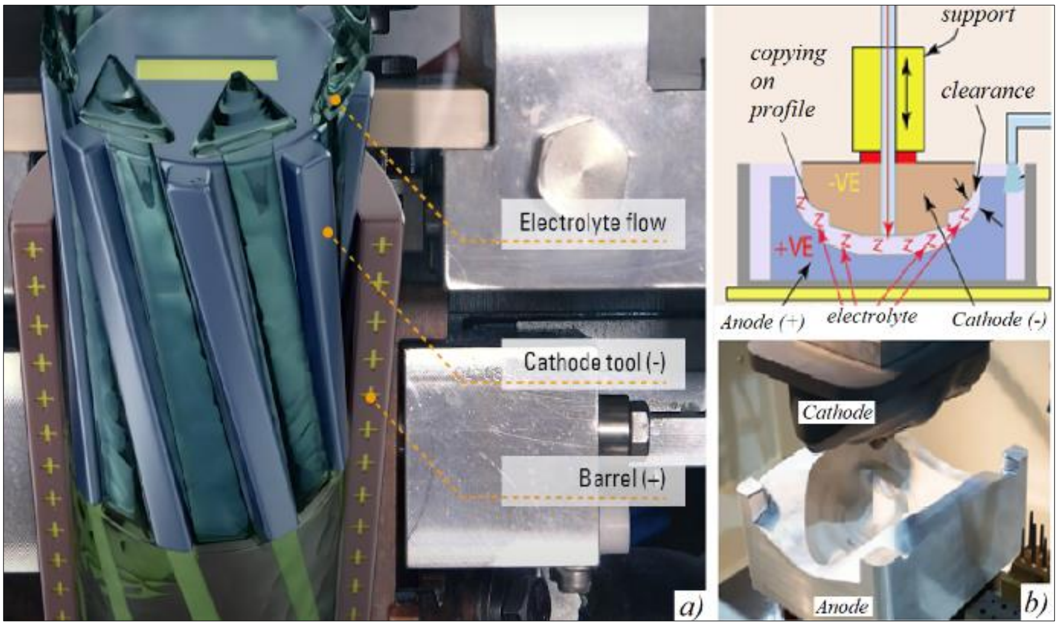

Fig 3: Dimensional electrochemical machining (DECM) [3, 17, 18, 19]

It is used mainly in the formation of details in difficult-to-process materials with expressed high requirements for the accuracy of the shape and the mutual position of the surfaces, such as:

- Molding of deep holes with special configuration (snow sockets, weapons barrels) [3, 17, 18, 19].
- Creation of working spaces in tools for injectable molding of polymers and metals [20, 21, 22].
- Electrochemical machining of engine turbine blades,
- Forming the surfaces of elements of instrumental equipment for press processing of sheet material [23] etc.

Electrochemical Cathodic Deposition (ECCD): Is a cathodic process for the electrolytic deposition of metal coatings on finished parts, known as galvanostegy, or for the primary formation from an ionic state of work pieces with a complex configuration, known as electroplating.

The coating growth process is divided into the following stages:

- Transfer of ions from the volume of the electrolyte to the surface of the electrode and their entry into the electric double layer. This process can be compared to a diffusion process, since the continuous deposition of metal on the cathode leads to a decrease in the number of positive ions in the volumes of the electrolyte in direct contact with the cathode.
- Passage of ions across the boundary between the two phases from the electrolyte to the metal. At this stage, the ions are converted into adsorbed ions (ad-ions) and atoms (ad-atoms), as a result of their connection with electrons.
- The third stage is related to the processes of diffusion of the ad-atoms along the surface of the electrode to the optimal energetic growth zones. Two- and three-dimensional nuclei of crystallization are formed in them [24].
- Electrochemical cathodic deposition (ECCD) in the processing of deep holes with a complex configuration is used in two main variants:
- **Hard anodizing:** A process in which a porous oxide layer is formed on parts of aluminum and its alloys [24]
- Deposition of protective wear-resistant coatings.

ECCD processes are implemented both with monolithic tools and with free abrasives [25]. In ECCD, additional effects are often applied to the monolithic tools to intensify the process-vibrational, laser and combined (ultrasonic, pulsed, magnetic, etc.) [26, 27, 28, 29].

The barrier layer at ECCD - fig. 4a limits the further formation of two- and three-dimensional crystallization germs as a result of surface diffusion. The increase in the thickness of the formed coating is also stopped by limiting:

- Island structure formation and island growth - growth of stable nuclei and their aggregation into randomly oriented islands. Growth of the insular structure.
- The coalescence of the islands (primary coalescence) - coalescence of the islands and growth of the latter in height.
- Formation of polycrystalline islands (secondary coalescence).
- Coalescence of the islands to form a continuous dense thin layer, growth of the layer and formation of a coating of the required thickness.

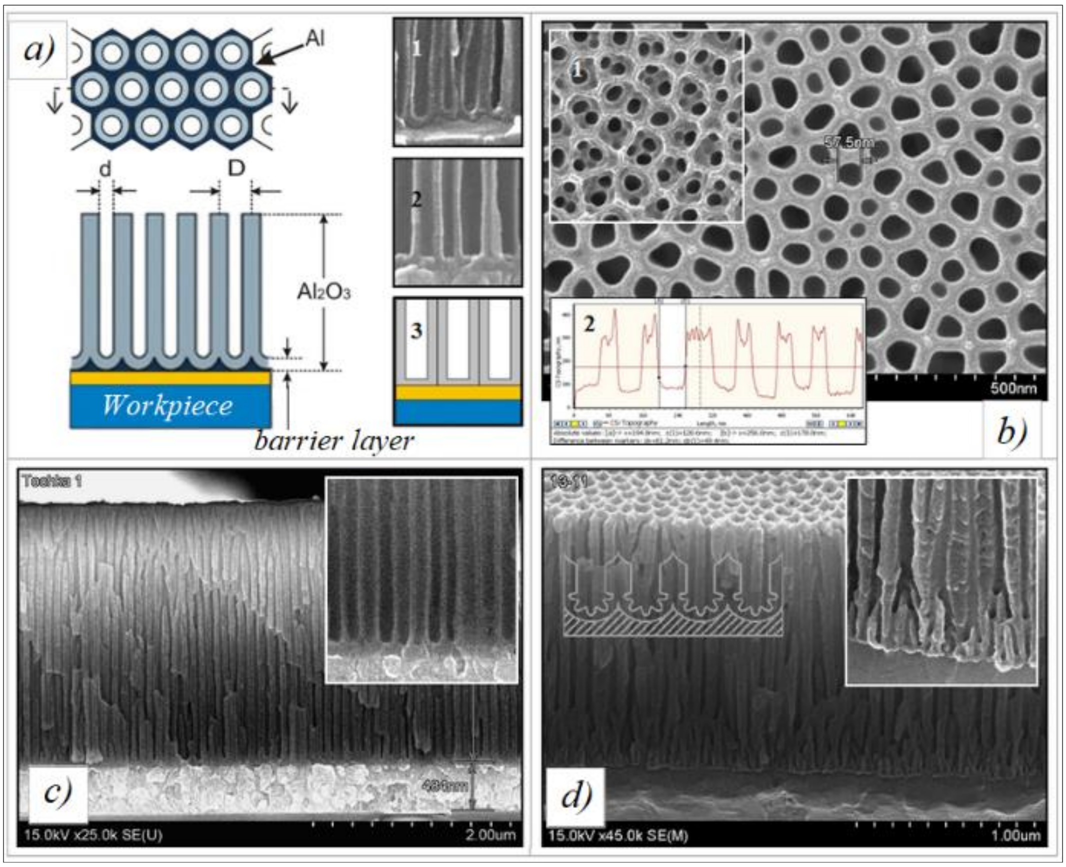

Fig 4: Formation of an anodized layer [30]: (a)-Scheme of porous anode layer (SEM) before (1) and after finish treatment of the barrier layer (2); (b) - transmission electron microscope view; (c, d)-cross-sectional views before and after deposition of an additional Ni layer in the pores.

In fact, the barrier layer interrupts the entire further process of the formation and growth of the polycrystalline coating according to one of the schemes shown in Fig. 5:

- Layer-by-layer growth of coatings (Frank-van der Merwe mechanism) - fig. 5a;
- Island growth of the coatings (Volmer-Weber mechanism) fig.5, b.
- Island-layer growth of coatings (Stranski-Krastonov mechanism) - fig. 5,c;

Where,

- $\Theta < 1$ – incomplete first layer,
- $\Theta = 1$ – first finished layer,
- $\Theta > 1$ – multilayer system.

In this regard, to improve the quality of coatings, additional layers of other metal are often used to improve the quality of the coatings – Fig. 3, d [31].

The roughness of the surface also depends on the type and structure of the material, the density and nature of the current, composition, temperature and speed of the electrolyte.

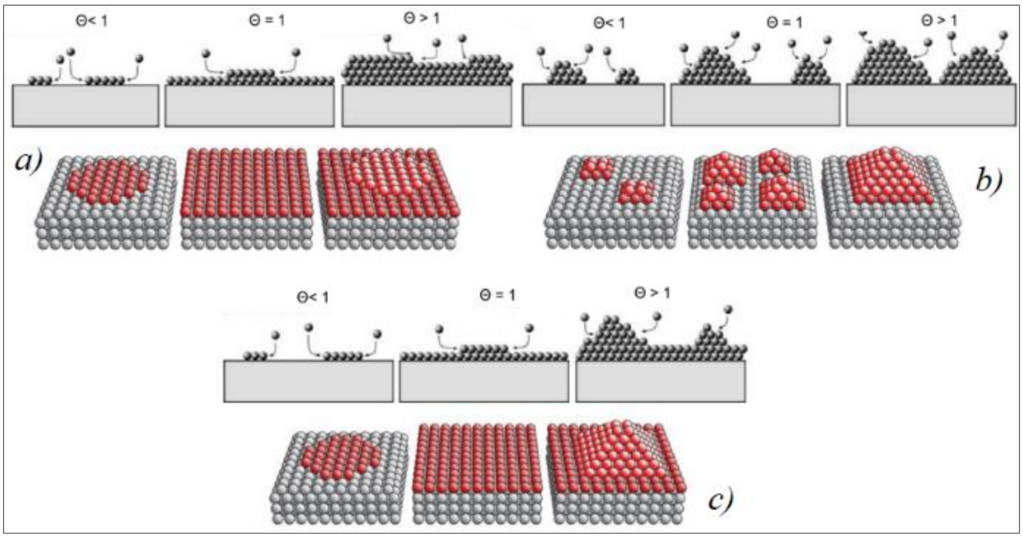

Fig 5: Scheme of the mechanism of formation and growth of thin layers [19, 31]: a) layer by layer), b) island - layer, c) island.

The formation of the microrelief is related to the intracrystalline dissolution and the different rates of dissolution of the individual components (crystals) of the alloys.

Characteristic of the use of more active electrolytes is the obtaining of a higher roughness, while with those with less activity ($NaNO_3$) the roughness is lower.

The height of the roughness of the surface layer at dimensional electrochemical machining (DECM) (in NaCl solution at T = 20 ÷ 25 °C) for structural steels is Ra = 0.32 ÷ 0.1 µm; for corrosion-resistant - Ra = 1.25÷0.32 µm; for titanium alloys Ra = 2.5÷1.25 µm and for aluminum alloys Ra = 2.5÷0.65 µm.

Fig. 6, a shows a three-dimensional topography of a rough electrochemically treated surface. A confocal laser microscope LS4100, Olympus, Tokyo [21, 6] was used. The measured roughness is Ra = 5.182 µm. Fig. 6b shows the surface after finishing treatment with an applied pulse voltage, the roughness is reduced to 0.760 µm Ra, i.e. with 85.3%.

3.2 Technological characteristics of electrochemical machining

The industrial installations for ECM, despite the differences in their construction determined by the different application and the different operations they can implement, necessarily include in their structure four main types of systems – Fig 7:

- **DC Power supply:** Source of direct current (DC direct current), ensuring the anodic dissolution process. The anode detail is usually assumed to be stationary, with the feed provided primarily by a profiled cathode tool [32, 33, 34]. The implementation for the process requires the tool to move towards the work piece at a constant speed while maintaining a constant gap between the electrodes (δ=0.05÷0.6 mm).

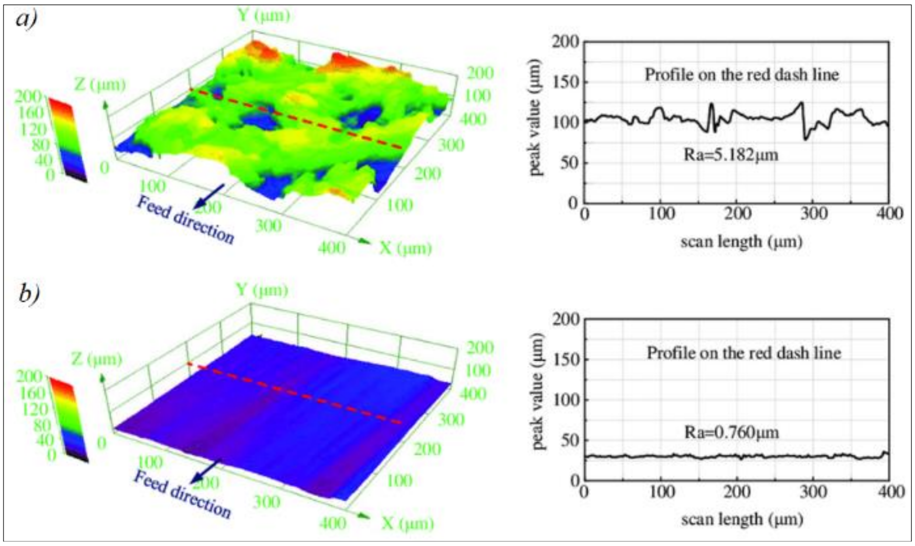

Fig 6: Surface morphology (left) and surface roughness (right) of the groove after (a) rough machining, and (b) finish machining [35].

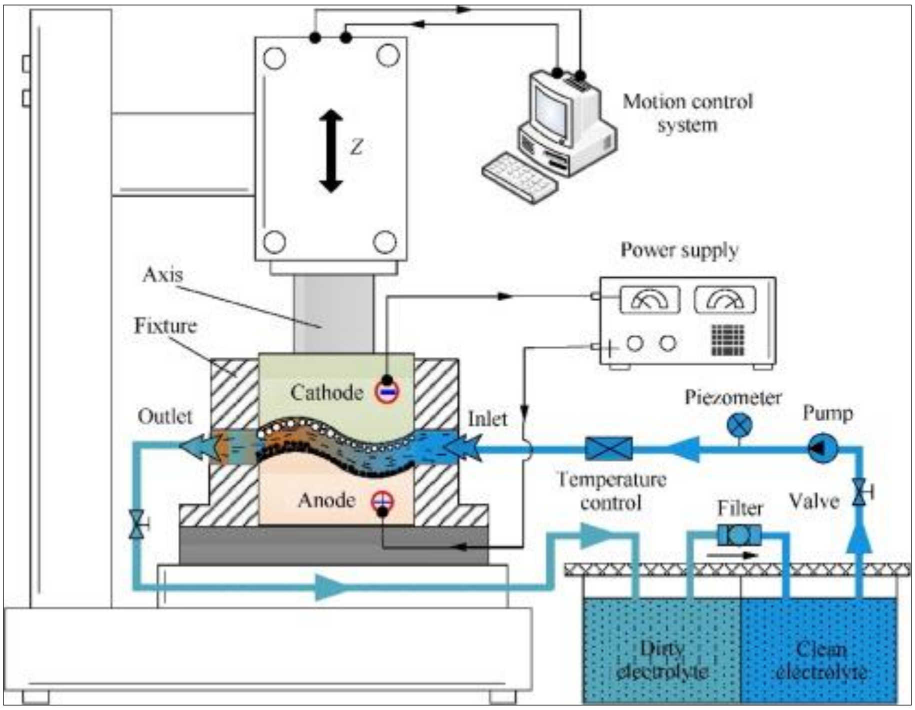

Fig 7: Main systems in industrial ECM installations [36, 37]

The value of the supply is directly proportional to the magnitude of the constant current varying within limits I = 20÷500 A/cm2. High current levels require voltage values to be kept relatively low U=5-25V, in order to prevent the possibility of short circuits [36, 37].

- **Electrolyte circulation system:** The products of the electrochemical reaction should be removed from the gap between the work piece and the tool. Accumulation of the reaction products causes decrease of the process efficiency and reduction of the rate of machining [23, 30]. Therefore, the electrolyte flow speed should be high Ve [m/s] (most often NaCl or $NaNO_3$ aqueous solution) - V_e=10÷60 m/s. The input pressure in the system is supported by pump units in the range P_i=0, 15÷3 MPa. The electrolyte is filtered continuously.
- **Control system:** Ensure constant monitoring of the electrical parameters of the process (voltage and current)), tool feed speed and parameters of electrolyte circulation system (inlet and outlet pressure of electrolyte, temperature of electrolyte). Monitors and corrects the parameters of the circulation system (pressure at the inlet and output of the electrolyte and the temperature of the electrolyte). Maintains a constant clearance between the equidistant on the instrument and the work piece [23, 25].
- **Mechanical system:** Ensures the accuracy of relative movement between the tool and the work piece. It consists of a housing, a work table, a support in which the tool is installed and a bath (preventing the spillage of the electrolyte). The steady state process is realized with a constant feed along the main axis with a value of f=0.1÷0.4 mm/min. ECM machines are most commonly CNC system equipment [34].

3.3 Basic parameters of dimensional electrochemical machining (DECM)

The basic parameters of dimensional electrochemical machining (DECM) characterize the effectiveness processing (output parameters) are [30, 32]:

- The accuracy of the resulting surfaces,
- The quality of the machining surfaces,
- The productivity of the process,
- The energy absorption of the process.

Their quantitative characteristics depend on a large number of indicators (input parameters) related to the conditions of the process, namely:

- The anodic current density iA [μA/dm2] - the current density in anodic dissolution is taken with a positive sign (+), and in cathodic deposition with a negative sign (-).
- Type, specific electrical conductivity, viscosity, hydrogen index pH, concentration and temperature of the electrolyte volume;
- Speed and nature of the electrolyte flow, hydrodynamic mode of the process;
- Magnitude of the interelectrode distance δ;
- Magnitude and character of the applied voltage U;
- Electrochemical equivalent of the processed metal or alloy;
- Size of the allowance and accuracy of the work piece;
- Accuracy, stability and hydrodynamic qualities of the tool;
- Geometric and kinematic accuracy and stability of equipment, sensitivity, speed and reliability of systems for control, management and regulation of mode parameters.

The manifestation of a significant part of these factors in the course of the process is interconnected and significantly complicated due to the presence of certain functional relationships between them. Revealing their impact on process performance requires extensive analysis.

3.3.1 Current density i_A

ECM current density is a key performance indicator. The high current density iA [μA/dm^2] accelerates the process of local dissolution of the surface of the work piece (anode) at ECM – Fig 8,a. In ECM, the current density has a very strong influence on the structure of the deposited coatings. At small values of the density, the concentration changes near the cathode are weak and the growth of the seeds becomes unimpeded, in which a coarse-grained structure is formed [34]. The increase in density causes a large concentration polarization, in which the number of ions in the near-cathode region decreases, the overvoltage increases, and this contributes to the formation of a large number of crystallization centers, i.e. a fine-grained structure is realized. However, the increase in density in aqueous solutions is limited, because above certain values it becomes possible to separate other ions from the electrolyte, resulting in porous coatings with many unwanted inclusions [12, 18, 34, 35].

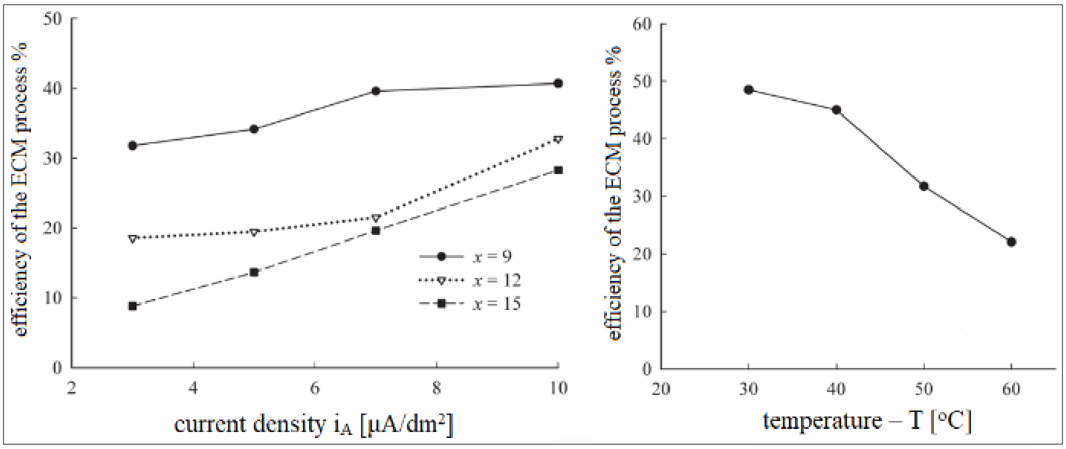

Fig 8: Influence of changing the value of controlled parameters on the efficiency of the ECM [12, 18, 35]: a) change in current density i_A [μA/dm^2], b) change in electrolyte temperature – T [°C]

3.3.2 Electrolytic volume

In the electrochemical machining of a large part of steels, NaCl solutions with a concentration of 8÷8% or $NaNO_3$ with a concentration in the range of 15÷20% are widely used. For the processing of titanium alloys, solutions of NaCl (5÷15%) and KBr (3÷10%) are suitable, and for aluminum and copper alloys $NaNO_3$ (10-25%) with the addition of acetic acid (1÷3%) [12].

In order to improve the technological performance of electrolytic solutions, a number of additives are introduced into them. Limiting the corrosion action requires adding $NaNO_2$ (0.02÷0.03%) to it. Coagulators of the polyacrylamide type (0.1÷0.5%) are introduced to accelerate the precipitation of the processing products. Surfactants are added to lower hydraulic losses and to limit cavitation [19, 35].

Neutral aqueous solutions of sodium or potassium chlorides, nitrates and sulfates are most often used as working media. Their necessary composition, concentration and additives are selected depending on the processed material and the technological requirements for the process. The percentage concentration of the electrolyte is determined by the mass of the corresponding substance in 100g solution [35].

Electrochemical machining is accompanied by the conversion of a significant part of the energy (up to 40÷50%) into heat at the expense of the active resistance of the electrolyte in the interelectrode space and, to a lesser extent, of the hydraulic losses during its circulation. An increase in the temperature of the electrolyte is associated with a decrease in the solubility of salts, a decrease in the electrical conductivity of the electrolyte, a deterioration in ion diffusion, an increase in overvoltage, and an increase in cathodic polarization [34, 35]. In ECM, this worsens the ability to form a coarse-grained structure, and in order to compensate for the negative effect, it is necessary to increase the current density. Technologically, this practice finds application in regulating the work of electrolytic baths [32], but in general it could be noted that the increase in temperature has a negative effect on the realization of ECM [38].

In anodizing, the increased alkalinity causes chemical corrosion of the aluminum billet outside the affected zone. In such cases, to maintain the neutral reaction of the electrolyte solution, corresponding additives such as boric, acetic or hydrochloric acid are introduced into it [10, 11].

The ability of the electrolyte to provide uniform thickness coatings on the cathode (part) with a complex shape is characterized by a quantity called the scattering ability of the electrolyte. Cyanide electrolytes have the best dispersive ability, and chromium electrolyte the worst. The ability of the electrolyte to cover the concave areas of the cathode (holes, cavities with a complex shape, etc.) is called the covering ability of the electrolyte [39]. This parameter is more important for galvanostatic, where it is important to cover the part on its entire surface, and it is not particularly due to the uniformity of the layer.

3.3.3 Speed and nature of electrolyte flow

A necessary condition for the normal course of the electrochemical treatment is the intensive removal of the separated products. In the majority of cases, this is achieved by forced circulation of the electrolyte through the working space. This determines the significant and sometimes decisive influence of hydrodynamic factors on the process parameters [38, 39].

Each ECM mode requires a certain minimum speed V_{el}, min of the electrolyte flow, satisfying the reduction of temperature, gas content and concentration of sludge in the near-electrode region, which guarantees uniformity in the speed of anodic dissolution V_a and cathodic deposition V_c. An increase in the flow rate above certain limit levels for any electrochemical system causes cavitation phenomena to occur and is highly undesirable.

3.3.4 Duration of the process

The duration of echo is of utmost importance for the quality of the received products. A number of scientists suggest experimental dependencies reporting this influence [38, 39]. Most often, as a qualitative indicator, the roughness of the products obtained after echo is applied – Fig. 9.

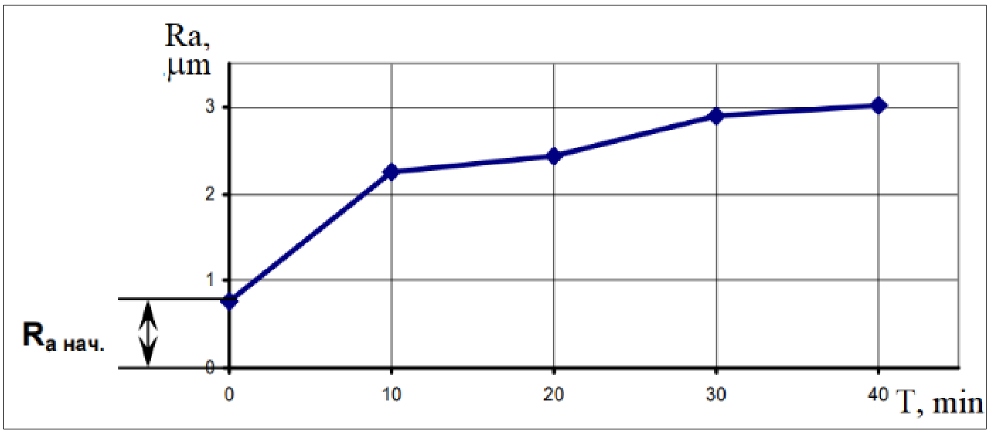

Fig 9: Change in roughness ECM in time function [38, 39]

From the figure, it can be seen that as time increases, the roughness of the treated surface increases. This increase is finite, reaching a certain level after which the roughness value remains constant. It is explained by the reduced intensity of the processes of anodic dissolution or cathodic deposition in the depth of the product, due to the formation of a barrier layer.

3.5 Advantages and disadvantages of EMC

The main advantages of ECM compared to conventional primary forming methods and those realized with and without chip removal are reduced to:

- The possibility of using electrochemical methods to machining work pieces from difficult-to-machining materials - heat-resistant, hard and titanium alloys, stainless, hardened and heat-resistant steels, etc. When applying ECM, the process parameters are not in direct correlation with the chemical composition, mechanical properties and structural state of the processed materials;

- when applying ECM, in most cases it is not necessary to apply additional finishing treatment;
- by means of ECM, complex form-forming surfaces are obtained, the obtaining of which by other methods is impossible or extremely economically unprofitable,
- the absence of real physical contact between the tool and the part, provides the possibility to apply the methods when processing thin-walled and tubular parts, which are easily deformed during mechanical processing, as well as parts made of fragile materials, prone to the appearance of cracks in the surface layers causing a significant deterioration of the operational properties,
- the application of the processes does not cause the appearance of burns, cracks, residual stresses, phase transformations and other thermal effects changing the structure of the treated surface,
- No tool wear,
- By means of ECM methods, low roughness and high accuracy of the shape and mutual position of the treated surfaces are achieved. In this case, the pressure of the electrolyte on the treated surface is low and rather causes the removal mainly of the defective surface layer from previous treatment.

The main disadvantages of ECM are:

- Expensive tooling and machinery,
- Relatively high energy intensity of the processes,
- Requirement for highly qualified service personnel,
- Only electrically conductive materials can be processed

The methods are not suitable for processing blanks with uneven allowances. Working conditions would be extremely difficult if in some areas the increase tends to zero. Then it is necessary to reduce the current density, and from there the performance is directly reduced.

4. Conclusion

Regarding the essence and technological characteristics of the electrochemical methods, some basic conclusions can be drawn about their applicability in the realization of dimensional electrochemical processing of deep holes with a special configuration in details subjected to intensive wear, before and after cathodic deposition of anodized or chrome coatings.

1. The operating conditions and technological characteristics of the electrochemical machining have been studied and analyzed. Their main parameters are indicated in the optimal limits of variation - current density, voltage, velocity and temperature of the electrolyte, inter-electrode distance and duration of the process.
2. Dimensional electrochemical machining (DECM) has been proven to be the primary method providing the required levels of productivity and process cost while meeting the quality requirements for obtaining deep holes with a special configuration in parts subject to intense wear.
3. The structure, chemical composition, mechanical, operational and technological properties of cathode electrochemically deposited anodized and chromium coatings are analyzed in detail.
4. It has been proven that the anodized and chrome coatings deposited on parts with electrochemically formed deep holes with a special configuration are characterized by high operational and technological indicators of hardness, wear resistance, corrosion resistance, strength under cyclic and temperature loads, high resistance in the presence of chemical active or abrasive volume.
5. The finding was confirmed that through electrochemical cathodic deposition (ECCD), with the selection of appropriate parameters, it is possible to form dense diffusion coatings with low residual stresses and good adhesion.

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