

ELECTROCHEMICAL MACHINING – SPECIAL EQUIPMENT AND APPLICATIONS IN AIRCRAFT INDUSTRY

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ABSTRACT

Electrochemical machining is an unique method of shaping in which, for optimal parameters tool has no wear, surface layer properties after machining are similar to the core material and surface quality and accuracy increase together with material removal rate increase. Such advantages of electrochemical machining, besides of some ecological problems, create industry interest in the range of manufacturing elements made of materials with special properties (i.e. turbine blades of flow aircrafts engines). In the paper the nowadays possibilities and recent practical application of electrochemical machining in aircraft have been presented.

KEYWORDS

electrochemical machining, machining of special materials, turbine blades of aircraft engines.

Introduction

Nowadays aircraft industry has serious problems which should be solved in the next few years. These problems results first of all from two reasons. The passenger and freight aircraft transportation development is the first reason. According to Airbus, Boeing and Rolls Royce forecasts the aircraft transportation will double during next 15th years and this trend is going to occur in the future. These companies foresee that that for 2032 it would be necessary to produce (only by these three companies) about 65 000–70 000 new airplanes [1, 2]. Adding to this obligatory service and renovation of existing aircrafts the expectations for aircraft industry are very huge. But it is not everything because in production of new aircrafts it will be impossible to apply existing construction solutions. It will be necessary to introduce new and innovative solutions which leading to high efficiency and reliability aircraft exploitation and new efficient technological processes of details or units manufacturing which can decrease significantly the costs of production. New production process must be ecological and friendly for surrounding, what means that

designers should take into account Life Cycle Analysis requirements. It has been also assumed that up to 2050 it is necessary to decrease aircraft engines emission of CO₂ (75%), NO_x (90%) and noise (65%). It will be connected with engine and details dimensions and the same the mass (weight) decrease [3, 4], what force significant changes in production process. It would be also necessary to improve control systems and active monitoring of details work and the stage of theirs wear. The range of this monitoring will be continuously increased. Under controlling and monitoring must be elements of hull cover, turbine blade or other parts of flow engine. These aspects of construction and aircraft exploitation forced also intensive development of Micro-Electro-Mechanical Systems (MEMS). MEMS development is impossible without development of micro and nano-details manufacturing methods. Similar problems, however in lower scale, occur in other branches of industry as car or domestic industry. In order to fulfill above specified requirements it would be necessary to apply a large amount of new, special materials and working out rational methods of their shaping in case as well as macro as micro-details.

Taking into account the fact that these new materials usually characterized high strength and wear resistance application for shaping traditional processes as cutting or grinding will be limited. Additional limitations in precise or micro-details manufacturing are connected with size effect [5]. Therefore unconventional and hybrid processes becoming more widely used in this areas of industry [6].

Basic unconventional processes are: electrochemical Machining (ECM), electrodischarge machining (EDM) and beam methods as: laser beam machining (LBM), electron beam machining (EBM) or ion beam machining (IBM) Main hybrid processes which could be applied in this area are: cutting processes supported by laser beam or ultrasonic vibrations, electrochemical or electrodischarge grinding, electrochemical – electrodischarge machining. In the paper the technological possibilities of electrochemical machining for macro and micro details manufacturing were discussed.

Challenges of aircraft engines manufacturing

In order to fulfill above mentioned changes it will be necessary to widely apply new materials and adopt existing or working out new manufacturing methods of aircraft details. First of all the composite materials as: Polymer Matrix Composites (PMC), Metal Matrix Composites (MMC) and Ceramic Matrix Composites (CMC) should be pointed. Taking into account aircraft engines industry, special applications have also steel and titanium or nickel based materials [6], i.e.: steel alloys (X22CrMoV211, X12CrNiWTiB16-13), Ti based alloys (Ti-6Al-4V, Ti-6Al-2Sn-4Zr2Mo-0.1Si), gamma titanium aluminides (γ -TiAl), Ni matrix superalloys (Inconel 718, Inconel 738, Inconel 939, Udimet 720, Nimonic 104, Nimonic 713). The range of these materials application is defined by temperature resistance (Fig. 1).

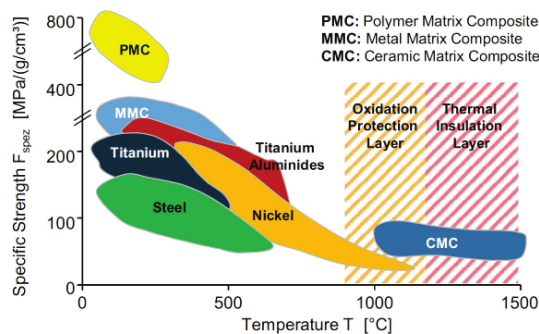


Fig. 1. Relationship between material strength and temperature [7].

In order to increase economic and ecological aircraft engines general efficiency it will be necessary to increase the functionality of the drive and temperature efficiency. Temperature efficiency can be increased by higher combustion temperature. But in this case it is necessary to use more temperature resistant light materials (gradient materials, single crystal, metal or ceramic matrix composites) and better conception of cooling (new geometry of cooling wholes, double bladed turbines) and apply covers which are thermal barriers i.e. Oxidation Protection Layer and Thermal Barrier Coatings. Because of limited distance between ventilator and earth also engine core dimension should be decreased. It will be possible to solve this problem by replacement existing turbine set consist of turbine blades mounted on the ring in special locks by monolithic turbine set (ring and blades) made of one piece of material (blisks) (Fig. 2). There are carried out works on improvement of aerodynamic properties of turbine blades (special surface smoothing, elliptical trailing edge of the blade) and hull cover (special foil – with structure as skin of shark).

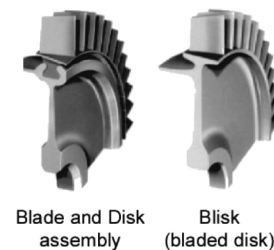


Fig. 2. Turbine set with mounted in the ring blades (on the left) and monolithic turbine set (on the right) [8].

Monolithic turbine set can have smaller dimensions and the same the mass in comparison to turbine set with mounted in the ring blades. Processes for “blisks” manufacturing are chosen taking into account turbine blades dimensions and material properties [6]. It is worth to underline that besides of High Speed Cutting and Linear Friction Welding for “blisks” manufacturing the or Electrochemical Machining Processes (ECM) is promising technology. Detailed description of this process is presented below.

Electrochemical machining process (ECM)

Electrochemical Machining has quite different properties in comparison with other manufacturing processes in which the tool is material (milling cutter (mill), cutting tool, drill, grinding wheel in cutting processes) or electrode – tool in electrodischarge

machining (EDM). In all specified processes together with metal removal increase tool wear also increases while accuracy of machined workpiece decreased; machined surface geometrical structure become worse and surface layer properties significantly changed – usually because of significant temperature increase. In properly design and carried out electrochemical machining process there is not mechanical contact between electrode-tool and workpiece (as it is in cutting processes) and there are no electrical discharges (as in electrodischarge machining) which are the reason of local melting or evaporating of electrodes material. Electrochemical machining can be understood as flow of electric charge. In outer electric circuit charge is transported by electrons. In space between electrodes there is electrolyte (water solution of salts, acids or hydroxides) and between electrode tool (cathode) and anode (workpiece) electric charge is transported by ions which are in electrolyte. Especially, through the border of anode and electrolyte electrical charge is transported by ions of dissolved anode material (for instance: Fe^{+n} , Cr^{+n} , Ni^{+n} , Ti^{+n}), which diffused inside interelectrode gap and take part in further electrochemical reactions. Products of these reactions (usually hydroxides of Fe, Cr, Ni, Ti and other anode components) are removed outside of interelectrode gap by electrolyte forced flow through space between anode and cathode. According to Faraday's law the mass of dissolved anode material is proportional to the charge transported through the interelectrode gap. Through border between electrolyte and cathode charge is transported mainly by hydrogen ions (H^+). These ions are deionized and on cathode surface at first H^2 particles and then bubbles of hydrogen are created which are also removed from interelectrode gap by electrolyte flow. From above presented ECM process description results that there are not any factors which could cause electrode tool wear. Current flow is accompanied by heat emission which should be continuously removed from interelectrode gap in order to avoid electrolyte boiling.

In order to reach in sinking operation high metal removal rate, satisfactory accuracy and surface quality it is necessary to have as high as possible current density and as small as possible interelectrode gap thickness. Together with current density increase the number of atoms removed from machined surface unit also increase and this is a reason of metal removal and surface quality increase. From technological experiments results that tolerance of workpiece dimensions is $\sim 0.1\text{--}0.2$ of interelectrode gap thickness. So, accuracy increases when interelectrode gap thickness decreases [9].

Conclusions resulted from above presented considerations are right as long as it is possible to keep optimal electrolyte flow with velocity high enough to remove electrochemical reactions products and heat so as hydrogen volumetric concentration was lower than 60–80% and electrolyte temperature was not higher then 60–80°C in each point of machined surface. Electrolyte flow should be also stable and without area of circulation or cavitations. The conditions of optimal electrolyte flow limits the maximal metal removal rate and accuracy. Hydrodynamic conditions can be improved and accuracy and metal removal rate increased by introduction electrode tool oscillations and carrying out ECM process in pressure chamber what make it possible to chocked electrolyte flow at its outlet from interelectrode space. By chocking the electrolyte flow it is possible to stabilize electrolyte flow in machining area, decrease significantly volumetric hydrogen concentration and increase water boiling temperature. As it was mentioned above electrolyte flow can be also significantly improved and accuracy increased by introduction electrode tool oscillations and pulse interelectrode voltage (pulse ECM). It gives possibility to obtain (Fig. 3):

- during pause time: large interelectrode gap, intensive electrolyte flow, intensive heat and electrochemical reaction products removal from machining space,
- during pulse time: small interelectrode gap thickness, high current density and metal removal rate however intensive heat and hydrogen emission occurs.

Voltage pulses are generated when electrode tool is nearest to workpiece (Fig. 3). Pulse frequency and duty cycle should be chosen so as to remove from interelectrode gap during pause time, together with electrolyte, heat and electrochemical reactions products rise during voltage pulse. However in this case of electrochemical machining mean metal removal rate significantly decreases. Therefore, in order to obtain as high as possible mean material removal rate machining process should be carried out in stages. In the first stage the constant voltage and constant electrode tool feed rate are applied and process parameters are optimized on criterion maximal metal removal rate. If after the first stage results are not satisfactory the second stage is introduced. In the second stage usually pulse ECM process with electrode tool oscillations, is applied and process parameters are optimized on criterion of assumed accuracy. In case when after second stage the surface quality is not satisfactory the third stage (polishing) is introduced. In comparison to the second stage on-

ly criterion is changed: process parameters are optimized on criterion of optimal surface quality. Because of the fact that during the first stage the main part of machining allowance is removed on criterion of maximal metal removal rate the mean machining process efficiency (for all stages) is usually satisfactory.

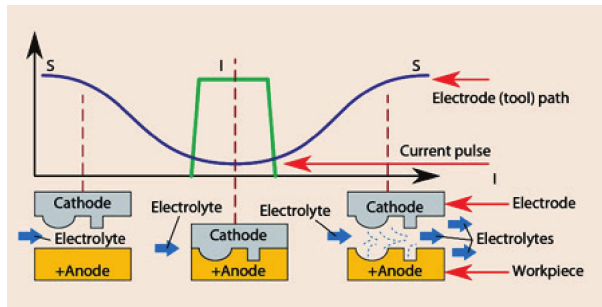


Fig. 3. Scheme of precise electrochemical machining with application of pressure chamber and electrode tool oscillations [10].

From above presented considerations results that ECM process is difficult for applying in industry. Other ECM process limitations are:

- relatively high cost of machine tools which must be built from corrosion resistant materials,
- negative influence of electrochemical reaction products on industrial production and natural environment (if harmful ECM process products are emitted outside the factory). For instance ions Cr^{+6} in concentration of 0.05 mg/dm^3 are strongly harmful (carcinogenic). Of course electrochemical machine-tools are equipped with units for reduction and neutralization of electrochemical reaction products but it is a reason for additional price of ECM machine tools increase. Because of above mentioned reasons industrial applications of ECM process are limited for cases, where only ECM process can give satisfactory surface layer quality (turbine blades of aircraft engines) or metal removal rate and accuracy in case of mezo and microdetails manufacturing. In this last case the very good results are obtain (reached) for sequential electrochemical/electrodischarge [11] or laser/electrochemical machining [21].

Characteristic of the electrochemical machine-tools

Analysis of the typical machine-tools design for electrochemical machining gives possibility to distinguish following functional elements: mechanical part,

control system, power supply unit, electrolyte supply unit and electrode – tool unit.

Mechanical part consist of following elements: machine body, working table (usually with displacement in X and Y axis), assembly of Z unit (including also spindle or tool vibration unit) and additional tooling required for machining process (i.e. tool and workpiece clamping). Design of mechanical part are connected with machine-tool construction constraints (i.e. dimensions of working area, drives accuracy or positioning accuracy) and technological constraints, which are defined by potential area of machine-tool application.

Control system is responsible for control of interelectrode gap thickness regulation (also including reaction on the critical states in machining area) and implementation of movements between electrode tool and workpiece (according to programmed patch).

Power supply is based on specially designed power energy source and the key factor is to provide appropriate voltage signal in order to obtain high localization of anodic dissolution. Moreover, if possible power energy source is equipped with modules for prediction of critical states in the gap (protection against short-circuit).

The main functions of electrolyte unit is to supply of electrolyte to machining area, filtration of contamination (product of dissolution) and measurement and stabilization of main physical properties of electrolyte (conductivity, pH and temperature). Because of environmental issues the obligatory standard is also to equip electrolyte unit with devices for utilization of electrochemical dissolution products.

For micromanufacturing application one of the main condition of high degree of machining elements miniaturisation is application of electrode tool with appropriate accuracy and stiffness and solve problem of electrode clamping. Application of electrochemical sinking is limited by possibilities of manufacturing of electrode which is projection of the machined shape. In case of machining with application of universal electrode tool possibilities of machined part miniaturisation depends on proper selection of machining condition and electrode-tool dimensions. The smaller the diameter of the electrode, the higher the resolution and accuracy of shaping, however problems with proper clamping and tool stiffness occurs. Mostly, the stepped electrode tool with simple cylindrical shape is prepared (machined) on the same machine-tool and is followed by machining without change of tool-clamping. Such solution gives possibility to carry out machining with electrodes diameter less than 0.1 mm , however it needs to integrate tooling for electrode preparation on the working table and include

appropriate software algorithms in machine control system [13].

Production of the ECM machine-tools are in area of interest of only a few manufacturers. These include EMAG ECM GmbH (Germany), PECM Industrial LLC (Russia), ECM Technologies (Netherlands) and PEMTec (Germany). Majority of available machines have similar functional parts but they have different design and vary in construction details. Typically, each producer offers machines in model series and the basis for classification are following criteria [14–16]:

- dimensions (concerns working table and machining chamber) which determines maximal dimensions and mass of the workpiece and range of movement in each axis,
- amount of numerical controlled axis,
- and maximal working current.

Other solution is modular machine design, which gives possibilities for easy modification or variant configuration of the machine tool. As example, one can specify machine tools produced by PEMTec [16] which consist of four configurable and individually customized modules i.e. mechanical part, control unit, pulse power supplier and electrolyte supply and recycling (Fig. 4).



Fig. 4. Modular electrochemical machine-tool offered by PEMTec [16].

Each application of electrochemical machining needs to design a specialized technological tooling, which is a key element of each electrochemical machine-tool. Properly designed technological tooling is a necessary condition for achieving required technological indicators. It contains design of shape and dimensions of electrode-tool, selection of appropriate way of electrolyte supply to interelectrode gap, selection of appropriate way of current supply to electrode-tool and workpiece, selection of appropriate way of workpiece clamping or additional solution i.e. connected with localization of anodic dissolution. Application of specialized technological tooling gives possibility to adapt each electrochemical machine-tool to wide range of applications including also precise and micromachining.

Electrochemical microdetails manufacturing

Microdetails machining when using methods in which tool is material object (i.e. cutting, grinding, electrodischarge machining) is difficult because of a few reasons. First of all it is necessary to produce, clamp and positioning tool with dimensions $D < 1$ mm in relations to workpiece, what is usually difficult. Secondly tool in such processes as cutting, grinding or EDM significantly wears. In cutting and grinding machining process can generate significant mechanical forces, which can distort or even destroy the tool or workpiece, what significantly limits metal removal rate, accuracy and dimensions of the workpiece. In electrodischarge machining (EDM) there are no mechanical forces but electrode – tool wears because of melting and evaporating during electrical discharges. In EDM the electrode tool wear can be limited by decreasing energy of individual pulses. The same metal removal rate is strongly decreased. In ECM tool is also material object, however as it stated in former part of the article in properly carried out electrochemical machining the electrode tool not wears, what is its valuable advantage. Because of this fact electrochemical machining of microdetails is developed in very dynamic way [10, 11, 17]. The new machine-tools are designed and build and new practical applications arise. One of the main conditions for efficiently applying of electrochemical machining in micromanufacturing is the increase in machining resolution. It can be obtain by decreasing electrode tool dimensions and voltage pulse time ($t_i \ll 1 \mu\text{s}$).

The machining can be carried out in kinematic of sinking, drilling or milling. Microcavities or microholes are manufactured in kinematic of sinking or drilling (for instance – cooling holes in details of aircraft engines [6, 18, 19]). Microdetails with free form shapes (3D) are usually manufactured in kinematic of milling [11], as it is presented in Fig. 5. In milling operation cylindrical electrode tool rotated and is displaced along properly designed trajectory and remove from workpiece material as a result of electrochemical dissolution process. Final shape of workpiece is obtain as a result of electrode tool trajectory reproduction in machined material (examples of application in Fig. 6). Of course to obtain smaller dimensions of the workpiece the electrode tool should has smaller diameter.

In ECM milling process, in order to minimize problems with manufacturing, clamping and positioning electrode tool should be manufactured on the same electrochemical machine-tool, which will be used for microdetails manufacturing. Electrode tool

can be manufactured in the way presented in Fig. 7. Such solution needs to equip machine-tool with special tooling, software and database with process characteristics.

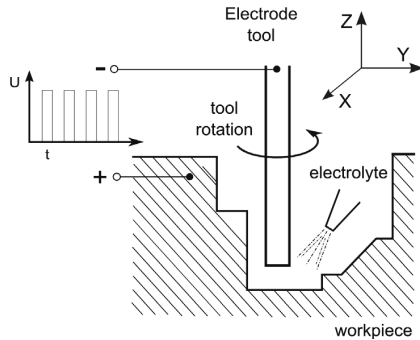


Fig. 5. Scheme of 3D microdetails electrochemical milling.

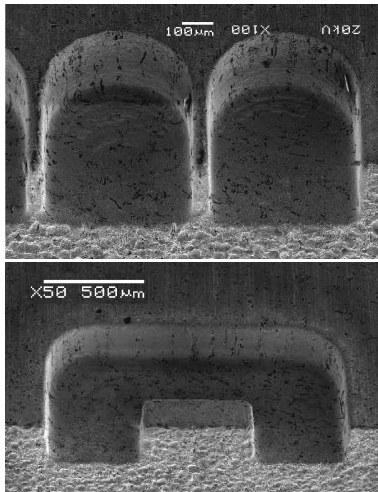


Fig. 6. Example of electrochemical milling applications.

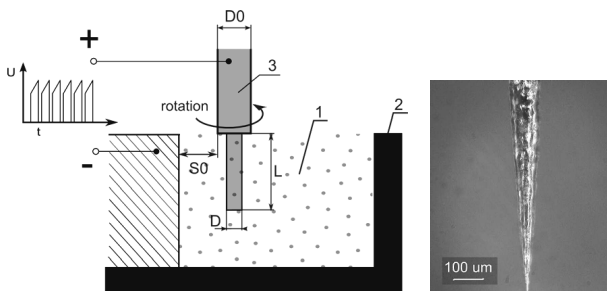


Fig. 7. a) Scheme of electrode tool manufacturing in ECM process (1 – electrolyte, 2 – chamber, 3 – manufactured electrode – tool, D_0 – electrode tool diameter in part for clamping, D – diameter of working part of electrode tool, S_0 – interelectrode gap thickness); b) tip of electrode – tool machined electrochemically, interelectrode voltage $U = 15$ V [13].

Electrochemical machining application in aircraft industry

Electrochemical machining can be successfully applied for machining special materials conducted electrical current as Ti and Ni alloys. In order to working out industrial technological processes the basic technological characteristic has been experimentally working out. From experiments presented in [6, 20] result that aircraft materials as Ti or Ni matrix composites can be electrochemically machined with satisfactory results in water solution of 12% NaCl and 20% NaNO₃. Velocity of electrode tool displacement can be changed in the range of ~0.5- 1.5 mm/min. Specific metal removal rate is for Ti alloys about 1.77 mm³/Amin and for Ni alloys is changed in the range of 1.51–2.13 mm³/Amin. For above mentioned technological indicators surface roughness parameter Ra is depended on current density and is equal ~1.4 μm for Inconel 718 and for Ti-6Al-4V Ra ~0.4–1.2 μm.

In many nowadays articles PECM is presented as about new discovered process. So, it is worth to underline that theoretical models of PECM have been worked out in former century (in seventies) in East Europe Counties (A.D. Davydov, G.N. Korcagin, F.N. Siedykin, J. Kozak) [9]. In this time PECM process was applied in industry. Now PECM is applied because of aircraft industry needs and dynamic increase of MEMS production. Efficient applications of PECM process is also possible thanks to new technical possibilities in the area of generators and control units production. Application of pulse voltage and electrode – tool oscillations create conditions for precision PECM with interelectrode gap thickness in the range of 10–100 μm instead of 100–1000 μm when applied is constant voltage. In PECM it is possible to obtain Surface roughness parameter Ra ~20–30 nm. For some materials it is possible to create surface as after polishing operations [6, 10].

In Fig. 8 the modern electrochemical machine tool for aircraft engine parts manufacturing was presented. Such machine has 7 or 8 axes (3 or 4 for workpiece positioning and 4 for carrying out electrodes movement and oscillation. It is possible to apply as electrolyte water solution of NaCl (in order to avoid passivation) for Ti matrix alloys and water solution of NaNO₃ for machining Ni matrix superalloys and TiAl. Electrolyte flow rate can be up to 1000 l/min with pressure up to 40 bar. The machine is also equipped with control and stabilization of electrolyte pH and temperature. Amount of Cr⁺⁶ ions is under monitoring and reduced to Cr⁺³, as a part of unit of electrolyte cloning (machine tool

is friendly from ecological point of view). Pulse current amplitude is up to 40 kA and pulses frequency reach 10 kHz. In rough operations it is possible to apply constant voltage with current density up to 3 A/mm². Maximal machined surface is up to 60 cm². Machining process is carried out in pressure chamber with controlling inlet and outlet pressure (chuckling electrolyte flow) what gives possibility to stabilize electrolyte flow. Maximal velocity of electrode tool displacement is up to 3 mm/min; electrodes oscillations amplitude 10 mm and frequency 100 Hz; Typical velocity of electrode tool displacement for PECM is ~0.1 mm/min. The possibilities of EMAG PO 900 BF machine tool application was presented in Figs. 9 and 10.



Fig. 8. The modern electrochemical machine tool EMAG PO 900 BF designed for machining the complete blisk [15].

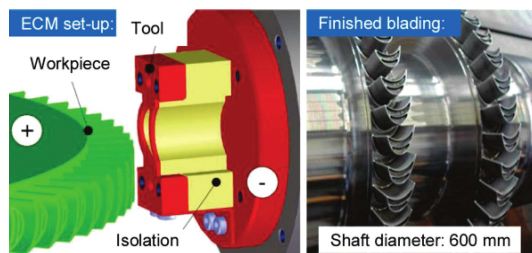


Fig. 9. Scheme of electrochemical machining monolithic turbine set made of steel ((X22CrMoV2111) for gaseous and steam turbine when using machine tool presented in Fig. 8 [6].

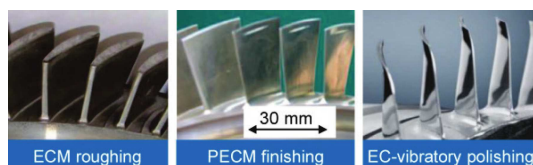


Fig. 10. Monolithic turbine blade after rough, finishing and polishing operations [6].

Summary

Nowadays electrochemical machining range of application in aircrafts and MEMS details manufacturing industry is dynamically increasing.

ECM as one of the few machining technologies which gives possibility to carry out the process in 3 stages with application of the same electrode tool and on the same machine. It improves machining accuracy and surface layer quality, by application of optimized parameters for these 3 machining stages: maximal metal removal rate (1st stage – constant voltage), maximal dimensional accuracy (2nd stage – pulse voltage) and maximal surface quality (3rd stage – polishing – pulse voltage).

It is worth to underline, that theoretical base of PECM have been worked out in seventieth of the former century, however in this time range of industrial applications was limited by low technical possibilities in drives, power suppliers and control units. Now technical level applied in electrochemical machine tools technical solutions make it possible to apply in industrial conditions precise electrochemical machining for macro and micro details manufacturing.

Because of wider and wider special materials application the range of ECM process application will dynamically increase in macro and micro parts manufacturing; especially in aircraft and MEMS industries.

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