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SOME ASPECTS OF ELECTROCHEMICAL MACHINING PROCESS MODELING AND APPLICATIONS

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Summary

Electrochemical machining process (ECM) can be applied for shaping advanced materials which are difficult or impossible for machining using conventional methods. In electrochemical machining the workpiece is an anode and material is removed as a result of electrochemical reactions “atom” by “atom”, without mechanical forces. This mechanism of material removal makes it possible to obtain high quality of machined surface layer with uniform properties. Very important advantage of ECM process is also the fact that there is no electrode – tool wear because the equivalent reaction to anodic dissolution is hydrogen generation on cathode surface and hydrogen can be easy removed from interelectrode gap by electrolyte flow. Because of this advantages ECM process is dynamically developed. Some aspects of ECM process mathematical modeling and practical applications are presented in the paper, taking into account literature review and author’s own research.

Keywords: elektrochemical machining, mathematical modeling, applications

Wybrane zagadnienia modelowania i praktycznego zastosowania procesu obróbki elektrochemicznej

Streszczenie

Procesy obróbki elektrochemicznej (ECM) są stosowane do kształtowania wyrobów wykonanych z materiałów specjalnych przewodzących prąd elektryczny, trudnych lub niemożliwych do obróbki metodami konwencjonalnymi. W obróbce elektrochemicznej przedmiot obrabiany jest anodą i materiał jest usuwany w wyniku reakcji elektrochemicznych bez oddziaływania sił mechanicznych. Proces taki usuwania materiału umożliwia uzyskanie wysokiej jakości warstwy wierzchniej obrabianych wyrobów. Zaletą procesu ECM jest brak zużycia elektrody roboczej (narzędzia). Reakcją ekwiwalentną do reakcji anodowego roztwarzania jest bowiem wydzielanie się wodoru, łatwo usuwanego przez przepływający elektrolit. Stąd obecnie procesy ECM są dynamicznie rozwijane. W pracy przedstawiono niektóre problemy związane z matematycznym modelowaniem oraz aplikacją procesów ECM, z uwzględnieniem danych literaturowych i wyników badań własnych.

Słowa kluczowe: obróbka elektrochemiczna, modelowanie matematyczne, zastosowanie

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1. General characteristic of ECM process

The first applications of ECM process took place mainly in case of sinking, where detail shape is obtained as the result of corrected electrode – tool shape reproduction in workpiece. The correction of electrode tool (ET) is the process of decreasing ET dimensions of interelectrode gap thickness – for outside surfaces and increasing ET dimensions for inner surfaces. So, in mathematical modeling of the ECM process, the most important problem is the evaluation of interelectrode gap thickness distribution. Knowing thickness of interelectrode gap it is possible to evaluate dimensions of workpiece for known ET shape or to change properly ET dimensions in order to obtain assumed shape and dimensions of workpiece. In ECM the material is removed as a result of electrochemical reactions occurring on anode (machined material). The principles of the process was precisely discussed by many researches [1-48]. In general case (Fig. 1,2) in any point of machined surface the interelectrode gap changes are described by equation (1). Solving this equation for steady state of the ideal process ($dS/dt = 0$, electrolyte properties are uniform and constant) the relationship (2) for $v_f > 0$ and relationship (3) for $v_f = 0$ are obtained. It is worth to underline that for the ideal ECM process, the properties of electrolyte and conditions of dissolution (anode) and deposition (cathode) reactions are constant on the whole machined surface. Of cource this assumption can be taken only for primary ECM process analysis. The full mathematical model of ECM sinking process has been presented in many publications. Publication: [1-3, 5, 12-14] are only given

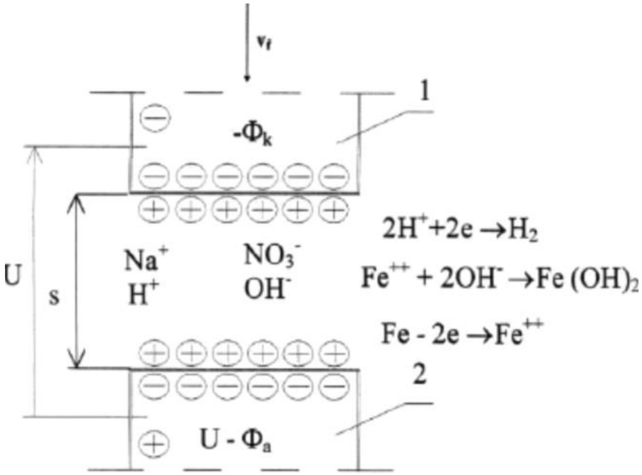

Fig. 1. Scheme of machined area in case of flat electrode tool in water solution of $NaNO_3$: ϕ_k – potential drop in cathode area, ϕ_a – potential drop in anode area; 1 – electrode-tool, 2 – machined detail, S – thickness of interelectrode gap, U – interelectrode voltage, v_f – velocity of electrode tool displacement; in some cases $v_f = f(t)$; t – time of machining; based on [6,19]

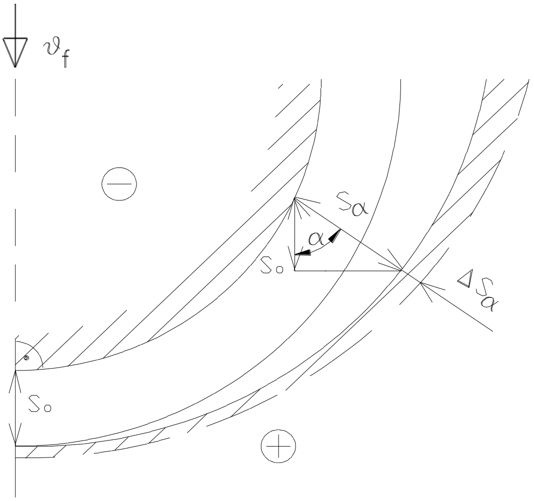

Fig. 2. Geometry of interelectrode gap in steady state of the process: v_f – velocity of electrode tool displacement, α – profile angle, ΔS_α – change of interelectrode gap thickness resulting from process parameters and electrolyte properties fluctuations along its flow, S_0 – thickness of initial gap; based on [6]

only given here as an example. The aim of this paper is not to present some new mathematical model and its solutions. The aim of the paper is to underline the difficulties of mathematical modeling of ECM process and to show how these problems have been partly solve in practice for some special conditions. Many well known scientists as: Kozak J., Davydov A.D, Mc Geough J.A., Rajurkar K.P., Klocke F., De Silva A., Kunieda M. or Sedykin F.V. [1-3, 8, 12, 22, 23, 25, 38, 39, 41-48] and many other outstanding researches have been involved in ECM process development. For further considerations it has been assumed that the thickness of an interelectrode gap “S” is the main indicator of the phenomena occurring into the machining area and machining accuracy.

$$\frac{\mathrm{d}S}{\mathrm{d}t} = \eta k_v \kappa \frac{(U-E)}{S} - v_f \cos\alpha \tag{1}$$

$$S_u = \frac{\eta k_v \kappa (U-E)}{v_f \cos\alpha} \tag{2}$$

$$S = \sqrt{2\eta k_v \kappa (U-E)t + S_0^2} \tag{3}$$

where: S_u – thickness of interelectrode gap for steady state of the process, S_0 – thickness of interelectrode gape for the beginning of the process ($t = 0$). η – current efficiency of the dissolution process, k_v – machined material electrochemical equivalent, κ – electrical conductivity of the electrolyte, E – sum of potential drops on the border of electrolyte and ET and machined detail surfaces, U – interelectode voltage, v_f – electrode – tool velocity, α – profile angle.

2. The hydrodynamic conditions in ECM process

From the primary analysis of the ECM process it results that electrochemical reactions on workpiece surface and electrode-tool surface can occur only in these points for which the space between the anode and the cathode is full of electrolyte of proper properties as: electrical conductivity, temperature, hydrogen concentration. The electrolyte specific conductivity is connected with temperature and hydrogen concentration and can be calculated from relationship [1,2]:

$$\kappa = \kappa_0 \, (1 + \alpha \, \Delta T) \, (1 - C_H)^{3/2} \tag{4}$$

where: κ – specific electrolyte conductivity, κ_o – specific electrolyte conductivity at inlet to machining area, α_T – temperature coefficient of electrolyte conductivity, C_H – hydrogen volumetric concentration; it has been assumed that influence of dissolution products concentration on electrolyte conductivity can be neglected.

The general and very simplified scheme of interelectrode area is presented in Fig. 3. In order to find out the distribution of electrolyte electrical conductivity it is necessary to find out the distribution of electrolyte temperature and hydrogen concentration [6]. According to considerations carried out in many papers for case presented in Fig. 3 it had been worked out that electrolyte temperature and hydrogen concentration can be calculated from relationships (5, 6,7) [6].

$$T(x) = T_0 + \frac{U v_f}{\eta k_v c_p \rho_0 q_0} x \tag{5}$$

where: ρ_o – electrolyte density, c_p – electrolyte specific heat, q_0 – electrolyte discharge, T_o – temperature at inlet to interelectrode area.

$$C_H = \frac{K}{1 + K} \tag{6}$$

where:

$$K = \frac{\eta_H k_{m,H} \kappa_0 (U - E) x p_n T(x)}{p(x) \rho_{H,n} T_n v_0} \tag{7}$$

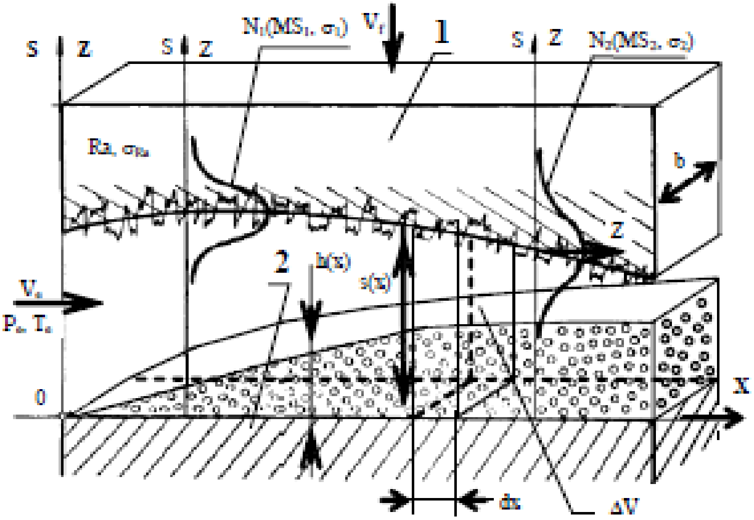

Fig. 3. Scheme of interelectrode area: 1 – workpiece, 2 – electrode-tool, b-electrode and workpiece width, *h*(*x*) – thickness of layer of mixture: electrolyte-hydrogen, ECM process has random character so distribution of interelectrode gap S is given in each interelectrode gap cross-section by value of $N_i(MS_i, \sigma_i)$ MS – mean value of gap thickness and its standard deviation σ_i, $i = 1,2 \dots n$ – number of cross section, based on [6]

Having the values of temperature and hydrogen concentration it is possible to calculate electrolyte specific conductivity and interelectrode gap thickness. The accuracy of these calculations depends on the accuracy of evaluation of electrodes polarization and specific coefficient of workpiece machinability. In case of machining presented in Fig. 3, the values of this ECM process indicators can be taken from relationships (8, 9) evaluated on the base of primary experiments in which some parameters will be measured and taken for calculations [1, 2]:

$$k_v = \frac{v_f}{j} \tag{8}$$

$$E = U - \frac{S v_f}{k_v \kappa} = U - \frac{S j}{\kappa} \tag{9}$$

where: *j* – mean value of current density.

Evaluating a’priori the data mentioned above, when machining free form surfaces (Fig. 2) is very difficult. So, in order to reach higher accuracy, satisfactory surface quality and simplify mathematical modeling of ECM process it is necessary to create uniform conditions in the machined area. It could be reached by application of: electrodes (anode, cathode) vibrations, pulse interelectrode voltage or universal electrodes and special electrodes kinematics. Some simplifications of ECM process modeling and its practical applications are presented below.

3. Practical application of sinking process

As it has been stated, more uniform conditions into an interelectrode space could be reached when some additional electrodes vibrations in one or two axes on the ET movement towards the workpiece are being applied as it is presented in Fig. 4 [12]. For this case of machining, the system for computer aided technological process designing has been worked out. This system includes a packet for process mathematical modeling and simulation. The system has been experimentally verified. In experiments have been taken into account two variants of ET vibration: the vibration in direction of ET displacement with amplitude *A* = 0.1 mm, frequency 30 Hz and the vibration in direction perpendicular to direction of ET displacement with amplitude *A* = 0.05 mm, frequency: *f* = 60 Hz. After analysing the modeling results and experiments it was stated that the accuracy of modeling is satisfactory. It is worth to underline that the application of ET ultrasonic vibrations is very promising for mezzo and micro surfaces [7, 22].

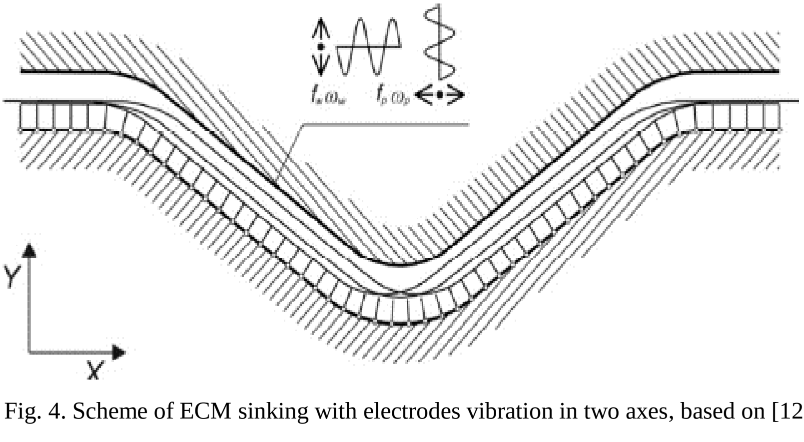

Fig. 4. Scheme of ECM sinking with electrodes vibration in two axes, based on [12]

The mathematical modeling can be significantly simplified for rotational surfaces machining [13]. Here, for improving hydrodynamic conditions, the rotations and oscillations of ET or workpiece have been introduced. For this case of machining, the computer aided system for technological process designing have also been worked out. This system includes a packet for mathematical modeling and simulation of the process. Satisfactory accuracy of mathematical modeling has been confirmed by experimental verification, carried out for machining with workpiece rotational movement: n = 800-1600 rot/min, and with vibrations: amplitude A = 0.1 mm; frequency f = 30-60 Hz.

In ECM monolithic aircraft turbines (blisks) production [16-18, 20, 23-25] an industrial success results from the application of pulse electrochemical machining [1, 2, 5, 6, 14, 15, 21, 23, 25, 29-31, 38-41, 47, 48], electrode vibrations and the fact that machining process was carried out in a pressure chamber (Figs. 5, 6, 7). The pressure in the electrolyte outlet is significantly bigger then atmospheric one. Thanks tothis higher pressure the electrolyte flow is very stable and the electrolyte fills each part of interelectrode area and hydrogen volumetric concentration is smaller than in classical conditions of machining.

Examples of others ECM process applications are presented in Fig.8.

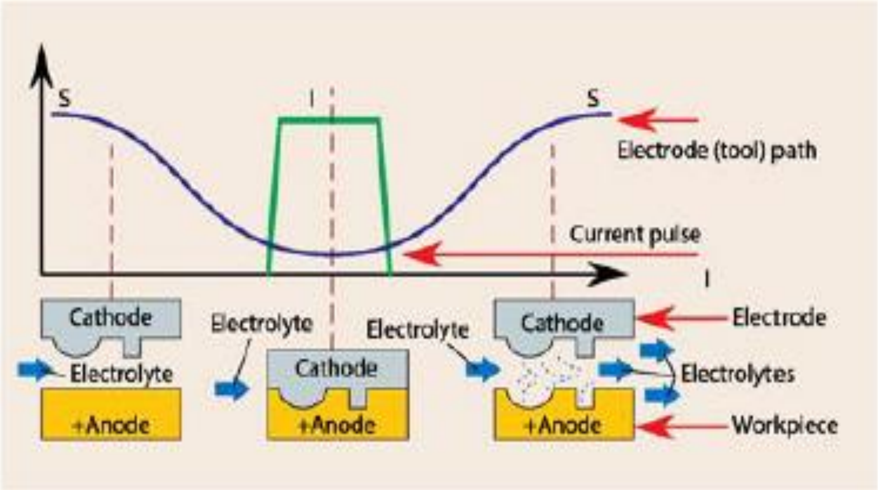

Fig. 5. Scheme of precise pulse electrochemical machining with application of pressure chamber and electrode tool oscillations (Tolerance of dimensions usually changes in the range of: ~ 0.03-0.10 mm), based on [23]

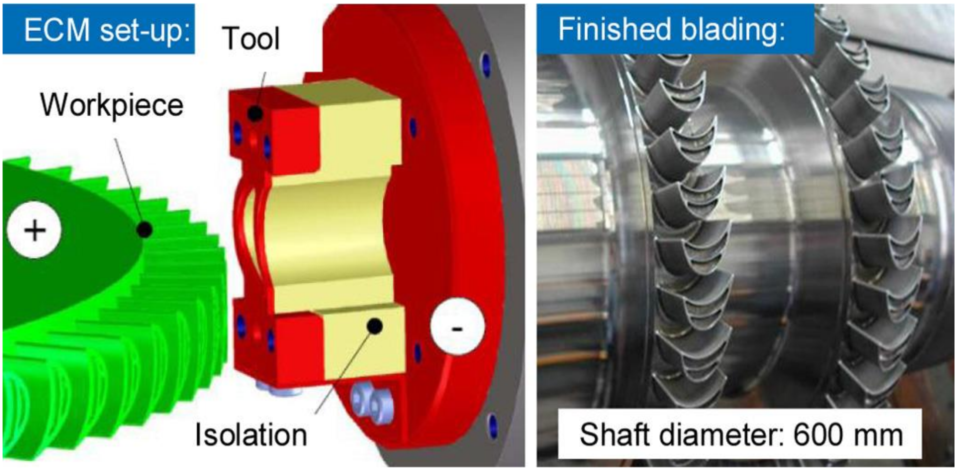

Fig. 6. Scheme of electrochemical machining of monolithic turbine set made of steel (X22CrMoV2111) for gaseous and steam turbines, based on [25]

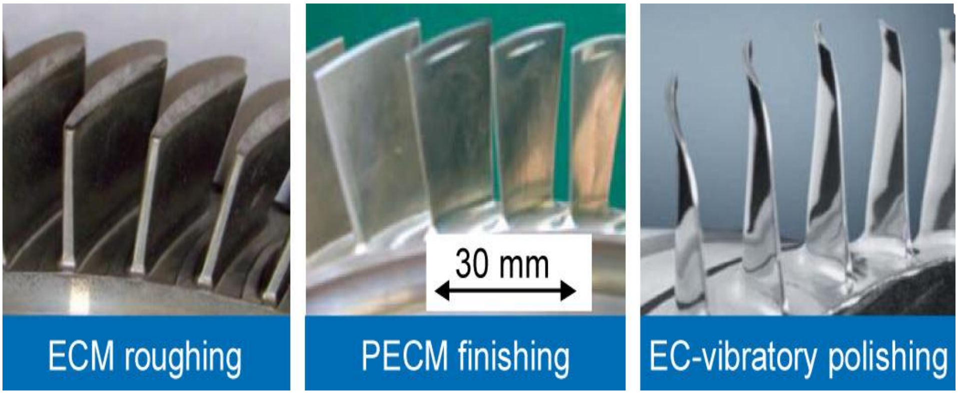

Fig. 7. The monolithic turbine blades after rough, finishing and polishing ECM operations, based on [25]

4. Electrochemical machining with universal electrodes

In this case of electrochemical machining: tool (cathode) and workpiece (anode) move relatively in a special way and the machined surface shape is obtained as reproduction of this relative trajectory. There are three general cases: ECM generated machining (ECGM), electrochemical milling or planning when using universal ET and Wire ECM cutting (Fig. 9-13, 16-18). In each case the area with intensive dissolution process is small and assumption that electrolyte conditions are constant can be taken for mathematical modeling without risk of significant error.

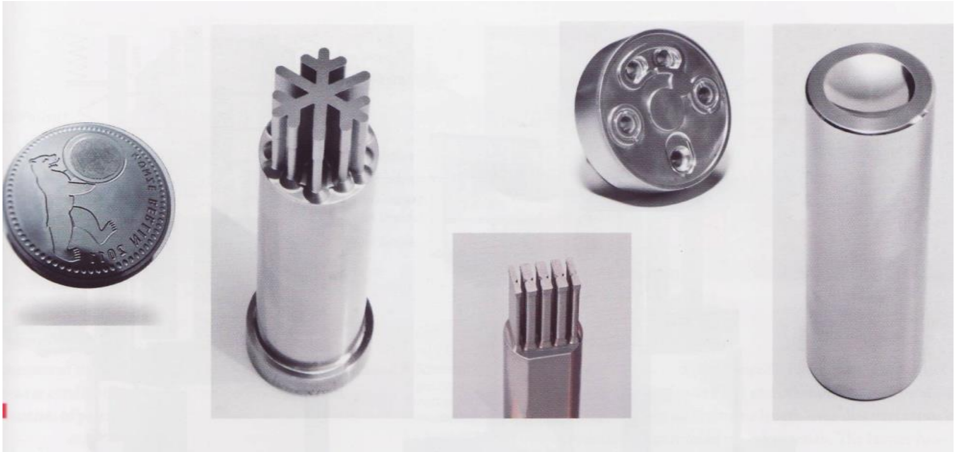

Fig. 8. Example of ECM manufactured parts, based on [23]

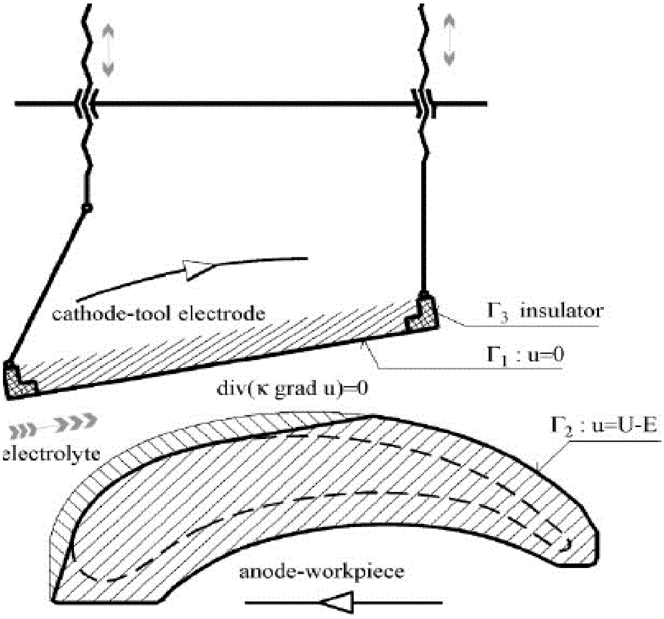

Fig. 9. Scheme of ECGM process; workpiece shape is obtain as result of relative movement of flat ET and workpiece, based on [26]

The mathematical modelling, computer simulation and experimental results of ECGM process presented in [26] make it possible to conclude that: ECGM with universal ET (plate) allows to machine parts of complex 3D shapes. Experiments show that the mathematical modeling gives satisfactory practical accuracy of machined workpiece dimensions.

Figure 10 present the general scheme of machining using an universal rotating electrode. Universal electrodes can have any shape (Fig. 10,11), however in case of macro-machining usually ball ended electrodes are applied while in micromachining usually flat ended cylindrical electrodes are applied [6, 27-34, 37-39, 43, 45-47]. The electrochemical machining process with universal electrodes (flat or ball ended as in Figs 10, 11) is stable and friendly for mathematical modeling but has one significant disadvantage: very small metal removal rate. Because of this fact it can be applied efficiently only for special operations (workpiece with thin walls – Fig. 12) [33], slots or pockets [37]) or finishing operations usually after rough classical milling or electrodischarge machining. The practical applications are presented in Fig. 12 and Fig. 13. The results of these research made it possible to create The Complex System for computer aided technological process simulation and designing – combined with ECM-CNC machine-tool.

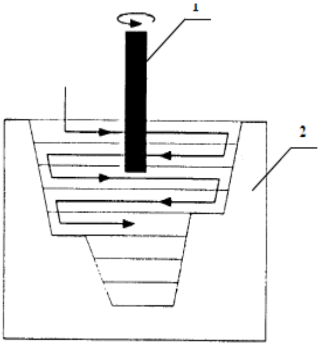

Fig. 10. The general scheme of machining using an universal rotating electrode–tool. 1 – rotating cylindrical electrode displaced along 3D trajectory, 2 – workpiece

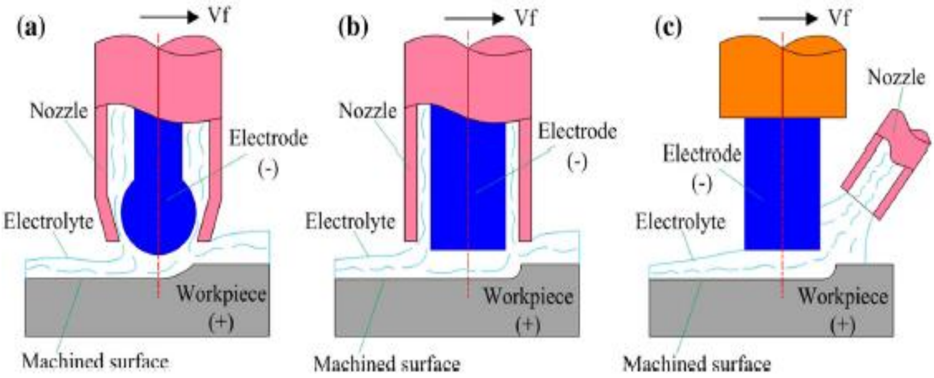

Fig. 11. Scheme of universal ET for milling or planning and different way of electrolyte supplying; a, b) usually macro and mezzo machining, c) usually micromachining, based on [33]

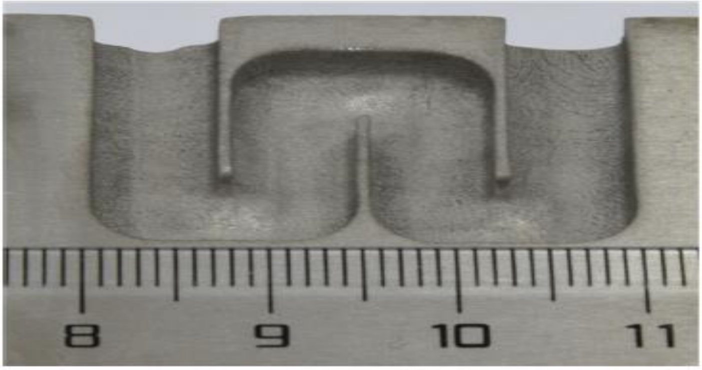

Fig. 12. Element (with thin walls) – material was removed by side wall of rotating electrode – tool; electrolyte was supplying by hole inside ET as is presented in Fig. 14, based on [33]

Fig.13. Workpiece after electrochemical smoothing (surface after rough milling) with ball ended electrode (R = 9 mm), time of finishing t = 45 min; other parameters: U = 16 V, v_p = 42 mm/min, S_0 = 0.2 mm, electrolyte – 15% water solution of $NaNO_3$, the initial waviness after milling D = 0.1 mm; the final waviness after ECM smoothing ≈ 0,0; $R_a \approx 2$ μm; based on [6, 19]

5. Electrochemical micromachining

ECM micromachining is usually carried out in operations of sinking (without ET rotations), drilling (with ET rotations), milling (with ET rotations) and planning (without ET rotations). Preparing for above mentioned operations, ET with so small dimensions is a very important and difficult problem. ET is usually manufactured on the same machine tool which is used for micro-details production [32, 33]. For micro-details or microstructures fabrication WECM cutting is also apply. Here the problem of removing products of dissolution process, hydrogen and heat out of the gap is solved by introduction a special electrode kinematic (Figs. 16, 17) and sometime wire-tool with a special structure (Fig. 18).

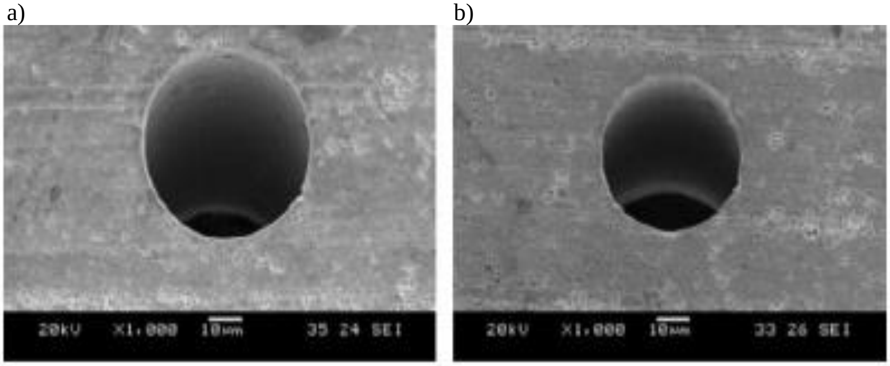

Fig. 14. Micro-holes fabricated by PECM drilling in plate made of WC-Co alloy of 200 µm; a) hole entrance φ = 48 µm, b) hole exit φ = 42 µm; electrolyte 0.5 M $NaNO_3$+ 0.2 M H_2SO_4; voltage pulse amplitude – 9 V, pulse duration 100 ns, pulse period 1 µs, federate 0.1 µm/s. Machining gap thickness 3-5 µm; based on [39]

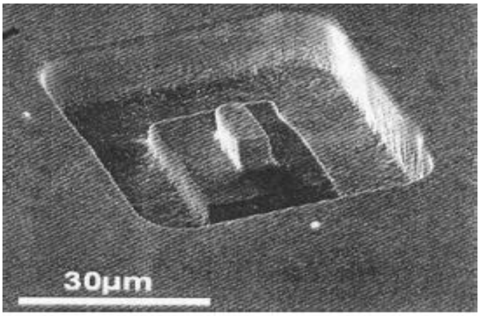

Fig. 15. PECM of 3D microstructure in Cu anode, ET – platinum wire diameter 10 µm; time of pulse 50ns, voltage pulse amplitude 1.6 V, pulses frequency 2 MHz, Structure in the middle of the hole have dimensions 5 x10 x 12 µm, based on [34]

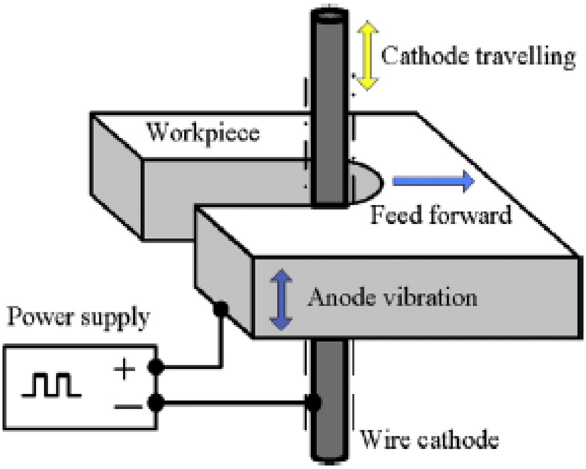

Fig. 16. Scheme of WECM process in case of micromachining. Diameter of Tungsten wire was 10 µm. Wire and workpiece vibrated and wire was feed toward workpiece, based on [35]

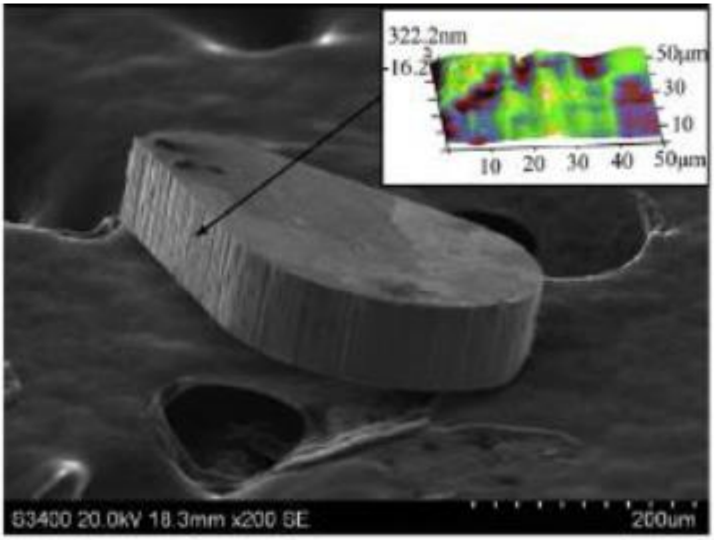

Fig. 17. Examples of WECM cutting microstures. Optimal condition: anode vibration: amplitude 5 µm, frequency 100 Hz, wire (cathode) speed 400 µm/s with vibration amplitude 100 µm, frequency 5 Hz, voltage pulse time 40 ns, pulse period 6 µs. Size of cutting parts 150 and 400 µm, Ra ~0.058 µm, based on [35]

The workpiece material (Fig.16) was cobalt based alloy with the thickness of 80 µm, electrolyte: 0.01 M HCl. The wire electrode feed rate was 0.02 µm/ s.

WECM was also applied for special microstrures (thin walled) manufacturing in stainless steel plate thickness 20 mm. Here also a relative movement between workpiece and wire has been applied but additionally the wire has a special ribbed structure, what significantly improves hydrodynamic conditions and the speed of cutting can be increased. Of course it is possible only when the wire diameter is relatively high.

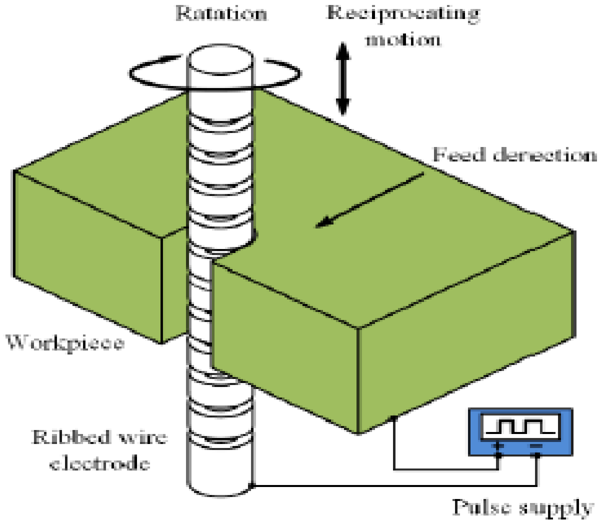

Fig. 18. Scheme of WECM for microstructures manufacturing with ribbed wire electrode; other parameters: pulse voltage 21 V, pulses frequency: 100 kHz, a pulse duty cycle 40%, electrolyte $NaNO_3$ concentration 15 g/L, electrode federate 1 μm/s, reciprocating amplitude 20 mm and reciprocating frequency 1.5 Hz, ribbed electrode rotation 5000 rot/minute, based on [36]

WECM is also applied for macro and mezzo details fabrication [39]. Here also the application of structured wire electrodes could be an innovative direction of development.

6. Conclusions

ECM development and wide practical applications result from below specified main advantages: high efficiency of dissolution process which not depends on workpiece mechanical properties, high quality of machined surface (material is removed “atom” by “atom”) and luck of electrode – tool wear (on cathode only hydrogen deposition occurs) – of course for optimal machining conditions. Mechanical forces are generated only by electrolyte pressure when it flows through interelectrode area. General idea of electrochemical machining process development was to increase uniformity of electrolyte properties in machining area. This condition can be fulfilled by application: electrode tool vibrations in classical sinking process, pulse voltage without or with electrodes vibrations (sometime in two axes), decreasing the machined area by application universal ET (ECGM, ECM – CNC or WECM). Above mentioned operations are being applied in manufacturing micro and macro-details.

In order to reach as high as possible manufacturing efficiency, the ECM machining process in carried out in stages with different aims in each stage: maximal metal removal rate, high accuracy, low surface roughness. The most spectacular applications are in aircraft industry (blisks); however in other areas ECM process also increase range of applications. Special attention is paid for micromachining processes development in such operations as: sinking, drilling, milling, planning and wire cutting.

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