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Electrochemical contactless machining – process characteristics, directions of development and practical applications

Abstract

Electrochemical machining was, is and will be widely applied in industry, because of its advantages: high metal removal, good surface layer quality without tool wear. The first applications took place in case of sinking, where detail shape is obtained as electrode-tool shape reproduction in a workpiece. The results of the process mainly depend on optimal electrolyte flow and are limited by temperature and hydrogen concentration increase. Because of these problems the pulse ECM process was worked out. In PECM process limitations of temperature and hydrogen concentration were overcome, accuracy increased, however metal removal rate was significantly decreased.

The next way of overcoming process limitations was the advanced kinematic (milling) and simple cylindrical electrode tool shape introduction. Here the shape of a workpiece is obtained as a result of electrode-tool trajectory reproduction and problem of electrode-tool correction doesn't exist. Practical applications of this way of ECM machining in case of macro details were rather limited to surface smoothing because o low metal removal rate. This way of machining is widely applied in case of micro-details (D< 1mm) manufacturing. Here ECM wire cutting operation have their applications.

In the paper will be presented: general problems of ECM process modeling and technological process designing. Examples of ECM process practical applications will be also presented.

Key words: electrochemical machining, electrochemical dissolutions, hydrodynamic conditions, turbines of aircrafts engines, micro technologies.

Elektrochemiczna obróbka bezstykowa – charakterystyka procesu, kierunki rozwoju oraz praktyczne zastosowania

Streszczenie

Obróbka elektrochemiczna bezstykowa (ECM) jest i będzie coraz szerzej stosowana w przemyśle z uwagi na jej zalety, takie jak duża wydajność obróbki oraz brak zużycia narzędzia. Pierwsze zastosowania ECM obejmowały operacje drążenia, w których kształt przedmiotu obrabianego uzyskuje się jako odwzorowanie kształtu elektrody roboczej w materiale obrabianym. Wyniki procesu zależą głównie od optymalnych warunków przepływu elektrolitu i są ograniczone przez wzrost temperatury elektrolitu oraz koncentracji objętościowej wodoru. Aby zlikwidować te ograniczenia, opracowano proces impulsowej obróbki elektrochemicznej (PECM), w którym zlikwidowano ograniczenia wynikające z przyrostu temperatury i koncentracji objętościowej wodoru, niestety kosztem istotnego zmniejszenia wydajności obróbki.

Drugim sposobem usunięcia ograniczeń procesu drążenia było wprowadzenie operacji frezowania i zastosowanie uniwersalnej cylindrycznej elektrody roboczej. Tutaj kształt przedmiotu otrzymuje się w wyniku odwzorowania trajektorii uniwersalnej elektrody roboczej, a ze względu na małe wymiary problem korekcji elektrody roboczej nie istnieje. Praktyczne zastosowania obróbki ECM uniwersalną elektrodą w przypadku obróbki makroelementów jest ograniczone ze względu na małą wydajność do operacji wygładzania. Ten sposób obróbki jest szeroko stosowany w obróbce mikroelementów (D< 1mm). Zastosowanie znalazły tutaj również operacje mikro-wycinania z zastosowaniem elektrody drutowej.

W artykule omówione zostaną podstawowe problemy modelowania procesu ECM oraz projektowania procesu technologicznego. Przedstawione zostaną również przykłady zastosowań praktycznych.

Słowa kluczowe: obróbka elektrochemiczna, roztwarzanie elektrochemiczne, warunki hydrodynamiczne, turbiny silników lotniczych, mikrotechnologie.

1. Introduction

Electrochemical machining consists of removing excess material in the form of atoms (ions) during the process of electrochemical dissolution proceeding in accordance with Ohm's and Faraday's laws. The diagram explaining the principles behind electrochemical removal machining is presented in Figure 1.

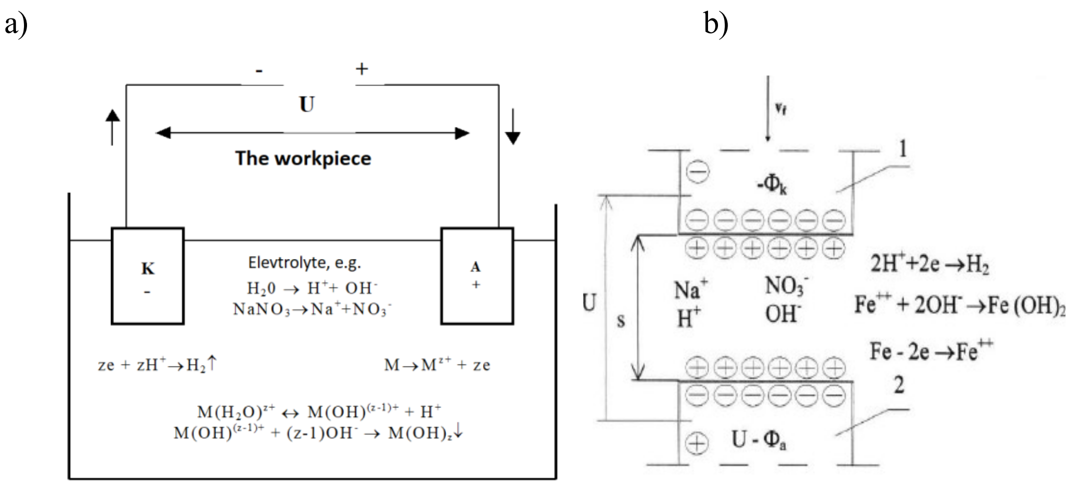


Figure 1. The diagram demonstrating the principle of removing excess material through electrochemical dissolutions: A – anode, K – cathode (Figure 1a) and diagram of machining surface for flat plate electrode boring (Figure 1b)

(source: Ruszaj, 1999)

In the process of electrochemical machining a workpiece is an anode (Figure 1) whereas an electrode-tool is a cathode. The inter-electrode space is filled with electrolyte – a water solution of appropriately selected salts, bases and acids. The principal electrochemical reaction occurring on the surface of the anode is ionization of anode's atoms. Ions of the material comprising anode M^{z+} (e.g. Fe^{2+} or Fe^{3+}) diffuse into the inter-electrode gap where they participate in further reactions. The ultimate product is usually $M(OH)_z$ hydroxide (e.g. $Fe(OH)_2$ or $Fe(OH)_3$). The process of dissolution proceeds in accordance with Ohm's and Faraday's laws. According to Faraday's First Law the mass M or volume V_W of the material removed within a time unit (efficiency) from a workpiece with a constant amperage $I = const.$ can be calculated using the following dependencies (Davydov, Kozak, 1990; Kozak 1975, 2018; Ruszaj, 1999).

$$M = \eta k_m It \ (1), \ \ V_W = \eta k_v It \ (2)$$

where: $k_v = \frac{k_m}{\rho}$; $\eta = \frac{I - I_p}{I}$. I – total current, I_p – current for secondary reactions, k_m, k_v – mass, volumetric electrochemical equivalent, η – current efficiency of dissolution process, ρ – specific weight of the dissolved material.

Therefore the efficiency of electrochemical dissolution is primarily dependent on amperage, current efficiency of dissolution process and electrochemical equivalent of the workpiece. For this reason electrochemical machining tools are equipped with power supply which enables generating amperage from several to thousands of amperes which, in turn, enables reaching efficiency of several dozens of cm^3 / min.

Flow of electric current through the gap (within the area of Ohm's decrease in potential) proceeds consistently with Ohm's law:

$$j = \kappa / grad\ \Phi / \ (3) \ \ j = \frac{\kappa(U - E)}{S} \ (4)$$

where: j – current density, κ – specific electrical conductivity of electrolyte, Φ – electrical field potential, S – width of the inter-electrode gap.

Under the assumption that distribution of electric potential across the width of the gap is linear equation (3) can be expressed in the form of equation (4). Equation (4) demonstrates that in order to increase local current density, and therefore amperage and efficiency of dissolution process, we have to counteract decrease in conductivity of electrolyte κ and the increase in sum of drops in electric field potential in the near-electrode layer E. It can be partially achieved through proper selection of conditions for machining, in particular the hydrodynamic conditions in the gap (Davydov, Kozak, 1990; Kozak, 1975, 2018; Ruszaj, 1999).

Providing appropriately high amperage equates with reaching high efficiency. However, efficiency is also dependent on the efficiency of the dissolution process. A major economic indicator for the electrochemical machining process is energy consumption. The relation between specific energy consumption "e" and parameters of the process is defined by equation (5): Volumetric electrochemical equivalent for an alloy can be calculated from the approximate dependency (6)

$$e = \frac{U}{\eta k_v} \quad (5) \qquad k_v = \frac{100}{\sum (C_i / k_{vi})} \quad (6)$$

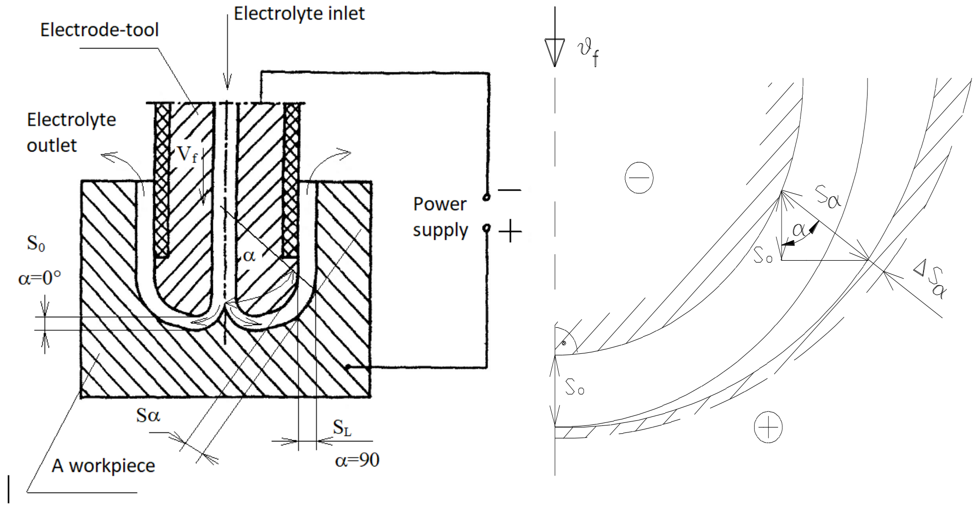
where: C_i – percentile share of the i-th component in the alloy, k_{vi} – electrochemical equivalent of the i-th component of the alloy.

2. Modeling the electrochemical machining

Boring is a type of contactless electrochemical machining characterized by the electrode-tool or a workpiece carrying out a closing feed motion with velocity v_f and by the fact that the machined surface is created by reproducing the shape of the electrode tool (Figure 2). Figure 2b explains how distribution of width of inter-electrode gap "S" influences the flank angel „α". This dependency for the transient state is described by equation "7" and by equation "8" for the steady state. In case of a fixed electrode-tool the process is transient in character and the width of the inter-electrode gap can be estimated by using equation "9" (Davydov, Kozak, 1990; Kozak, 1975, 2018; Ruszaj, 1999).

$$\frac{dS}{dt} = \eta k_v \kappa \frac{(U - E)}{S} - v_f \cos\alpha \ (7); \quad S_u = \frac{\eta k_v \kappa (U - E)}{v_f \cos\alpha} \ (8); \quad S = \sqrt{2\eta k_v \kappa (U - E)t + S_0^2} \ (9)$$

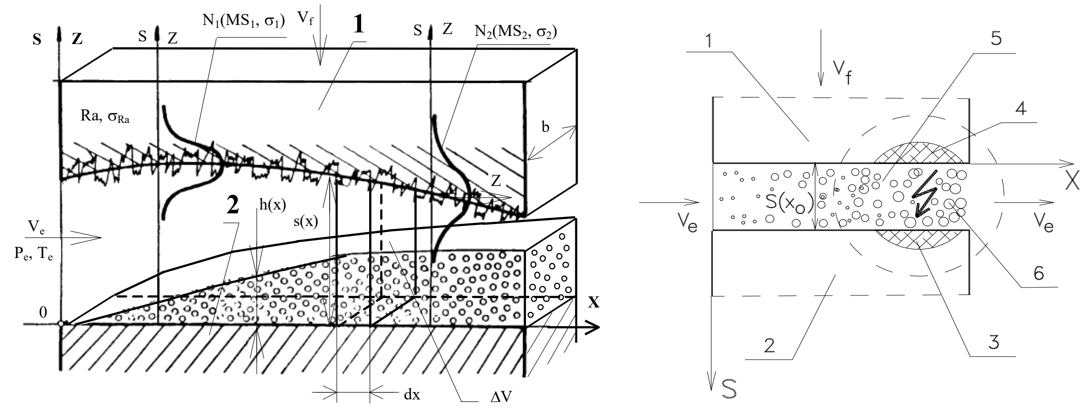
It must be emphasized that the width of the inter-electrode gap is the basic technological indicator for the ECM process and determines hydrodynamic conditions and precision of machining. As a result of mathematical modeling and experimental work it has been ascertained that precision of machining increases along with decreasing the width of the inter-electrode gap – tolerance T = (0,15-0,20) S. However, the width of the inter-electrode gap can be decreased only until critical values of temperature and volumetric concentration of hydrogen are reached.



a) b)

Figure 2. Diagram of the workspace geometry for machining contoured spaces (Figure 2a) and distribution of width of the inter-electrode gap for machining contoured spaces (Figure 2b)

The existing studies on the issue indicate that ensuring optimal hydrodynamic conditions across all points of the machining area is necessary for rational realization of the electrochemical machining process. In case of machining large contoured spaces doing so is very difficult owing to the phenomena which may occur in the machining area e.g. in the areas of electrolyte retention, the area of electrolyte circulation or the cavitation area (Figure 3a). In each of these areas an excessive increase in temperature of electrolyte or volumetric concentration of hydrogen may occur and ultimately lead to local electric discharges which could damage – frequently irreversibly – the electrode-tool and the machined workpiece (Kozak, 2018; Skoczypiec, Ruszaj, 2005) (Figure 3b).



a) b)

Figure 3. Diagram of machining utilizing a flat rectangular electrode (Figure 3a) 1 – the workpiece, 2 – the electrode-tool, $h(x)$ – thickness of the layer filled with electrolyte-hydrogen mix, $N_i(MS_i, \sigma)$ – distribution of frontal width of the inter-electrode gap with average MS_i and standard deviation σ_i, $i = 1,2 ...n$. Diagram of damage to an electrode as a result of electrical discharge (Figure 3b) – 1 – the electrode-tool, 2 – the workpiece, 3 – the material removed from the machined surface as a result of electrical discharge, 4 – the material removed from the electrode-tool surface as a result of electrical discharge, 5 – inter-electrode gap area wherein critical state occurred, 6 – gas bubbles

Influence of hydrodynamic conditions on the process of electrochemical machining was presented for the simplest form of machining utilizing a flat rectangular electrode (Figure 3a). The case has been studied with the assumption of the steady state and numerous simplifications (Davydov, Kozak, 1990; Kozak, 1975, 2018; Ruszaj, 1999). By using the mass and energy conservation principles for the principal volume of the electrolyte dv = „b S(x) dx" (Figure 3a) the distribution of temperature of electrolyte T(x) and volumetric concentration of hydrogen C_H (x) were determined.

$$T(x) = T_0 + \frac{Uv_f}{\eta k_v c_p \rho_0 q_0} x \; \ldots\ldots\ldots \quad (11)$$

where: ρ_e – density of electrolyte, c_p – specific heat, q_0 – electrolyte expenditure at the intake of the inter-electrode gap, T_o – temperature of the electrolyte at the outlet of the inter-electrode gap.

$$C_H = \frac{K}{1+K} \text{ (12): } K = \frac{\eta_H k_{m,H} \kappa_0 (U - E) x p_n T(x)}{p(x) \rho_{H,n} T_n v_0} \quad (13)$$

where: κ – specific conductivity of the electrolyte, κ_o – specific conductivity of the electrolyte at the intake into the machining area (x=0), α_T – the temperature dependency ratio for conductivity to temperature, C_H – volumetric concentration of hydrogen.

By knowing the distribution of temperature and volumetric concentration of hydrogen we may calculate distribution of conductivity of electrolyte from dependency (14) and calculate width of the gap from dependencies (7,8,9).

$$\kappa = \kappa_0 (1 + \alpha \Delta T) (1 - CH)^{3/2} \quad (14)$$

The equations presented above indicate that under suboptimal hydrodynamic conditions (distribution of velocity and pressure of electrolyte) the temperature of electrolyte and volumetric concentration of hydrogen reach critical values and electrical discharge occurs as presented in Figure 3b. Therefore the technological process and machining process have to be designed in a manner which will minimize probability of electrical discharges. It is particularly significant because despite the difficulties with designing and realization of the technological process the ECM process is utilized with increasing frequency, particularly in aviation, space, car and machine industry due to the demand for shaping specialized alloy materials. The scale of the issue indicated above is dependent on dimensions of machined components and scale of production. Developing a process for machining contoured spaces (e.g. blades for industrial turbines of aviation engines) in industrial conditions is difficult and time consuming but costs spread over thousands of pieces of an item – therefore it is desirable to incorporate such process into practice despite the need for solving difficult process of correction of shapes and dimensions of electrode-tool. In industrial application stabilization of electrolyte flow conditions is achieved through (Kozak, 2018; Paczkowski, 2012; Ruszaj, 1999; Ruszaj et al., 2003; Ruszaj et al., 2005; Ruszaj, Czekaj et al., 2005, Ruszaj, Skoczypiec, Gawlik, 2016):

increasing pressure of electrolyte in the machining area achieved through realization of the process in special pressure chambers resulting in the pressure at the electrolyte outled being, indeed, higher than the atmospheric pressure. Such process not only decreases volumetric concentration of hydrogen in the machining area but also stabilizes conditions for flow of electrolyte.

pulse realization of the ECM process usually boils down to powering up the machining area with pulse voltage and properly synchronized vibrations of the electrode-tool. Usually in the breaks between voltage pulses the electrode-tool is moved away from the machined surface, the width of the inter-electrode gap widens and the heated electrolyte and hydrogen are completely removed from the machining area. Because of this the process is being realized in cooled and pure electrolyte in the next pulse and therefore the hydrodynamic conditions stabilize and precision of machining increases at the cost of significant reduction in efficiency.

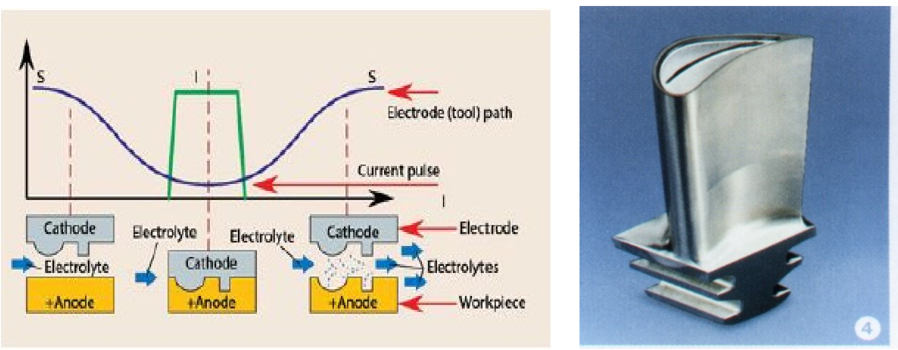
electrochemical machining utilizing a universal electrode (whittling, milling, drilling); in this case we avoid the excessive growth in temperature and volumetric concentration of hydrogen through reducing the machining area by reducing the surface of the electrode-tool and moving the electrode-tool along the properly designed trajectory. In such case the shape of the machined area is a reflection of the trajectory of the electrode-tool.

Practical examples of pressure chamber machining, pulse machining and machining utilizing a universal electrode shall be presented in the further part of this paper.

3. Practical applications of the ECM process

3.1. Practical applications of the ECM process

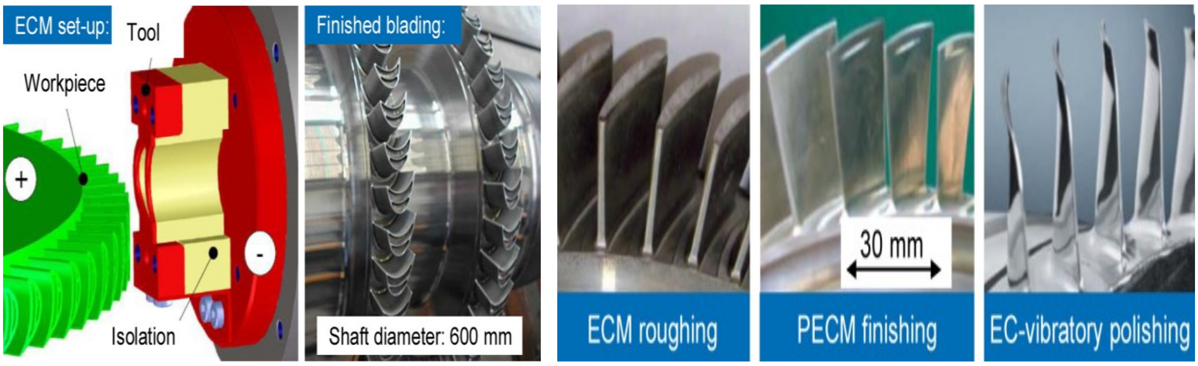
As it has been mentioned previously the electrochemical machining has been for many years utilized for machining matrices, casting molds and turbine blades for aviation turbine engines. Recently the scope of application of this method expands to precision machining of components made from specialized alloys. This industrial success is a result of application of pulse electrochemical machining. Pulse voltage and vibrations of the electrode-tool in the pressure chamber have been utilized (Figure 4a) (Dong et al., 2016; Klocke et al., 2013; Klocke et al., 2014; Kozak, 2018; Paczkowski, 2012; Ruszaj, 1999; Ruszaj et al., 2003; Ruszaj et al., 2005; Ruszaj, Czekaj et al., 2005; Ruszaj, Skoczypiec; Gawlik, 2016; Tang, Gan, 2014; Wijers, 2014). Pressure of the electrolyte at the outlet of the chamber was substantially higher than the atmospheric pressure. Due to this the flow of electrolyte was stable and volumetric concentration of hydrogen was lower than in classic conditions (without pressure chamber). Until now turbine blades for turbine engines were manufactured separately and attached to the turbine via a locking mechanism (Figure 4b). Recently the ECM process has been applied to manufacturing monolithic engine turbines (so called "blisks") (Figure 5).



a) b)

Figure 4. Diagram of precision pulse electrochemical machining (Figure 4a) and example of a typical electrochemically machined blade (Figure 4b – brochures of Kőppern company) – the lower part of the blade, the so called "lock", is used to fix a blade to a turbine

(source: Wijers, 2014)



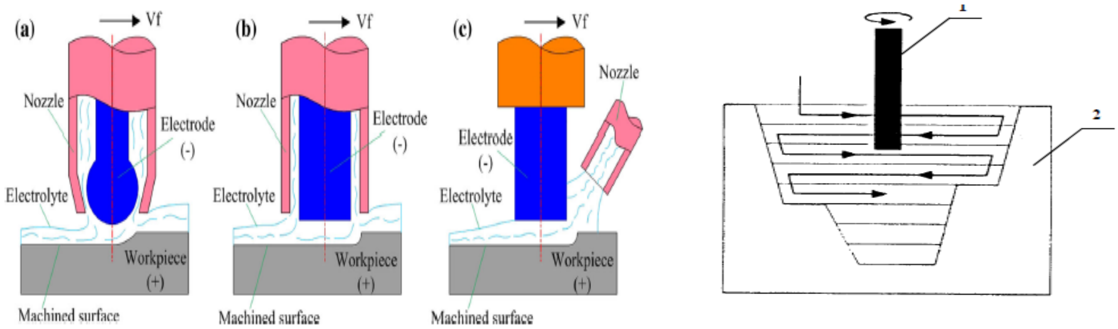
a) b)

Figure 5. A diagram of machining of blades in a monolithic "blisk" turbines constructed from ((X22CrMoV2111) material; (Figure 5a); manufacturing of blades takes place over three stages (Figure 5b) – classic rough machining, finishing pulse electrochemical machining and electrochemical vibratory polishing

(source: Klocke et al., 2014)

3.2. Electrochemical machining through use of universal electrodes

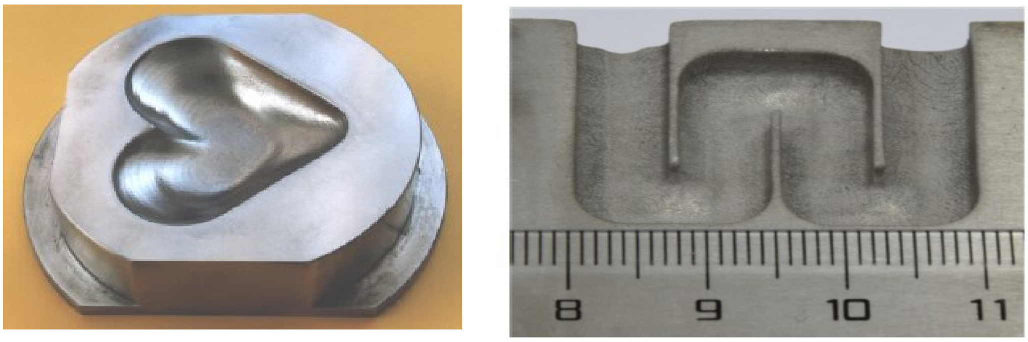
Electrochemical machining utilizing electrodes with a surface significantly smaller than the surface of the workpiece is being realized by using appropriately designed kinematics of the electrodes. In this case the same electrode can be used for machining surfaces with various shapes and dimensions. Examples of such electrodes are displayed in Figure 6a. The required shape and dimensions of the machined surface are produced through using proper kinematics of the electrode the examples of which are presented on Figure 6d. In order to achieve the proper shape of the machined surface in case of the ECM technique corrections to shape and dimensions of the electrode-tool are required – a very difficult task due to irregular distribution of the width of the inter-electrode gap. In the case presented in Figure 6 the shape of the workpiece is a reproduction of the trajectory of a universal electrode tool. Owing to the fact that there are no significant changes in physical properties of the electrolyte in the machining area this issue appears much easier from the perspective of mathematical modeling of the ECM process. However, this technique has one significant drawback – relatively low efficiency of machining; still, it finds its use in smoothing surfaces post rough machining or electrical discharge machining (Figure 6a), in machining of thin-walled elements (Figure 6b) and during machining of specialized micro-structures on the surfaces of workpieces (Figure 8) and machining of micro-components – the components with dimensions < 1 mm (Figure 9).



a) b)

Figure 6. ECM shaping principle utilizing universal electrodes (Figure 6a) and diagram of removing surplus material layer by layer (Figure 6b) [26]

(source: Hindua, Pattavanitch, 2016; Ruszaj, 1999)



a) b)

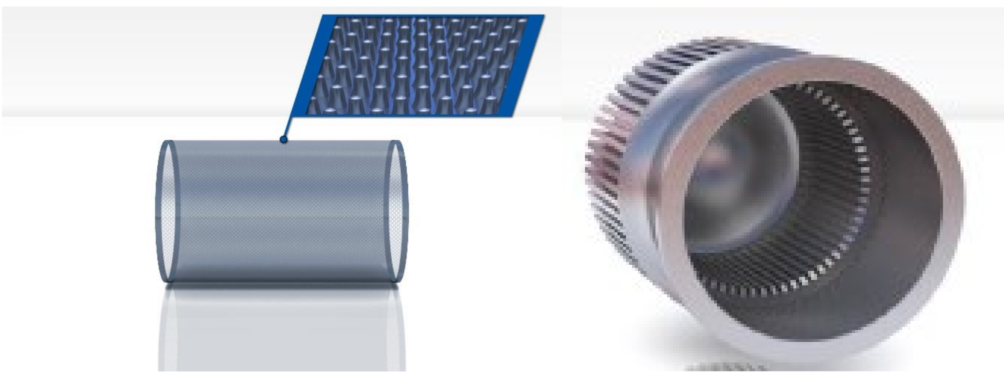
Figure 7. An example of a surface finished through electrochemical machining (Figure 7a) and an example of a thin-walled element (Figure 7b)

(source: Hindua, Pattavanitch, 2016; Niu, 2017, Ruszaj, 1999)

Surfaces displayed on figure (7a) were initially machined mechanically and then smoothed out electrochemically by using a spherical electrode with R = 9 mm, duration of ECM smoothing was 45 minutes, inter-electrode voltage: U = 16 V, rate of spherical electrode movement v_p = 42 mm/min, electrolyte – 15% water solution of $NaNO_3$, roughness of the surface post ECM smoothing was $R_a \approx 2$ µm (Ruszaj, 1999).

3.3. Electrochemical machining of micro-components

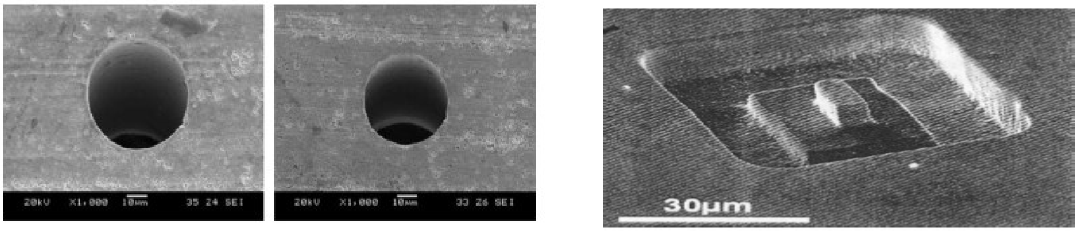
Manufacturing of micro-components, components with dimensions smaller than 1 mm, through ECM is realized in the following operations: machining (without electrode rotating), drilling (with a circular motion of the tool), milling (with the electrode performing a circular motion) and whittling (no circular motion of the electrode). Manufacturing of an electrode-tool (a cathode), often with dimensions significantly smaller than the workpiece, is a very important and difficult issue for micro-machining. The electrochemical wire-cutting technique is frequently utilized for manufacturing micro structures or micro-components. In each of the aforementioned operations width of the inter-electrode gap is very small and it is hard to dissipate heat and remove hydrogen from the gap effectively. Frequently the sole effective method for solving this problem is significantly reducing efficiency of the process. Below we present examples of surface micro structures and micro-components manufactured through an electrochemical process (Hoi, 2013; Schulze et al., 2010; Skoczypiec, Grabowski, Ruszaj, 2012; Skoczypiec, Ruszaj, Lipiec, 2010; Bhattacharyya, Munda, Malapati, 2004; Choi et al., 2013; Xianghe, 2016).



a) b)

Figure 8. A component – a tool for shaping a microstructure through surface layer forming process (Figure 8a) and a component (Figure 8b) manufactured from an Ni alloy with 90 internal ribs with thickness of ~600 µm

(source: http://electrochemicalmachining.com)



(a) (b) c)

Figure 9. A micro-hole drilled in a WC-Co alloy plate with a thickness of 200 μm; (a) diameter of the hole at the electrode insert point $\varphi = 48$ μm, b) diameter of the hole at the electrode exit point $\varphi = 42$ μm; the 0.5 M $NaNO_3$+ 0.2 M H_2SO_4 electrolyte has been used; pulse voltage with amplitude of 9 V; voltage pulse duration 100 ns, voltage oscillation period t = 1 μs, rate of movement of the electrode 0.1 μm/s., width of the inter-electrode gap S = 3-5 μm; a 3D structure (Figure 9c) created on a copper plate through milling with an electrode with a diameter of 10 μm, through use of pulse voltage with 1.6 V amplitude, pulse duration 50 ns, pulse frequency 2MH, the column in the central part has dimensions of 5 x10 x 12 μm (source: Bhattacharyya, Munda, Malapati, 2004; Choi et al., 2013)

4. Conclusions

Contactless electrochemical machining is a method of shaping material in the smallest possible increments, i.e. atom by atom. In contact with the electrolyte the atoms of the machined workpiece undergo ionization and, subsequently, diffuse under the influence of force of electrical field into the inter-electrode gap where they participate in electrochemical reactions. Thus mechanical forces do not participate in removal of surplus material and the temperature in the area of machining does not exceed 100ºC. Therefore the properties of the surface layer of the workpiece do not change and remain consistent with the original material (Oczoś, Lubimov, 2003). The operation used most frequently for machining kokil matrices, molds or blades for turbine engines is electrochemical machining in which shape of the workpiece is produced as a reproduction of the shape of the electrode tool. Thus the dimensions of the electrode-tool must be corrected by the value of thickness of the inter-electrode gap. It is a difficult and time-consuming task. However, it must be emphasized that in properly adjusted conditions the electrode-tool is not wearing-out. Thus it is possible to machine multiple copies of a component using a single set of tools. Stability of the machining process can be increased by realizing the process in a pressure chamber, providing pulse voltage power supply to the gap and utilizing vibrating motion of the electrode. Such variant of machining is called pulse electrochemical machining. In this variant a significant increase in dimensional accuracy and improved quality of the surface layer are achieved at the expense of decreasing efficiency of machining. A very effective measure for avoiding increase in temperature and volumetric concentration of hydrogen is reducing the surface of the electrode-tool, i.e. utilizing universal electrodes (e.g. spherical). In this case shape of the workpiece is achieved through reproducing trajectory of the electrode – it is possible to machine workpieces of different shapes and dimensions using the same electrode-tool. Owing to the fact that in the considered example efficiency of machining is low this variant of machining is utilized to smooth out surface of macro-details or to form micro-components.

Owing to the merits of electrochemical machining indicated herein the scope of its application is dynamically expanding in the field of manufacturing of macro, mezo and micro-components for space, aviation, military and car industries.

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