Electrochemical Methods of Micropart's Manufacturing

Sebastian Skoczypiec

Abstract This chapter introduces basics of electrochemical micromachining (ECMM). In this process, no mechanical contact between tool and workpiece occurs, and machinability is not connected with material mechanical properties, and therefore, it is an attractive technology, especially when shaping 3-D sculptured surfaces in difficult-to-cut materials. However, the key problem in ECMM is to localize dissolution to achieve satisfactory accuracy. In this chapter, specificity of electrochemical micromachining and recent trends in this area are presented. The conditions of electrochemical dissolution are discussed, and the possibilities of shaping accuracy increase are indicated in details. The special attention is paid to the results of application of voltage pulses and integration with other technologies in hybrid and sequential machining.

Keywords Electrochemical · Electrodischarge · Hybrid machining · Laser · Micromachining

Electrochemical machining (ECM) is an anodic electrochemical dissolution process in which material is removed by electrochemical dissolution when applying constant or pulse voltage between tool (cathode) and workpiece (anode) [1]. Through the thin gap (<<0.5 mm) between tool and workpiece, an electrolyte flows. Due to the presence of electrolyte in interelectrode gap, the electric charge is transported by ions, whereas by electrons in outer circuit. The electrochemical reactions on the electrode–electrolyte borders are mainly responsible for the change of conduction from electronic to ionic. One of these reactions is dissolution of workpiece material, which takes place according to Faraday's law. The dissolved material and other electrochemical reaction products are transported outside the gap by forced flow of the electrolyte.

S. Skoczypiec (✉)
Institute of Production Engineering, Faculty of Mechanical Engineering,
Cracow University of Technology, al. Jana Pawła II 37, 31-864 Kraków, Poland
e-mail: skoczypiec@mech.pk.edu.pl

K. Gupta (ed.), *Micro and Precision Manufacturing*, Engineering Materials,
https://doi.org/10.1007/978-3-319-68801-5_2

Since the fifties of the last century, ECM has been becoming an effective method for producing a wide variety of parts for the defense, aerospace, automotive, and medical industries. As regards to the micromachining application, the following advantages of this process can be mentioned: (i) no tool wear, (ii) high productivity, (iii) excellent surface quality. Therefore, recent advances in machining accuracy and precision prove that ECM becomes an attractive technology for precise micromachining. However, in order to make ECM suitable for such application, it is necessary to develop modified machining system which should provide high localized machining with gap width below 100 μm.

1 Specificity of Electrochemical Micromachining (ECMM)

Microfabrication through electrochemical action includes cathodic processes (i.e., electrodeposition, electroplating, electroforming, through-mask electroplating), anodic processes (i.e., electrochemical micromachining, electroetching, electropolishing), or open circuit processes (chemical polishing, chemical milling, chemical etching). Majority of these technologies are adapted to manufacture planar (2-D) structures, and only electrochemical micromachining (ECMM) is suitable for manufacturing 3-D complex surfaces. In ECMM, the allowance can be removed by tool shape reproduction in the machined surface (referred as electrochemical sinking, Fig. 1a) [2]. The major problem in sinking is to design and produce electrode tool with sophisticated shape. The electrode preparation cost is high, and

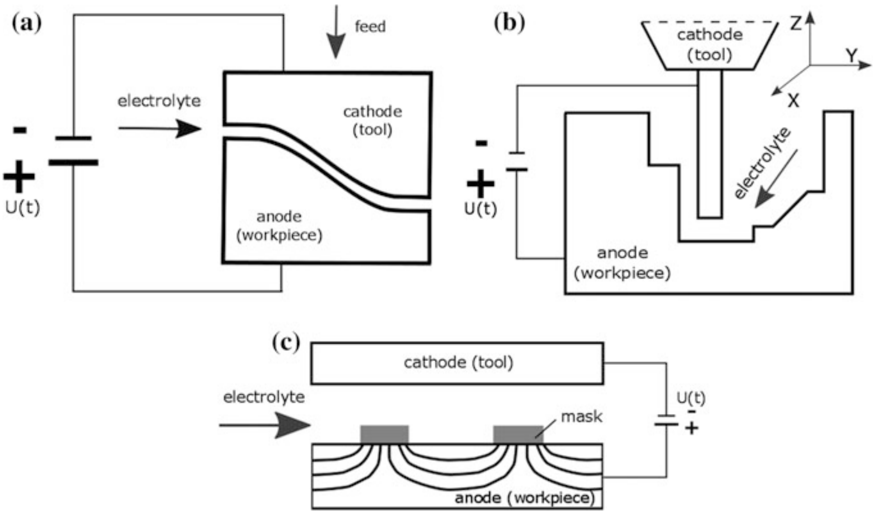

Fig. 1 Variants of electrochemical micromachining: **a** sinking, **b** machining with universal electrode tool, and **c** through-mask electrochemical micromachining

problem with effective gap flushing occurs; therefore, the range of dimensions is limited (machined area is in range of mm^2). Therefore, in micromachining dominate operations where simple electrode tool (i.e., cylindrical with spherical or flat or tip, wire) can be applied [3, 4]. In this case, the machined shape results from the electrode tool path (similar to milling, Fig. 1b). It is also worth to mention about through-mask electrochemical micromachining (TMEMM), which was developed especially to generate the microdimple array with controlled shape and density (Fig. 1b). This process also includes masking to produce insulation layer or protect selected areas of workpiece from dissolution [5].

Application of the ECMM is related to top-down machining philosophy. It means that in order to produce smaller parts, production system which is commonly used in macromanufacturing, is applied after suitable modifications. These modifications relate to machining resolution increase and machine tools and tooling precision improvement. Figure 2 presents various important factors responsible for making ECMM suitable for micromanufacturing. Machining resolution is closely related to unit removal, which can be defined as a part of the workpiece removed during one cycle of removal action. Unit removal gives information about the smallest adjustable dimensions of the part, so unit removal of sub-micrometer range is necessary when the micropart is machined or when high precision of the part is required. Theoretically, in ECMM, the smallest unit removal is ion; however, the anodic dissolution is always connected with disadvantageous effect of widening the machining area on the distance significantly higher than working electrode diameter and interelectrode gap (Fig. 3). This is called as a delocalization effect, and the

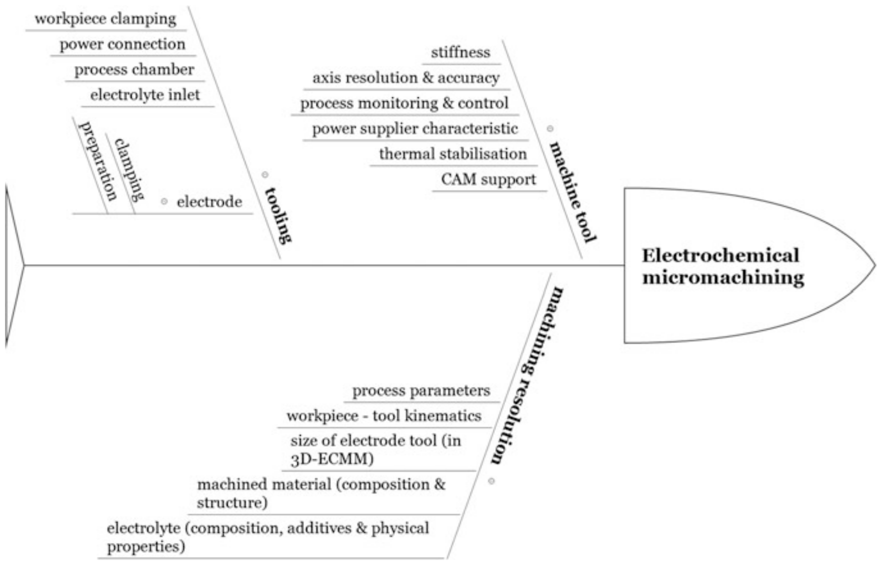

Fig. 2 Various factors of electrochemical micromachining responsible for its successful adoption to micromanufacturing

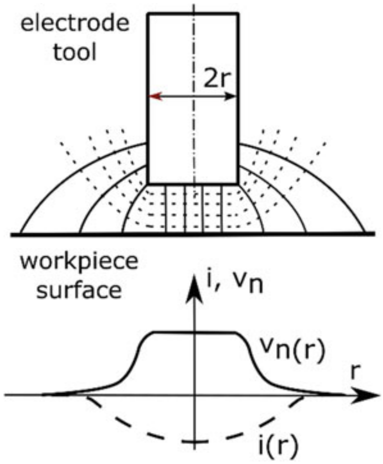

Fig. 3 Scheme of the machining area with electrical field distribution and corresponding distribution of current density i and dissolution velocity v_n

distribution of electric field in machining area is responsible for this phenomenon. Therefore, the dissolution should be controlled and limited only to specific workpiece areas. Minimization of unit removal is not enough to scale down the ECM process. It also requires adaptation of appropriate machine tools and tooling.

Recent research trends in the field of ECMM are focused around selection of optimal condition of dissolution under the small gap (<100 μm). These include especially [6]: (i) clarification of the phenomena during dissolution, (ii) modification of (resulting from primary electrical potential distribution) distribution of current density on workpiece surface, (iii) selection of proper electrolyte (composition, concentration, and additives), (iv) design of technological process (design of electrode tool shape or path, simulation of machining), (v) modification and development of machine tool (including also power supplier and technological tooling), (vi) control of the machining process (controlling the gap thickness and preventing the critical states), (vii) introduction of additional energy sources into area of dissolution to improve material machinability or machining conditions, (viii) integration with other technologies in sequential or complete machining process.

2 Localization of Electrochemical Dissolution

Dissolution localization can be defined as possibility to concentrate energy needed to remove material in relation to machined surface. The localization is narrower term than machining accuracy and can be identified with unit removal. High dissolution localization is prerequisite for high process resolution and accuracy; however, it is not sufficient. Localization is strictly connected with current density distribution over the machined surface. Taking into account simple case presented in Fig. 3, one can observe that there is some distance from the electrode tool edge where dissolution occurs. Although current density decreases with distance from electrode, its value is large enough to dissolve distant material. To achieve high localized process, this effect has to be minimized.

Localization of electrochemical dissolution can be quantified by localization factor, which is calculated based on relation between dissolution velocity v_n and interelectrode gap thickness S. In good localized process, the curve $v_n(S)$ should be as steep as possible, so the material removal rate decreases sharply with gap thickness increase. For ideal process (curve 1 on Fig. 4), following relation takes place:

$$\frac{v_{n1}}{v_{n2}} = \frac{S_2}{S_1}$$

While high localized process should be characterized by steeper $v_n(S)$ relation (curve 2 on Fig. 4) which can be described by equation:

$$\frac{v_{n1}}{v_{n2}} = \left(\frac{S_2}{S_1}\right)^n$$

and n can be defined as localization factor. n = 1 for ideal process and to localize the dissolution, n should be as high as possible. Additionally in a good localized process, the gap thickness threshold S_L should occur (for $S > S_L$, there is no dissolution).

In recent years, several studies were carried out aimed to modify the primary current density distribution for increase in ECM localization and accuracy. The major ways include (Fig. 5):

- **decrease of interelectrode gap thickness**: accuracy is inversely proportional to interelectrode gap thickness; therefore, one of the main directions of development is to carry the process with as small as possible interelectrode gap with as high as possible technological reliability,

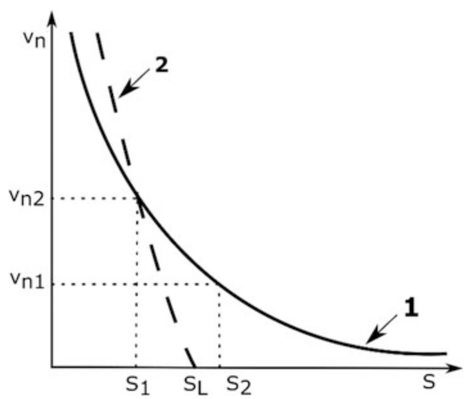

Fig. 4 Relation of dissolution velocity $v_n(S)$ from interelectrode gap thickness S; S_L limiting gap thickness

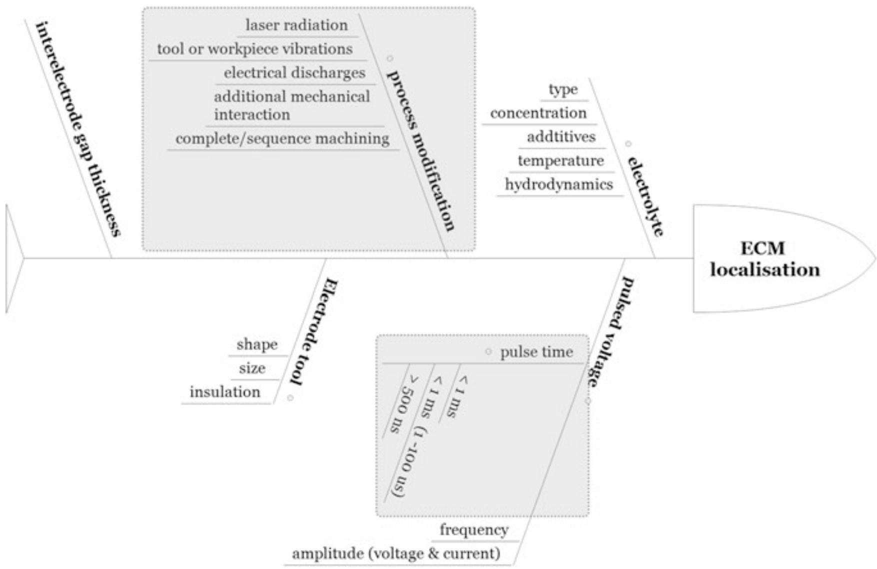

Fig. 5 Various factors responsible for improvement in anodic dissolution localization in the ECMM

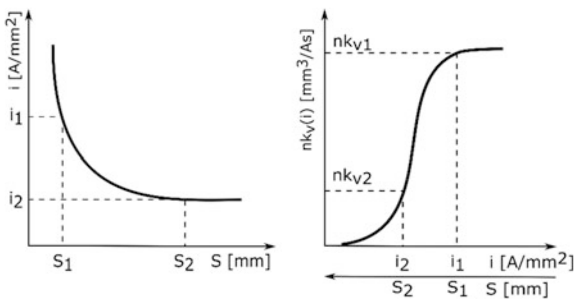

Fig. 6 Schematic relations between gap thickness *S* and current density *i* (left) and between current density *i* and electrochemical machinability ηk_v for passive electrolyte (right)

- **selection of proper electrolyte:** it gives possibility to obtain hyperbolic tangent-like relation between electrochemical machinability and current density (Fig. 6). This relation depends mainly on electrolyte properties (understood as its type and those resulting from the process). In ECMM application of passive electrolytes, for which lower limit of current density occurs (for $i < i_0$ no dissolution takes place) is preferred,
- **machining in electrolyte—gas mixture:** supply into the gap homogeneous mixture of electrolyte and gas (air, nitrogen, or carbon dioxide) allows to limit dissolution in areas where gap thickness is higher than assumed (in this area, gas expands to bubbles and electrolyte conductivity significantly decreases),
- **electrode tool insulation or special design:** in order to protect from dissolution distant areas of workpiece, which should not be machined, selected areas of the

electrode tool are coated with insulation layer (epoxy resin, ceramics, DLC or Teflon). In some cases, it is also possible to modify shape of electrode tool in order to concentrate dissolution in selected area (i.e., application of disk-like electrodes for hole drilling and groves machining or shaping of 3-D structures),

- **application of pulse voltage**: depending on pulse length, it gives possibility to: (i) increase process reliability (millisecond pulses), (ii) the use of electrolyte temperature increase (microsecond pulses), or (iii) use of transient phenomena (nanosecond pulses) to localize dissolution,
- **assistance of additional energy sources (hybrid machining)** or **integration with other technologies**: in complete or sequence machining.

From above-presented solutions, the most promising are application of voltage pulses and integration with other technologies/energy sources in complete or hybrid machining process. Sections 3 and 4 present the recent developments in this area.

3 Pulse Electrochemical Micromachining (PECMM)

Based on the duration of pulse time $t_{i,}$ the pulse electrochemical micromachining (PECMM) can be classified into three variants: (i) with pulse time 500 ms > t_i > *1* ms; (ii) with pulse time t_i < 1 ms (usually t_i in range 1–100 µs); (iii) with pulse time t_i < 500 ns. In the first two variants, the machining is carried out in a diffusion limited state, which generally means that the physical properties of the electrolyte in the gap determine distribution of electric current density *i*. In such case, *i* is mainly dependent on diffusion rate. While in PECMM with nanosecond voltage pulses, current density *i* is determined by activation overpotential.

3.1 Millisecond and Microsecond Pulse Electrochemical Micromachining

Accuracy of electrochemical machining increases with machining gap decrease. However, to carry out stable machining process with small gap thickness is difficult. In such case, increase of electrolyte temperature and contamination is significant; therefore, critical conditions (i.e., electrical discharges) can easily occur in the gap. Therefore, application of millisecond range voltage pulses (ms-PECMM) gives possibility to interrupt the dissolution process and refill the gap with fresh electrolyte. Additionally, in ms-PECMM: (i) reduction of the electrolyte properties that change along the gap reduces the impact of changes of electrolyte conductivity on shape errors; (ii) amount of hydrodynamics defects on workpiece surface decrease (smaller gap reduces electrolyte flow velocity). These give possibility to increase dissolution reliability under small gap condition; however, additional effect of dissolution localization does not take place. ms-PECMM enables precise machining

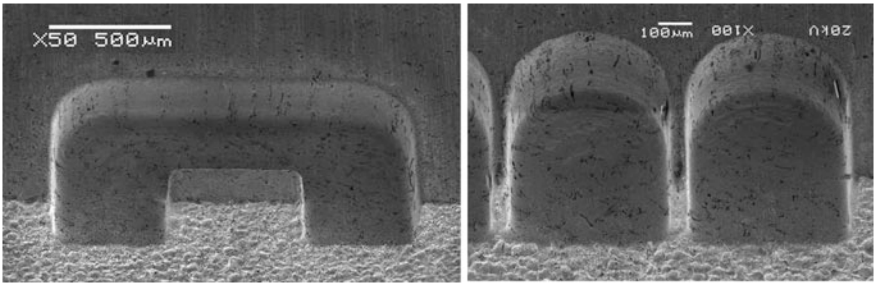

Fig. 7 Example of µs-PECM applications: microstructures machined in milling kinematics with following parameters: pulse time t_i = 1 µs, pause time t_p = 10 µs, pulse voltage U = 20 V, electrolyte 1% $NaNO_3$, electrode feed rate v_p = 50 µm/min, electrode rotation speed 500 1/min, electrode diameter D = 0.4 mm

with gap thickness of about 0.01–0.1 mm (in ECM, typical gap is in range of 0.1–1 mm).

A further reduction of the pulse time to the microsecond range (µs-PECMM) improves whole above-mentioned effects connected with dissolution homogeneity and reliability. However, in µs-PECMM, the gap thickness is smaller, and the electrolyte temperature increases more intensively. It is the reason of more intense electrolyte conductivity increase, and therefore, machining is carried out with higher current density *i*. Therefore, according to the relation between current density and electrochemical machinability in areas with smaller gaps, dissolution is more efficient (Fig. 6) and relation $v_n(S)$ is steeper. The key for µs-PECMM is avoiding electrolyte boiling in the gap; therefore, pulse length is limited by critical pulse time, which should be calculated based on thermal limitation in the gap [7]. µs-PECMM can be adopted for micropart and precision and manufacturing (see example in Fig. 7), and the limits of adaptation are defined by critical conditions in the gap. To ensure stable dissolution process, efficient gap flushing is necessary. It can be achieved electrically (by applying adequately long pulse pause) or mechanically (by applying pulse electrode tool vibration). When conditions of dissolution are optimal, the accuracy of µs-PECM can reach 5 µm.

3.2 *Nanosecond Pulse Electrochemical Micromachining (Ns-PECMM)*

The idea of nanosecond pulse electrochemical machining was developed in the end of the last century [8]. In ns-PECMM, the dissolution process is driven by the cyclic electric double layer (EDL) charging and discharging process. In workpiece areas where EDL charge reaches the activation overpotential, the dissolution starts. However, the time of EDL charging to the activation overpotential is a function of gap thickness; therefore, pulse time determines maximal distance between tool and workpiece where dissolution occurs. When machining is carried out with a longer pulse time ($t_i > 0.5$ μs), the EDL is charged uniformly over the machining surface (dissolution is determined by diffusion); therefore, trainset effect connected with cyclic EDL charging and discharging is negligible. In ns-PECMM, due to extremely short pulse time, dissolution is carried out in accordance with Butler–Volmer equation, which exponentially relates current density i and overpotential. It means that large change of the current density is caused by a small change of the electrode potential. Due this effect, dissolution localization is also improved [9, 10].

The high capabilities of ns-PECMM have been identified in the research conducted. For example, 1.4301 steel can be machined with lateral gap ≈200 nm what gives possibility to obtain edge radius ≈1 μm [11]. The workpiece in ns-PECMM can be machined with many kinematic variants as hole drilling or sinking [12–14], with application of universal electrode tool [3, 15, 16], or in kinematic similar to wire cutting [4, 17]. However, it is worth to underline that majority of work presented in literature results of successive ns-PECMM application were obtained in laboratories, and this technology is not popular in the industry. The problems of commercialization are connected with difficulties in upscaling the process [18]. In ns-PECMM, the increase of electrode tool area is limited by reactance of the power supply circuit, what limits charging rate of EDL. In such case, achieving the activation overpotential requires increase of the pulse time $t_{i,}$ what results in change to diffusion limited process (and process characteristic like μs-PECMM). Machining of areas in range of 1 mm^2 by ns-PECMM needs application of high current pulse power suppliers and careful selection of type and doping of electrolyte. Therefore, ns-PECMM is most effective with application of universal electrode tool with pin, conical, cylindrical, or disk-like tip and diameter less than 100 μm. The area of ns-PECMM application small series or single production of prototypes and tools with 3-D shapes is suggested. However, machining results depends from tool size, workpiece material composition and heterogeneity of the structure. Therefore necessity to precise choice of the electrolyte composition and its additives for each machining material significantly limits flexibility of this method.

4 Electrochemical Machining Integration with Other Technologies

Integrated or hybrid machining technologies are latest research topics these days. Hybrid machine tools are based on the combination of different manufacturing technologies in single workstation to obtain high-quality product [19]. Hybridization results in decrease in machining time, reduction in machining cost, and part quality enhancement, while reasons for developing hybrid machining processes (HMP) are to exploit their advantages together and to avoid their limitations when they are applied individually [20].

4.1 Hybrid Electrochemical Micromachining Processes

4.1.1 Electrochemical and Mechanical Interaction

The idea of combining electrochemical and mechanical interaction for efficient material removal was developed in the 1960s in the form of the electrochemical grinding (AECG). In AECG, a metal bonded abrasive tool is used as a cathode, and thus, the simultaneous mechanical and electrochemical material removal takes place. Zhu et al. [21] present an example of successful application of grinding and electrochemical removal in the micromachining domain (precise machining of small holes). They applied abrasive coated metal rod as a cathode tool to remove the material in pre-machined pilot hole. Depending on the machining parameters (like machining voltage, cathode rotation speed, and feed rate), the way of material removal can be balanced between mechanical and electrochemical. In this process, small holes of diameter down to 0.6 mm with sharp edges and without burrs were drilled.

An example of effective combination of electrochemical and mechanical energy to remove material electrochemically assisted microturning process is mentioned [22]. In this case, electrochemical assistance changes the machinability while the microcutting directly removes the material (Fig. 8). Produced in electrochemical reaction oxide layer has different mechanical properties than machined metal and can be removed with reduced cutting force. Research presented in [22] shows that electrochemical assistance of microturning decreases the average cutting force from a few to tens percent. In addition, surface machined with electrochemical assistance indicates decrease of plowing effect what leads to surface quality improvement (Fig. 9). This method can be applied to machine only passivating materials such as stainless steel, aluminum or titanium alloys. It is also worth emphasizing that electrochemical assistance gives benefits when the depth-of-cut is ≤ 1 μm.

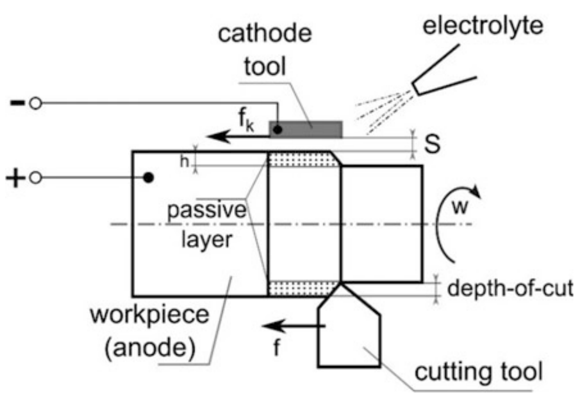

Fig. 8 Scheme of electrochemically assisted microturning process: *S*—interelectrode gap, *h*—passive layer thickness, *f*—cutting tool feed rate, f_k—cathode feed rate (*fk* = *f*), *w*—rotational speed [22]

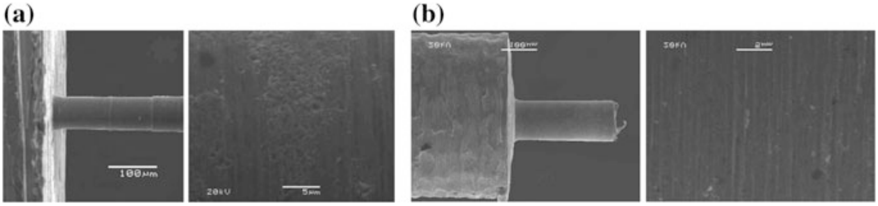

Fig. 9 SEM images of the shaft surface after microturning without (**a**) and with electrochemical assistance (**b**); machined material: 1.4301 steel, depth-of-cut 1 μm, $f = f_k$ = 0,02 μm/s, w = 60,000 1/min, U = 3 V, electrolyte 1% $NaNO_3$ [22]

4.1.2 Electrochemical Machining Supported by Electrode Vibrations

Application of the combination of synchronized low-frequency pulsed voltage and the oscillating electrode enables machining with reduced working gaps (in range 10–50 μm) and significantly higher current densities. When minimum gap thickness is achieved, voltage is switched on for period from 500 to 5000 μs (depends on application), which lead to removal process; however, due to small gap, only low amount of electrolyte is transported through machining area. While during pulse pauses, when the distance between anode and cathode is maximized, excellent supply of electrolyte takes place, and the waste electrolyte is replaced with the fresh one. Oscillation movement of electrode tool is superimposed by its forward movement. It is worth to underline that in this process, high amount of time is used for gap flushing; therefore, material removal rate is reduced in comparison to ECM. Due to high localization, vibration-assisted PECMM is applied for the manufacturing of complex microstructures or precise machining of cutting tools or structured metal parts (i.e., razor shave cabs).

In [23, 24], authors proposed application of low amplitude (5 μm or less) and low frequency (tens or hundreds Hz) of vibration of tool to improve the flow of electrolyte during machining of high-ratio microstructures. Research was carried with application of MHz range pulse voltage frequency with no synchronization between tool periodical movement and electrical signal. Obtained results prove that tool vibration gives possibility to increase mass transport in the gap, improve stability of micromachining due to improved flow of electrolyte, and lead to material removal rate increase. The same authors also proposed application of low amplitude tool vibration to improve shape accuracy of borehole [25]. Also in this case, current density increases and additional effect of borehole quality improvement occurs (more cylindrical, lesser overcut, and better surface finish). Authors conclude also that amplitude of vibrations can be used as parameters to adjust borehole taper angle.

The other proposition is to apply vibration in ultrasonic frequency range. According to [26], it can be mentioned that ultrasonic vibration (i) improves products removal from the gap, (ii) supports diffusion, (iii) decreases the rate of passivation, (iv) changes electrochemical machinability, and (v) improves hydrodynamic condition. Whole this effects permits machining with high current density. Young et al. [27] applied ultrasonic vibrations with frequency of 40 kHz and an amplitude of 4 μm straight to the electrolyte volume. Such a solution is simpler to design and to control than to apply vibration to the workpiece or tool. They drilled microholes with diameter less than 100 μm and depth up to 300 μm with ns-PECMM setup, which was not available for machining without ultrasonic vibrations. Decrease of machining time leads also to decrease diameter at entrance, and thus, machining precision was also improved.

4.1.3 Electrochemical–Electrodischarge Machining

Discussing electrochemical–electrodischarge machining, it should be pointed that in the literature, this term is connected with two different hybrid machining methods. The first one is also referred as spark-assisted electrochemical machining (SAEM) [28, 29]. In SAEM, electrochemical reactions between electrode tool and auxiliary electrode cause the formation of hydrogen gas film around electrode tool, and it is a medium wherein arc discharges take place. It leads to remove material by combined mechanism of local heating and chemical etching. It is an emerging micromachining process especially preferred to fabricate microchannels, grooves, holes, and 3-D complex shapes on nonconductive materials like glass, ceramics, or quartz. It is worth to underline that in SAEM process, electrochemical reactions only create conditions for material removal; however, they are not used directly to remove material.

Electrochemical–electrodischarge machining (ECDM) involves combination of electrochemical reactions and electrical discharges to remove material. In this process, depending on the machining parameters (gap thickness, voltage, current density, and pulse on/off time), the material is removed by electrochemical dissolution or simultaneous electrochemical dissolution and electrical discharges. The share of discharges in the removal process is directly connected with the intensity of the electrochemical reactions. When the electrochemical process is carried out close to critical state, the electric current flow generates Joule heating, the electrolyte begins to boil and evaporate, and gas–vapor layer is created near in the gap. Finally, electric discharges occur, and the material is removed in a typical way for the EDM process. The electrical erosion is localized in areas of the workpiece where the current density is higher than the critical value (it depends on gap thickness) and for the rest of the surface, the metal dissolves electrochemically. The benefits of this process are a significant increase of the material removal rate in comparison to ECM and EDM, respectively, and decrease of tool wear in comparison to EDM. Electrochemical discharge machining can be used in different kinematic variants, although hole drilling and die sinking are preferred [30].

4.1.4 Jet-Assisted Electrochemical Machining

In Jet-ECM, the cathode tool is created by small nozzle which ejects electrolyte with high pressure (jet velocity in range of tens of m/s). The jet has well-defined geometrical shape (which can be treated as a tool), which hits the workpiece in perpendicular direction to its surface. In this process, the dissolution is restricted to limited area of the jet and high current densities, local material removal and high localization is achieved [31, 32]. In some application, to form closed electrolytic jet, this process is assisted by surrounding air [33], or to enhance material removal, electrolyte-guided laser beam is applied [34]. Due to excellent supply of fresh electrolyte and efficient removal of dissolution products in Jet-ECM, continuous voltage can be used. Jet-ECM allows to machine microstructured planar surfaces and complex three-dimensional shapes by changing position of nozzle and adjusting electric current.

4.1.5 Laser-Assisted Electrochemical Machining

The combination of the laser radiation and electrochemical impact on the machined material can be applied as combined process (see next paragraph) and as a hybrid machining process. The anodic dissolution begins, when the energy of the metal ions become higher than the desired reaction activation energy E_a. This energy is determined by the electrical potential and surface temperature. At a higher temperature, there is a greater proportion of electroactive ions with the energy $E \geq E_a$; therefore, changing the surface temperature leads to increase of current density on the workpiece–electrolyte interface. This effect is described by exponential Arrhenius equation, so increase of workpiece surface temperature results in several time current density increase (Fig. 10) [35]; therefore, the selective workpiece heating gives possibility to localize the dissolution. According to [36], the best choice for workpiece surface heating in ECM is green laser with wavelength in range 470–560 nm.

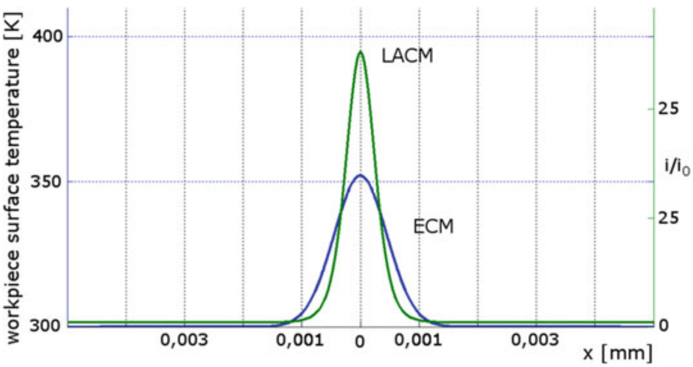

Fig. 10 Effect of workpiece surface temperature increases on current increase, ΔT = 60 K, laser beam waist w_0 = 1.8 mm (i_0—current density during electrochemical process without heating, i—current density during electrochemical process thermally enhanced)

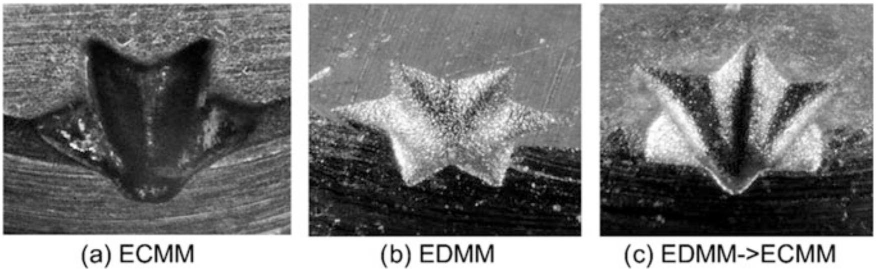

Fig. 11 Photographs of cavities machined during: **a** electrochemical sinking, **b** electrodischarge sinking, and **c** sinking when using the EC/EDMM sequence [42]

In case of material removal, the most effective solution is application of electrolyte jet-guided laser beam. After using effective solution, De Silva et al. [34] found higher material removal rate in axial rather than in lateral direction with improvement in dimensional precision. In addition to the localization effect, the laser beam favors surface depassivation, what improve machining of passivating materials like titanium, aluminum alloys, or stainless steel. Application of laser assistance improves material removal rate for these materials up to 50% and improves shape accuracy (noticeable reduction of overcut occurs).

Due to much higher activation energy, the most promising is introduction of the laser beam in the electrochemical deposition process. In this case, laser assistance results in almost a thousand times increase of deposition velocity. Typical example of such effective laser application is described in [37]. The copper anode is immersed in mixture of $CuSO_4$, H_2SO_4, and HCl with 5 mm distance from cathode surface. The interelectrode voltage value is set slightly below the copper deposition border, and then the workpiece surface has been selectively heated with application of DPSS green laser. In these areas, the copper deposition occurs (layer thickness about 10 μm).

The potential application of laser-enhanced electrochemical machining is workpiece surface structuring, especially for biomedical and bearing applications. With laser-enhanced ECM, fabricate series of micrometer-sized cavities of different size, shape, and separation distance is possible, that can be useful for the changes of such surfaces' functional properties.

4.2 Sequential Electrochemical Micromachining Processes

4.2.1 Laser and Electrochemical Processing Sequence

In sequential integration of laser and electrochemical machining, the laser is used for positive or negative workpiece surface masking. The process is carried out in similar way to the lithographic one, but instead of series of chemical treatments, the laser radiation is applied. In positive masking, it takes place in four steps: anodizing, laser masking, electrochemical dissolution, and ultrasonic cleaning [37, 38]. In negative masking, as the result of the laser impact, thin layer of nonconductive oxides (Cr_2O_3, FeO, and Fe_2O_3) and some structural changes on the workpiece surface occur [40, 41]. These areas are characterized by significantly lower electrical conductivity, and therefore, ratio of electrochemical dissolution is smaller in comparison to native material. Thanks to fiber optics, and technological equipment positive laser masking and electrochemical dissolution can be carried out on the same machine tool. Over lithographic methods, this process has following advantages, i.e., relatively inexpensive way of mask registration (masking takes place in air, no major requirement for room cleanliness), environment-friendly processing (significantly less chemical agents), and greater process flexibility (the process is more effective in short and prototype series). But the main disadvantage compared to lithography is relative long time of mask registration (tens of minutes).

4.2.2 Sequential Electrochemical—Electro Discharge Processes

The characteristics of electrochemical and electrodischarge micromachining as presented in [42] indicate the number of essential complementary advantages and many similarities between both processes. Therefore, in the recent years, many ways of electrochemical and electrodischarge machining combinations in one sequence have been proposed. The presented research has been focused on applying electrochemical treatment to improve the surface layer quality of EDM-ed microparts [43–47]. These ideas include the realization of processes in sequence on the same machine tool and with the same electrode, although the differences concern power supply and the working fluids medium system. In [43], the milling kinematic sequence was carried out with the application of different working fluids and independent power suppliers for EDMM and ECMM. For such system, the removal of 13 μm allowance thickness during ECM finishing gives the possibility of decreasing EDM-shaped surface roughness from Ra = 0.707 μm to 0.143 μm. In addition, the recast layer, burrs, craters, and micropores are removed. The results as presented in [44] also show that correct drilling sequence design allows machining efficiency to be improved by 9.2 times with simultaneous improvement of hole precision and shape accuracy. The other approach is to apply the same machining liquid (partially deionized water) and the same power suppliers. In such case, nature of machining (ECMM or EDMM) results from the appropriate process control (change from EDMM to ECMM can be achieved by the decrease of power supply capacitance and electrode feed rate [46]). Such strategy gives the possibility to improve Ra from 1 to 0.6 μm in sinking and from 0.9 to 0.2 μm in ECMM followed by EDMM milling operation. In literature, EDMM and ECMM were also carried out with the same pulse voltage signal (voltage amplitude 60 V, frequency 500 kHz, and duty factor in range 0.25–0.4) [47]. The developed control strategy is based on an electrode tool feed rate which ranges from 50 to 10 μm/s. In the case of 50 μm/s, the electrical discharges dominate in material removal mechanism due to small interelectrode gap, while reducing the feed rate to 10 µm/s promotes material dissolution and reduces the surface roughness to Ra = 0.022 µm. In sequence EDMM followed by ECMM, one disadvantage is a decrease in accuracy and edge rounding during the ECMM finishing in comparison to the part machined by EDMM. To minimize this effect, an application of 704-silica side-insulation electrode tool was proposed in milling operation [44]. This gave the possibility of minimizing hydrogen bubble generation on the electrode sidewall and allowed to obtain uniform side-machining gap.

Carrying out ECMM followed by EDMM on the same machine tool allows for an essential reduction of the disadvantages and enhances the advantages of both methods [42]. Application of the ECMM -> EDMM sequence allows for an almost double decrease in the machining time in comparison to EDMM (Fig. 12a). Additionally, the mean edge radius of cavities is significantly smaller than that in ECMM (Fig. 12b). It is also worth to underline that the thickness of allowance machined in EDMM phase is only 100 µm; therefore, the effect of tool wear on the cavity shape is negligible (Fig. 13).

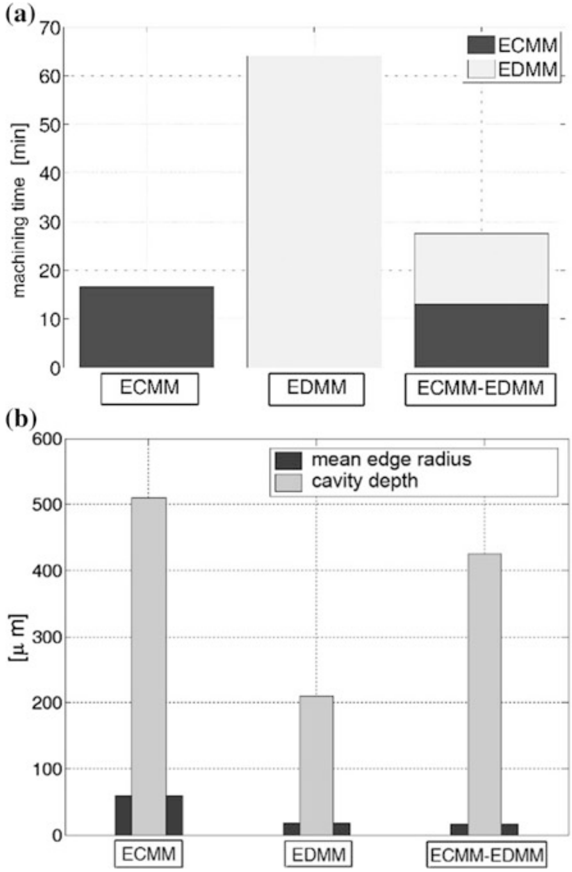

Fig. 12 Comparison of machining time (**a**) and mean edge radius and cavity depth (**b**) for the ECM, EDM, and ECMM followed by EDMM sequence (machining results presented in Fig. 11) [42]

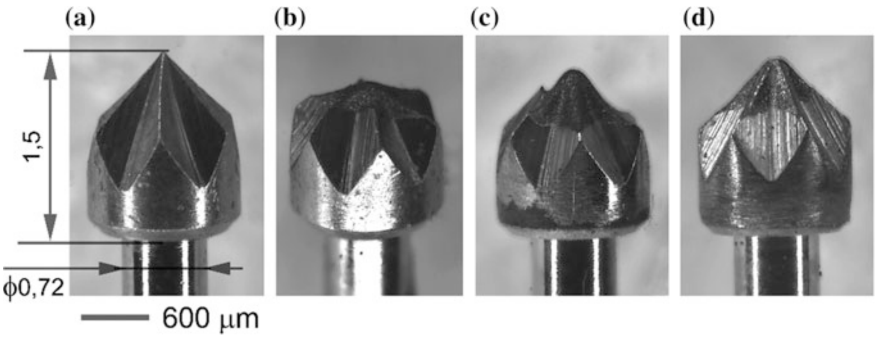

Fig. 13 Photographs of the electrode tool after: **a** ECMM, **b** EDMM, **c** an improperly designed EC/EDMM machining sequence, and **d** a properly designed EC/EDMM machining sequence of the cavity presented in Fig. 12 [42]

5 Summary

In this chapter, specificity of electrochemical micromachining and recent trends in this area are addressed. The special attention was paid to developments and limitations connected with shaping accuracy increase. In this area, the most promising are (i) application of voltage pulses (in range of milli-, micro-, and nanoseconds) and (ii) integration with other technologies/energy sources in complete or hybrid machining process. In both of these areas, significant progress in recent years has been observed that makes ECM a very attractive micromachining technology. The preferred application areas for electrochemical micromachining include: (i) machining of microholes with circular or polygonal cross section; (ii) surface structuring to improve structural and tribological properties of parts for medical applications, bearing, or tooling industry; (iii) manufacturing of 3-D structures, tools, (i.e., micromolds), parts of technological tooling, and prototypes of MEMS parts.

References

1. Davydov AD, Volgin VM, Lyubimov VV (2004) Electrochemical machining of metals: Fundamentals of electrochemical shaping. Russ J Electrochem 40(12):1230–1265
2. Wang W, Zhu D, Qu N, Huang S, Fang X (2009) Electrochemical drilling inclined holes using wedged electrodes. Int J Adv Manuf Technol 47(9–12):1129–1136. https://doi.org/10.1007/s00170-009-2247-9
3. Kim, BH, Ryu SH, Choi DK, Chu CN (2005) Micro electrochemical milling. J Micromech Microeng 15(1):124–129. https://doi.org/10.1088/0960-1317/15/1/019
4. Wang S, Zhu D, Zeng Y, Liu Y (2010) Micro wire electrode electrochemical cutting with low frequency and small amplitude tool vibration. Int J Adv Manuf Technol 53(5–8):535–544. https://doi.org/10.1007/s00170-010-2835-8

5. Chen X, Qu N, Li H, Xu Z (2016) Electrochemical micromachining of micro-dimple arrays using a polydimethylsiloxane (PDMS) mask. J Mater Process Technol 229:102–110. https://doi.org/10.1016/j.jmatprotec.2015.09.008
6. Rajurkar KP, Sundaram MM, Malshe AP (2013) Review of electrochemical and electrodischarge machining. Procedia CIRP 6:13–26. https://doi.org/10.1016/j.procir.2013.03.002
7. Kozak J (2004) Thermal models of pulse electrochemical machining. Bull Pol Acad Sci Tech Sci 52(4):313–320
8. Schuster R (2000) Electrochemical Micromachining. Sci 289(5476):98–101. https://doi.org/10.1126/science.289.5476.98
9. Kirchner V, Xia X, Schuster R (2001) Electrochemical nanostructuring with ultrashort voltage pulses. Acc Chem Res 34(5):371–377. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/21727446
10. Kock M, Kirchner V, Schuster R (2003) Electrochemical micromachining with ultrashort voltage pulses–a versatile method with lithographical precision. Electrochim Acta 48(20–22):3213–3219. https://doi.org/10.1016/S0013-4686(03)00374-8
11. Cagnon L, Kirchner V, Kock M, Schuster R, Ertl G, Gmelin WT, Kück H (2003) Electrochemical Micromachining of Stainless Steel by Ultrashort Voltage Pulses. Z Phys Chem 217(4–2003):299–314. https://doi.org/10.1524/zpch.217.4.299.20383
12. Fan Z, Hourng L (2011) Electrochemical micro-drilling of deep holes by rotational cathode tools. Int J 555–563. https://doi.org/10.1007/s00170-010-2744-x
13. Jo CH, Kim BH, Chu CN (2009) Micro electrochemical machining for complex internal micro features. CIRP Ann—Manuf Technol 58(1):181–184. https://doi.org/10.1016/j.cirp.2009.03.072
14. Maurer JJ, Mallett JJ, Hudson JL, Fick SE, Moffat TP, Shaw GA (2010) Electrochemical micromachining of Hastelloy B-2 with ultrashort voltage pulses. Electrochim Acta 55(3):952–958. https://doi.org/10.1016/j.electacta.2009.09.004
15. Liu Y, Zhu D, Zhu L (2012). Micro electrochemical milling of complex structures by using in situ fabricated cylindrical electrode. Int J, 977–984. https://doi.org/10.1007/s00170-011-3682-y
16. Yong L, Di Z, Yongbin Z, Shaofu H, Hongbing Y (2010) Experimental investigation on complex structures machining by electrochemical micromachining technology. Chin J Aeronaut 23(5):578–584. https://doi.org/10.1016/S1000-9361(09)60257-0
17. Zeng YB, Yu Q, Wang SH, Zhu D (2012) Enhancement of mass transport in micro wire electrochemical machining. CIRP Ann—Manuf Technol 61(1):195–198. https://doi.org/10.1016/j.cirp.2012.03.082
18. Skoczypiec S (2016) Discussion of ultrashort voltage pulses electrochemical micromachining : A review. Int J Adv Manuf Technol 87:177–187. https://doi.org/10.1007/s00170-016-8392-z
19. Lauwers B, Klocke F, Klink A, Tekkaya AE, Neugebauer R, Mcintosh D (2014) Hybrid processes in manufacturing. CIRP Ann—Manuf Technol. https://doi.org/10.1016/j.cirp.2014.05.003
20. Gupta et al (2016) Chapter-1 Overview of hybrid machining processes. In (eds.) Hybrid machining processes, Springer, pp 1–7
21. Zhu D, Zeng YB, Xu ZY, Zhang XY (2011) Precision machining of small holes by the hybrid process of electrochemical removal and grinding. CIRP Ann—Manuf Technol 60(1):247–250. https://doi.org/10.1016/j.cirp.2011.03.130
22. Skoczypiec S, Grabowski M, Ruszaj A (2016) The impact of electrochemical assistance on the microturning process. Int J Adv Manuf Technol 86:1873–1880. https://doi.org/10.1007/s00170-015-8320-7
23. Ghoshal B, Bhattacharyya B (2015) Vibration assisted electrochemical micromachining of high aspect ratio micro features. Precis Eng 42:231–241. https://doi.org/10.1016/j.precisioneng.2015.05.005
24. Ghoshal B, Bhattacharyya B (2015) Investigation on profile of microchannel generated by electrochemical micromachining. J Mater Process Technol 222:410–421. https://doi.org/10.1016/j.jmatprotec.2015.03.025

25. Ghoshal B, Bhattacharyya B (2014) Shape control in micro borehole generation by EMM with the assistance of vibration of tool. Precis Eng 38(1):127–137. https://doi.org/10.1016/j.precisioneng.2013.08.004
26. Skoczypiec S (2010) Research on ultrasonically assisted electrochemical machining process. Int J Adv Manuf Technol (2011) 52:565–574. https://doi.org/10.1007/s00170-010-2774-4
27. Yang I, Park MS, Chu CN (2009) Micro ECM with ultrasonic vibrations using a semi-cylindrical tool. Int J Precis Eng Manuf 10(2):5–10. https://doi.org/10.1007/s12541-009-0020-5
28. Krötz H, Wegener K (2015) Sparc assisted electrochemical machining: a novel possibility for microdrilling into electrical conductive materials using the electrochemical discharge phenomenon. Int J Adv Manuf Technol 79(9–12):1633–1643. https://doi.org/10.1007/s00170-015-6913-9
29. Singh T, Dvivedi A (2016) Developments in electrochemical discharge machining: A review on electrochemical discharge machining, process variants and their hybrid methods. Int J Mach Tools Manuf 105:1–13. https://doi.org/10.1016/j.ijmachtools.2016.03.004
30. Yin Q, Wang B, Zhang Y, Ji F, Liu G (2014) Research of lower tool electrode wear in simultaneous EDM and ECM. J Mater Process Technol 214(8):1759–1768. https://doi.org/10.1016/j.jmatprotec.2014.03.025
31. Kunieda M, Mizugai K, Watanabe S, Shibuya N, Iwamoto N (2011) Electrochemical micromachining using flat electrolyte jet. CIRP Ann—Manuf Technol 60(1):251–254. https://doi.org/10.1016/j.cirp.2011.03.022
32. Lipiec P, Wyszynski D, Skoczypiec S (2013) Primary research on jet ECM processing of difficult to cut materials. Key Eng Mater 554–557:1793–1799. https://doi.org/10.4028/www.scientific.net/KEM.554-557.1793
33. Hackert-Oschätzchen M, Meichsner G, Zinecker M, Martin A, Schubert A (2012) Micro machining with continuous electrolytic free jet. Precis Eng 36(4):612–619. https://doi.org/10.1016/j.precisioneng.2012.05.003
34. De Silva AKM, Pajak PT, McGeough JA, Harrison DK (2011) Thermal effects in laser assisted jet electrochemical machining. CIRP Ann—Manuf Technol 60(1):243–246. https://doi.org/10.1016/j.cirp.2011.03.132
35. Skoczypiec S (2015) Application of laser and electrochemical interaction in sequential and hybrid micromachining processes. Bull Pol Acad Sci Tech Sci 63(1):305–314. https://doi.org/10.1515/bpasts-2015-0035
36. Zhang H, Xu J, Wang J (2009) Investigation of a novel hybrid process of laser drilling assisted with jet electrochemical machining. Opt Lasers Eng 47(11):1242–1249. https://doi.org/10.1016/j.optlaseng.2009.05.009
37. Wee LM, Li L (2005) Multiple-layer laser direct writing metal deposition in electrolyte solution. Appl Surf Sci 247(1–4):285–293. https://doi.org/10.1016/j.apsusc.2005.01.142
38. Chauvy PF, Hoffmann P, Landolt D (2003) Electrochemical micromachining of titanium using laser oxide film lithography: Excimer laser irradiation of anodic oxide. Appl Surf Sci 211(1–4):113–127. https://doi.org/10.1016/S0169-4332(03)00256-3
39. Chauvy PF, Hoffmann P, Landolt D (2003) Applications of laser lithography on oxide film to titanium micromachining. Appl Surf Sci 208–209:165–170. https://doi.org/10.1016/S0169-4332(02)01361-2
40. Shin HS, Chung DK, Park MS, Chu CN (2011) Analysis of machining characteristics in electrochemical etching using laser masking. Appl Surf Sci 258(5):1689–1698. https://doi.org/10.1016/j.apsusc.2011.10.010
41. Shin HS, Park MS, Chu CN (2010) Electrochemical etching using laser masking for multilayered structures on stainless steel. CIRP Ann—Manuf Technol 59(1):585–588. https://doi.org/10.1016/j.cirp.2010.03.134
42. Skoczypiec S, Ruszaj A (2014) A sequential electrochemical-electrodischarge process for micropart manufacturing. Precis Eng 38 (2014):680–690. https://doi.org/10.1016/j.precisioneng.2014.03.007

43. Zeng Z, Wang Y, Wang Z, Shan D, He X (2012) A study of micro-EDM and micro-ECM combined milling for 3D metallic micro-structures. Precis Eng 36(3):500–509. https://doi.org/10.1016/j.precisioneng.2012.01.005
44. He XL, Wang YK, Wang ZL, Zeng ZQ (2011) Micro-hole drilled by EDM–ECM combined processing. Key Eng Mater 562–565:52–6
45. Hu MH, Li Y, Zhu XG, Tong H (2011) Influence of side-insulation film on hybrid process of micro EDM and ECM for 3D micro structures. Adv Mater Res 230–232:517–521
46. Kurita T, Hattori M (2006) A study of EDM and ECM / ECM-lapping complex machining technology. Int J 46:1804–1810. https://doi.org/10.1016/j.ijmachtools.2005.11.009
47. Nguyen MD, Rahman M, Wong YS (2012) Enhanced surface integrity and dimensional accuracy by simultaneous micro-ED/EC milling. CIRP Ann—Manuf Technol 61(1):191–194. https://doi.org/10.1016/j.cirp.2012.03.011