Chapter 2
Electrochemical Hybrid Machining Processes

Abstract This chapter introduces electrochemical HMPs developed by combining electrochemical machining (ECM) with conventional finishing processes such as grinding, mechanical honing, buffing, deburring and superfinishing with an objective to overcome their limitations and to enhance their finishing capabilities. Electrochemical HMPs are generally recognized as micro-finishing processes which are used to finish gears, cylinders, micro-shafts, and other micro-, meso- and macro-engineered components in order to improve surface finish and/or to correct micro-irregularities. The current chapter also presents brief details of electrochemical-type advanced drilling processes which have been developed to meet specialized drilling requirements.

Keywords ECM · Electrolyte · Dissolution · Finishing · Burr

Electrochemical machining (ECM) is a 'copying' process in which an approximate complementary image of a cathode tool is reproduced on the anode workpiece through controlled electrolytic dissolution (ED) by circulating an appropriate electrolyte in the inter-electrode gap (IEG). ECM is a self-regulating process due to the ED being governed by Faraday's laws of electrolysis which mandates that the material removal rate (MRR) is inversely proportional to the inter-electrode gap and directly proportional to electrolyte conductivity and DC voltage applied across the inter-electrode gap.

Being a non-contact machining process, ECM offers many advantages, namely (i) process performance being independent of mechanical properties of the workpiece material which basically implies that materials of any hardness and/or toughness can be machined; (ii) production of largely stress-free surface; (iii) good surface finish and integrity; (iv) higher productivity due to higher MRRs. It does, however, also suffer from inherent significant limitations, namely (i) passivation of workpiece surface by non-conducting metal oxide layer formation due to the evolution of oxygen gas at the anode; (ii) applicability to only electrically conducting materials; (iii) corrosion of machining elements and surroundings due to the use of an electrolyte; (iv) chemical damage caused to workpiece surface; (v) the dependence of accuracy on the inter-electrode gap which requires efficient flushing

K. Gupta et al., *Hybrid Machining Processes*,
Manufacturing and Surface Engineering,
DOI 10.1007/978-3-319-25922-2_2

of sludge; and (vi) process performance being sensitive to electrolyte characteristics. ECM is invariably used in the machining of difficult-to-machine but electrically conducting materials, which are extensively used in automobiles, aerospace, defence, cutting tools, dies and moulds and biomedical applications. However, conventional finishing processes such as grinding, mechanical honing, buffing and superfinishing are inexpensive and give good surface quality, but the use of abrasives imparts some inherent limitations such as (i) high tool wear; (ii) low productivity; and (iii) mechanical damage to the finished surface. One of the recent developments in the field of ECM is to combine it with some conventional machining/finishing or AMP to develop an electrochemical HMP (ECHMP). This overcomes the limitations of ECM and the other constituent process and allows exploiting their capabilities and advantages simultaneously with higher overall efficiency and productivity. The majority of material removal during an ECHMP is done by electrolytic and chemical dissolutions, while the role of the conventional machining/finishing action is basically limited to depassivate the electrochemically machined surface by removing non-conducting layers of metallic oxides and other compounds from the anode. This enhances the MRR and surface quality by changing the IEG conditions conducive for enhanced ED process.

2.1 Electrochemical Grinding (ECG)

2.1.1 Introduction

Grinding with diamond as abrasive is probably the only practical conventional process for finishing difficult-to-machine materials such as cemented carbides, high-strength-temperature-resistant (HSTR) alloys, and creep-resistant alloys. The scarcity of diamond and the challenges involved in diamond grinding wheel manufacture make this process extremely costly. ECG was developed by hybridizing ECM with the abrasive action of conventional grinding to machine hard and fragile electrically conducting materials efficiently, economically and productively without affecting the useful properties of these materials. ECG offers accurate and largely surface residual stress-free machining with no burrs and heat affected zone (HAZ) and, therefore, little distortion.

2.1.2 Equipment and Working Principle

Figure 2.1 depicts a typical set-up for an ECG process in which a metal-bonded abrasive grinding wheel acts as cathode and the workpiece as anode connected to a suitable DC power supply. The non-conducting abrasive particles protrude just beyond the surface of the bonding material of the wheel helping to maintain a constant inter-electrode gap and act as spacers. The grinding is performed as usual,

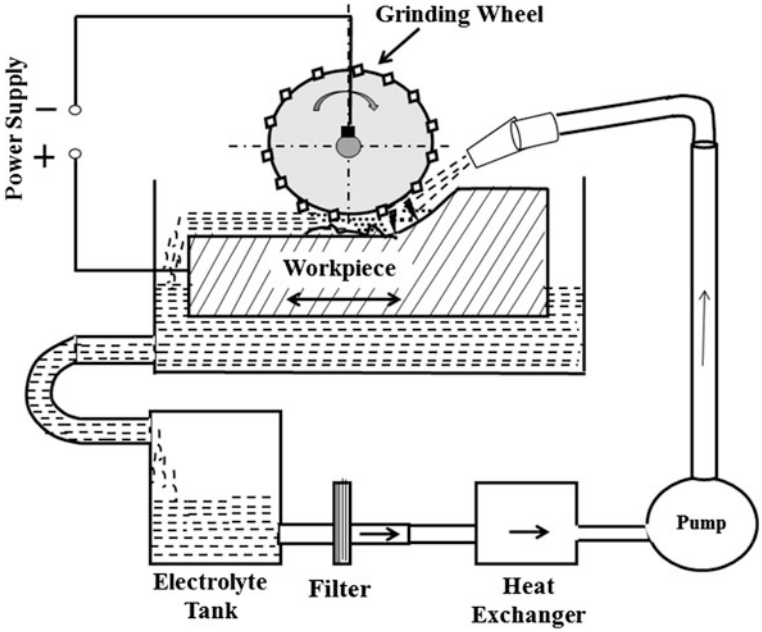

Fig. 2.1 Schematic of a typical set-up for ECG process

but instead of coolant, a spray of an appropriate electrolyte is used. Bonding materials such as copper, brass, nickel or copper impregnated resin are commonly used for the manufacture of metal-bonded grinding wheels. The main functions of the abrasive particles in the ECG process are as follows: (i) to maintain the electrical insulation between anode workpiece and cathode grinding wheel and to maintain the effective IEG between them; (ii) to continuously remove any passive layer that may be formed on the workpiece surface by chemical reaction; and (iii) to determine workpiece shape and size. A commonly used abrasive is alumina (Al_2O_3) of mesh size 60–80. The main functions of the electrolyte used in the ECG process are (i) to produce the desired finish by ED; (ii) to conduct heat away from the inter-electrode gap; (iii) to flush reaction products away from the inter-electrode gap; and (iv) to minimize chemical wear of the conducting grinding wheel by maintaining its chemical inertness. Generally, sodium chloride and sodium nitrate are used as electrolytes in ECG [1–3].

2.1.3 Process Mechanism and Parameters

The electrochemistry of the ECG process implies that the electrochemical reactions (i.e. anodic dissolution, evolution of oxygen at anode and hydrogen at cathode and oxidation–reduction) occur at the workpiece material electrolyte boundary layer, while the other chemical reactions (i.e. chemical combinations, complex formations and precipitation) occur in bulk of the electrolyte solution [1]. As the grinding wheel rotates, the workpiece material is removed by simultaneous ED and mechanical removal by abrasive grinding. About 90–95 % of the material is removed by the ECM action with the mechanical grinding action accounting for the rest 5–10 %. The life of the grinding wheel used in ECG may be about 10 times more than that of a conventional grinding wheel due to the very small contact length (in the shape of an arc) between the wheel and the workpiece.

The contact arc in ECG can be divided into 3 zones as illustrated in Fig. 2.2. In **zone I**, the material removal is purely due to electrochemical dissolution. Material removal occurs at the leading edge of the ECG wheel. Rotation of the ECG wheel helps in drawing electrolyte into the inter-electrode gap. The electrochemical reaction products (including gases) contaminate the electrolyte and reduce its conductivity. The presence of sludge may in fact increase the conductivity of the electrolyte, whereas the presence of gases typically decreases it. The net result is a decrease in electrolyte conductivity. It effectively yields a smaller inter-electrode gap. As a result, abrasive particles come in contact with the workpiece surface and material removal by abrasive action commences. Thus, a small part of the workpiece material is removed in the form of chips. In **zone II**, the gas bubbles in the gap yield higher MRRs. Chemical or electrochemical reaction may result in the formation of a passive layer on the workpiece surface. The abrasive particles not only remove material from the work surface in the form of chips but also remove the non-reactive oxide layer. The removal of the non-reactive oxide layer is important as it promotes ED. In **zone III**, the material removal is done completely by electrochemical dissolution. This zone starts at the point where the wheel lifts just beyond the work surface. In this zone, pressure is released slowly. This zone contributes by removal of burrs that formed on the workpiece in **zone II** [2, 3].

The main process parameters that affect performance, efficiency and effectiveness of the ECG process are as follows: applied voltage and current density; type, concentration and delivery method of electrolyte; type, speed, pressure and

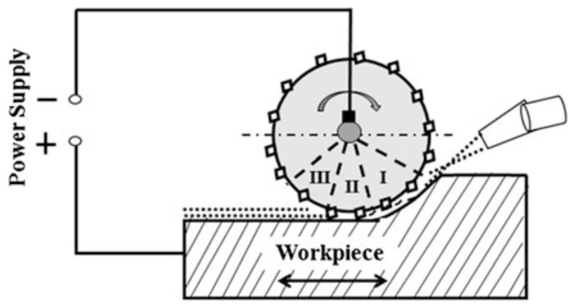

Fig. 2.2 Three zones of the contact arc in the ECG process

kinematic accuracy of the grinding wheel; and feed rate of workpiece. Selection of optimum values of these parameters helps to optimize surface finish and MRR.

2.1.4 Advantages, Limitations and Applications

Main advantages offered by ECG are as follows: negligible thermal damage to workpiece; limited grinding wheel wear; and no distortion of the workpiece. Metallographic examination of the surfaces finished by ECG revealed absence of structural changes, micro-cracks or any other defect [1]. Its main limitations are as follows: applicable for only electrically conductive work materials; not suitable for soft materials; requires tool dressing preparation for the grinding wheel; higher power consumption; corrosion problems of ancillary equipment due to the electrolyte; and high capital costs due to specialized grinding wheels.

ECG can routinely produce surface roughness values up to 0.1 µm. It has many industrial applications which include the following: grinding cemented carbide cutting tools, and thin-walled components; grinding of creep-resisting alloys (i.e. Inconel, Nimonic); grinding of titanium alloys, and metallic composites; burr-free sharpening by grinding of hypodermic needles; finishing of turbine blades made of superalloys; reprofiling of worn traction motor gears without affecting its hardness; form grinding of fragile aerospace honeycomb materials; and removal of fatigue cracks from steel structures used under seawater.

2.2 Electrochemical Honing (ECH) and Pulsed ECH

2.2.1 Introduction

Electrochemical honing is a hybrid fine finishing process combining the capabilities of *ECM* (capability to machine material of any hardness, production of stress-free surface with good finish and higher MRR) with the capabilities of *mechanical honing* (ability to correct shape/geometry-related errors, controlled generation of functional surfaces having cross-hatch lay patterns and compressive residual stresses) in a single process. At the same time, it overcomes some limitations of ECM along with certain limitations of mechanical honing (reduced tool life, low productivity due to frequent failure of honing sticks, inability to finish hardened workpiece and possibility of mechanical damage to the workpiece). ECH, therefore, provides a higher productivity alternative with many benefits that may produce surfaces that are not attainable by either of the processes when used individually [4].

2.2.2 *Equipment and Working Principle*

2.2.2.1 Finishing of Internal Cylinders by ECH

Figure 2.3a presents a schematic of the ECH set-up for finishing of an internal cylinder. It consists of five major subsystems: (i) DC power supply; (ii) tool for ECH process; (iii) the kinematic system for tool motion; (iv) electrolyte supply and cleaning system; and (v) machining chamber for holding and positioning workpiece. A power supply unit provides a DC voltage (3–40 V) and constant current (up to 200 A) across the electrolyte flooded inter-electrode gap. The positive terminal of the power supply is connected to the workpiece by means of a carbon-brush and slip ring assembly, while the negative terminal is directly connected to a brass ring mounted over the axle of the cathodic tool.

An ECH tool for finishing of cylindrical workpieces (shown in Fig. 2.3b) typically consists of a Teflon (PTFE) body over which a hollow stainless steel sleeve is placed having provision for an even number of equally spaced honing sticks to protrude out circumferentially by a light spring mechanism which can be used to adjust the required honing pressure. These honing sticks being electrically

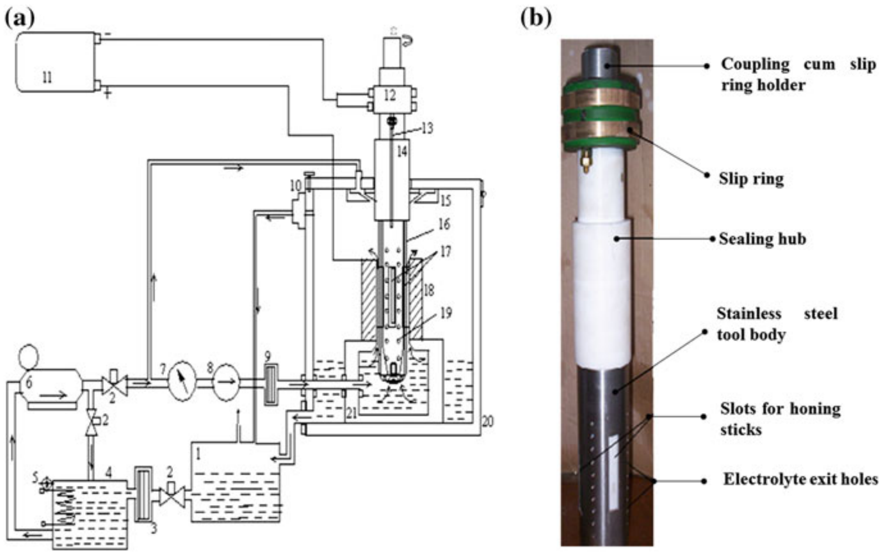

Fig. 2.3 **a** Schematic diagram of an ECH set-up; and **b** photograph of the tool used for finishing internal cylinders by ECH [5], with kind permission from Springer. *1* Electrolyte settling tank; *2* Flow control valve; *3* 1st stage filter cum magnetic separator; *4* Electrolyte storage tank; *5* Temperature control system; *6* Stainless steel electrolyte supply pump; *7* Pressure gauge; *8* Flow meter; *9* 2nd stage filter cum magnetic separator; *10* Mist collector; *11* DC power source; *12* Carbon brush and slip ring assembly; *13* Copper connector; *14* Seal hub; *15* Hydraulic cum mechanical seal; *16* Tool body; *17* Honing sticks; *18* Workpiece; *19* Electrolyte exit holes; *20* Work chamber; *21* Fixture cum electrolyte inlet sleeve

non-conducting maintain a uniform inter-electrode gap and preferentially remove the non-conductive passive layer of metal oxide from the high spots to correct errors/deviations in geometry/shape of the cylindrical workpiece. The tool is provided a precisely controlled combination of rotation and reciprocation simultaneously. Rotary motion is provided by a speed-controlled DC servo motor, while the reciprocating motion is provided by a microprocessor-controlled stepper motor.

2.2.2.2 Finishing of Gears by ECH

The equipment for gear finishing by ECH has all subsystems same that used in finishing of internal cylinders, except the machining chamber, which is significantly different for gear finishing by ECH. Figure 2.4a, b shows photograph of the machining chamber for high-quality finishing of spur gear developed by Naik et al. [6] and for helical gears by Misra et al. [7].

Gear finishing by ECH requires that the anodic workpiece gear meshes with a specially designed cathode gear for the ECM action to occur while simultaneously meshing with a honing gear so that the mechanical honing can also take place. All three gears should have the same involute profile and module. The honing gear is a helical gear and can be either an abrasive impregnated gear or manufactured from a material substantially harder than the workpiece gear. It is mounted on a floating stock to ensure dual flank contact between the honing and workpiece gear. For *finishing spur gears* by ECH, the honing gear is mounted in cross-axis arrangement with the workpiece gear to reduce the tooth surface contact and therefore pressure required for finishing (Fig. 2.4a).

Helical gear finishing by ECH does not require cross-axis arrangement because the honing and cathode gears have opposite helix angles than the workpiece gear. Therefore, if the workpiece gear is a right-handed helical gear, then the cathode and honing gears will be left-handed and vice versa (refer to Fig. 2.4b).

The cathode gear is to be designed and fabricated such that while meshed with the electrically conducting anodic workpiece gear, no short circuiting should occur while maintaining the required inter-electrode gap necessary for the ED of the workpiece gear. For the cylindrical gears, this is ensured by sandwiching a conducting layer between two non-conducting layers and undercutting the conducting layer by a distance equal to the inter-electrode gap as compared to the non-conducting layers. The axes of shafts of the workpiece and cathode gears are parallel to each other for finishing the spur and helical gears (Fig. 2.4a, b). The rotation of the workpiece gear is controllable by means of a DC motor, while cathode and honing gears rotate by virtue of their engagement with the workpiece gear. Since the entire face width of the cathode gear is not electrically conducting, a reciprocating motion is also required for the workpiece gear. This is implemented by a controlled stepper or servo motor, therefore ensuring finishing of the entire face width of the workpiece gear.

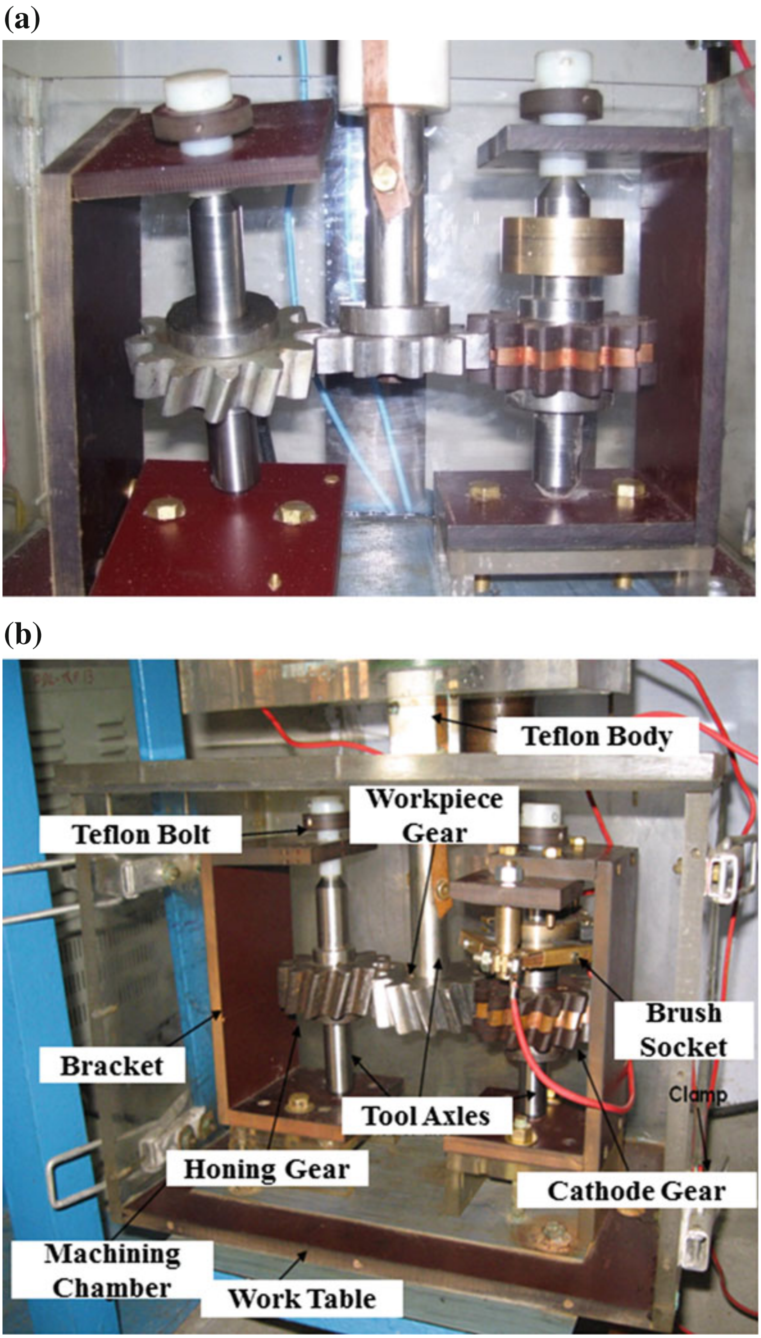

Fig. 2.4 Photographs of machining chamber for high-quality finishing of **a** spur gear [6] and **b** helical gear [7] by ECH process, with kind permission from Sage

Finishing of *bevel gears* by ECH is much more difficult than cylindrical (i.e. spur or helical) gears due to their complex geometry which inhibits reciprocation of the workpiece gear that is required for finishing the entire face width. This problem was solved by Shaikh et al. [8] that envisaging a novel concept of a *twin complementary cathode gear* arranged as shown in Fig. 2.5a. In this arrangement, one of the cathode gears '4' has a conducting layer of copper sandwiched between two insulating layers of metalon, while the other complimentary cathode gears '3' have an insulating layer of metalon sandwiched between two conducting layers of copper. The workpiece gear '1', which acts as the anode, is mounted on the spindle of a bench drilling machine. To avoid short circuiting, an inter-electrode gap is provided between the cathode and anode gears by undercutting the conducting layer equal to the required distance of the inter-electrode gap as compared to the insulating layers. A honing gear '2' is mounted to the rear of the workpiece gear. The workpiece gear is actively rotated, thereby ensuring rotation of both the honing and cathode gears due to the inter-meshing. The surface contact established because of the close meshing between the honing and workpiece gears facilitates the removal of the passivating layer and consequently exposes fresh workpiece surface for further finishing by the electrochemical action [8]. A photograph of the machining chamber based on this principle is shown in Fig. 2.5b. The finishing occurs as a result of the ED that takes place when the required quality of an appropriate electrolyte (generally mixture of NaCl and $NaNO_3$) is available at the inter-electrode gap at the appropriate temperature and pressure along with a suitable DC current between the anode and cathode gears.

During the process of material removal from the tooth flank, the electrolyte forms a passivating metal oxide layer on the workpiece gear tooth surface which inhibits further finishing by the electrolysis action. This layer is abraded by the honing gear. Surface peaks both along the tooth face and along the involute profile have minimum thickness of the oxide layer; therefore, they are exposed early for further finishing by electrolysis action once again. As the process carries on, the geometric accuracy of the workpiece gear is rapidly improved.

Pathak et al. [10] showed that the use of a pulsed power supply during ECH (a process referred to as pulse-ECH or PECH), simultaneously improves surface finish and micro-geometry of the bevel gear by a significant margin, thus enhancing their service life and operating performance. They achieved more than 50 % improvement in location errors (i.e. pitch error and run-out) in PECH-finished bevel gears as compared to ECH-finished bevel gears as reported by Shaikh et al. [8]. Misra et al. [11] used PECH for improving surface finish of spur gears and reported that gravimetric electrolyte composition of 75 % sodium chloride (NaCl) and 25 % sodium nitrate ($NaNO_3$) with an electrolyte temperature of 30 °C yielded the best results. This proves superiority of PECH over the ECH process for gear finishing applications. However, the use of PECH may take longer time to achieve the desired quality of the gears, making this process less productive than ECH.

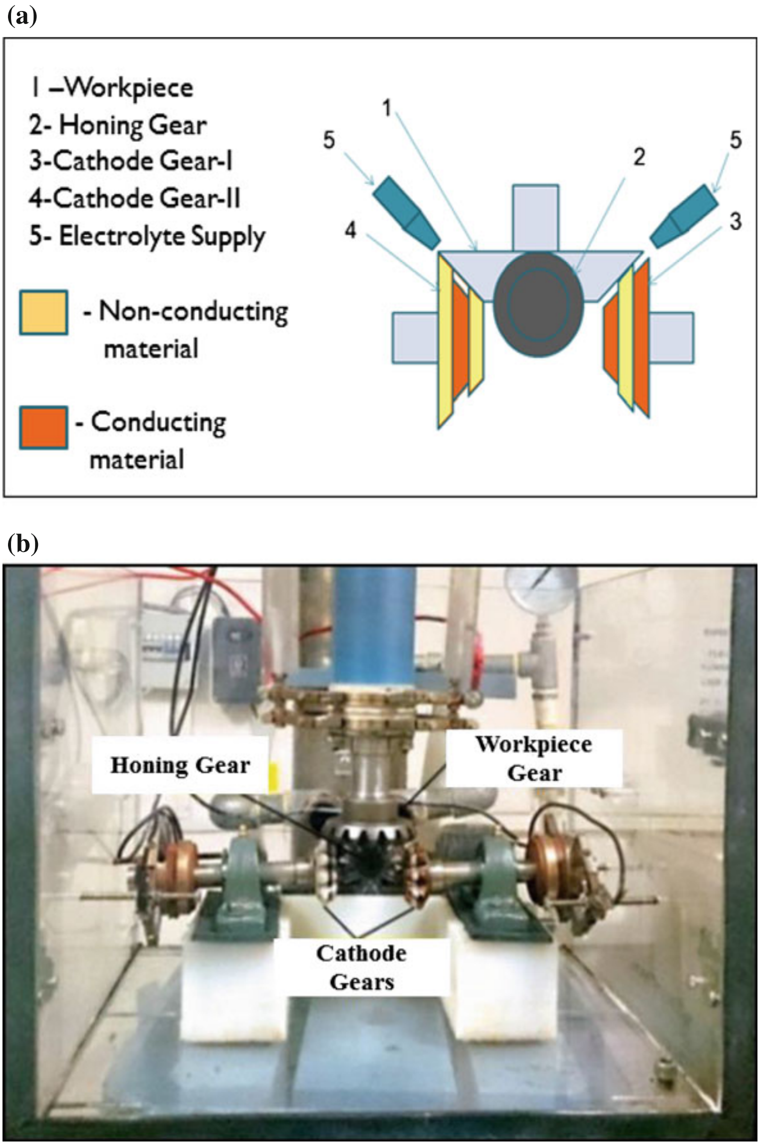

Fig. 2.5 **a** Concept of twin complementary cathode gears for high-quality finishing of bevel gears by ECH; **b** photograph of the machining chamber based on this concept [9], with kind permission from Elsevier

2.2.3 Process Parameters and Mechanism

Parameters related to the power supply, electrolyte, honing tool and workpiece affect performance, efficiency and effectiveness of the ECH process. These parameters include the following: type of power supply (continuous or pulsed); applied voltage and current; type, composition, concentration, flow rate, temperature and pressure of the electrolyte; type and size of abrasives used in the honing tool; honing tool hardness; honing pressure; rotary and/or reciprocating speed of the honing tool (for internal cylinders) or workpiece (for gears); and electrochemical properties of the workpiece.

Mechanism of finishing the gears by ECH explained by Shaikh and Jain [9] involves cyclic sequence of finishing by ED and mechanical honing which improves the geometric accuracy and surface finish of the workpiece gear. More than 90 % of the material is removed by ED. As far as the surface topography is concerned initially, the distances between peaks on the workpiece and cathode surfaces are less than the corresponding distances between valleys (Fig. 2.6a). Consequently, more material is removed from the peaks of the workpiece surface as compared to its valleys by ED, thus truncating the highest peaks and giving rapid improvement in the workpiece surface finish. At the end of the ED process, a passivating metal oxide layer is formed on the workpiece surface (Fig. 2.6b, d and f), which is removed by the honing action so that further ED can continue. At the end of honing action, certain valleys may still be covered with the passivating layer as shown in Fig. 2.6c, e and g.

In the next cycle of ED, these peaks will be exposed for further smoothing. Consequently, these peaks are truncated along with material above the valley giving a smoother surface as shown in Fig. 2.6g. As the ECH process continues, surface finish and geometric accuracy initially improve rapidly but follow the law of

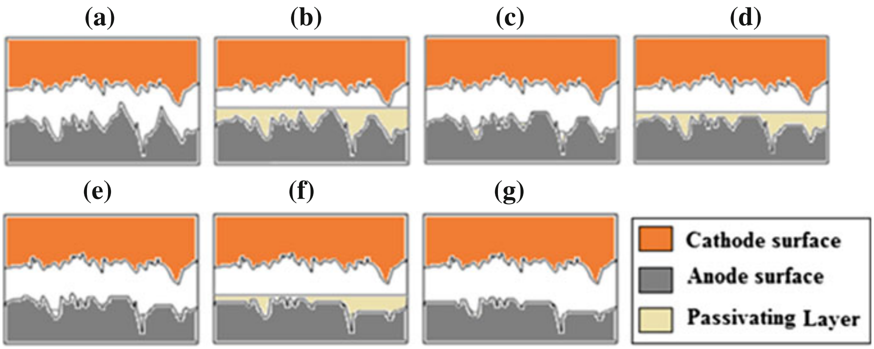

Fig. 2.6 Sequential finishing by the ECH process depicting the surface profiles of the anode and cathode. **a** Initial surface before ECH; **b** after first phase of electrolytic dissolution; **c** after first phase of honing action; **d** after second phase of electrolytic dissolution; **e** after second phase of honing action; **f** after third phase of electrolytic dissolution; and **g** after third phase of honing action [9], with kind permission from Elsevier

diminishing return due to increasing inter-electrode gap between the surfaces of the cathode and workpiece gears and consequent decreasing MRR. Therefore, whenever the desired surface finish or geometric accuracy or both are achieved, the process can be stopped.

Based on the above-mentioned mechanism of material removal, Shaikh and Jain [9] developed models of MRR and the arithmetic mean of maximum peak-to-valley heights (R_z) for the flank surface of bevel gears finished by the ECH process as a function of rotary speed of the workpiece gear and the inter-electrode gap current. The model also indirectly took into account the effects of other electrolytic parameters such as concentration, temperature and flow rate. The contribution of ECD in the MRR and surface roughness was modelled using Faraday's law of electrolysis, while the contribution of the mechanical honing was modelled considering material removal as a process of uniform wear [9].

2.2.4 Advantages, Limitations and Applications

ECH offers many useful advantages as follows: (i) material of any hardness (but electrically conducting) can be finished by ECH; (ii) it produces surfaces with a distinct cross-hatch lay pattern that is beneficial for oil retention; (iii) ECH not only produces high-quality surface finish and surface integrity but also has the ability to correct errors/deviations in geometry/shape such as out of roundness or circularity, taper, bell-mouth hole, barrel-shaped hole, axial distortion and boring tool marks for cylindrical surfaces and the ability to correct form errors (i.e. deviations in lead and profile) and location errors (i.e. pitch deviations and run-out) for cylindrical and conical gears; (iv) it is faster when compared to ECM and mechanical honing. ECH can finish materials up to 5–10 times faster than mechanical honing and four times faster than internal grinding. The benefit is more pronounced for higher material hardness; (v) low heat generation thus making it suitable for the processing of parts that are susceptible to heat distortions; (vi) increased life of abrasive sticks/tool due to the limited contribution of mechanical honing to the process; and (vii) low working pressure implies less distortion while finishing thin-walled sections.

Despite the numerous advantages, ECH does exhibit some limitations as follows: (i) it can be used for finishing electrically conductive materials only; (ii) it is more costly than the mechanical honing due to the cost of the electrical and fluid handling elements, need for corrosion protection, costly tooling and longer set-up time. This makes ECH more economical for longer production runs than for tool room and job-shop conditions; (iii) it cannot finish blind holes easily; and (iv) ECH cannot correct location of hole or perpendicularity [4].

Materials that can be finished by ECH include cast tool steels, high-alloy steels, carbide, titanium alloys, Incoloy 901, 17-7PH stainless steel, Inconel and gun steels. ECH is an ideal choice for superfinishing, improving the surface integrity and increasing the service life of the critical components such as internal cylinders, transmission gears, carbide bushings and sleeves, rollers, petrochemical reactors, moulds and dies, gun barrels and pressure vessels, which are made of very hard and/or tough wear-resistant materials, most of which are susceptible to thermal distortions. Therefore, ECH is widely used in the automobile industry, aerospace, petrochemical industry, power generation and fluid power industries. It has been successfully used for finishing bore sizes ranging from 9.5 to 300 mm and length up to 600 mm [4]. ECH can achieve surface roughness up to 50 nm and tolerances of ±0.002 mm [5].

2.3 Electrochemical Buffing (ECB)

2.3.1 Introduction

Electrochemical buffing (ECB) is a non-contact-type electrochemical hybrid machining process (ECHMP), combining process principles and advantages of electrochemical finishing (ECF) and the conventional buffing process. The most significant challenges of the conventional buffing process are the dependence of surface quality on operator's skills, residual stresses, micro-cracks and control of buffing pressure, i.e. pressure with which the buff is pressed against the workpiece. The most significant limitations of the ECF process are as follows: formation of a passivating metallic oxide layer at the anode (workpiece) which prohibits further finishing by the electrolytic process and poor surface finish due to selective dissolution, sporadic breakdown of the anodic film, flow separation and formation of eddies and evolution of hydrogen gas at the cathode. Hybridization of ECF with conventional buffing in ECB process overcomes most of these limitations by exploiting the individual capabilities and advantages in a single process simultaneously.

2.3.2 Equipment and Process Mechanism

Figure 2.7 depicts the working principle of the ECB process in which a rotating buffing pad impregnated with fine abrasive particles is pressed against the workpiece in the presence of an electrolyte. The buffing pad acts as the cathode, while the workpiece becomes the anode. A suitable DC voltage is applied in the presence of an appropriate electrolyte usually sodium nitrate or sodium chloride. The polishing performance of ECB is not affected by the electrolyte temperature because the ECF action acts to assist conventional buffing only. This eliminates need of a heat exchanger [12].

Electrolyte used in the ECB process is generally 20 wt% of aqueous solution of sodium nitrate which is quite environment-compatible. Sodium nitrate solutions do not deteriorate with time and therefore lends itself to long-term frequent use. Harmless and safe nature of sodium nitrate solution makes the polishing action by

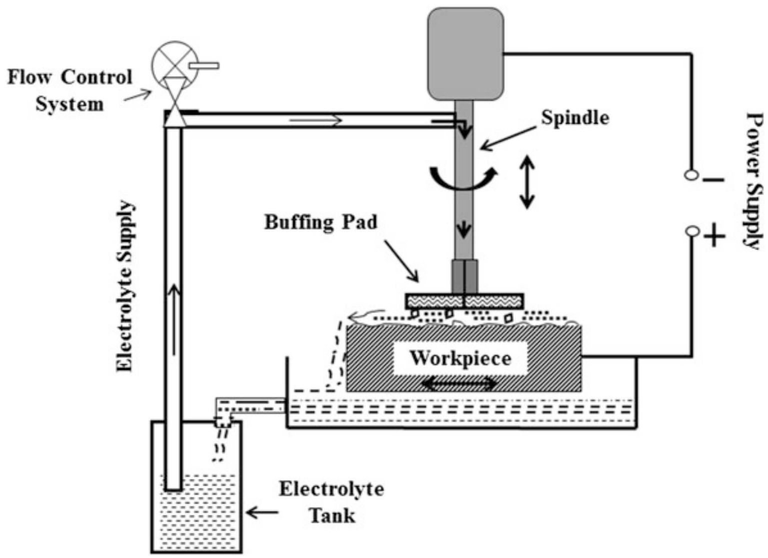

Fig. 2.7 Working principle of ECB process

ECB simpler because it does not require strong-acid compatible plumbing and other components such as flanges and gaskets, unlike electropolishing (EP) process which uses harmful mixture of hydrofluoric and sulphuric acid requiring carefully controlled handling of it and many additional facilities [12]. ECB not only offers extended electrolyte service life, but also simple operational procedures and affordable liquid waste handling. ECB may therefore be considered as one of the green hybrid machining process.

The key process control parameters that affect the performance of ECB process are electrolyte flow rate, type and size of abrasive particles, rotary speed of the buffing pad, buffing pressure, buffing duration, DC voltage and current density.

2.3.3 Applications

ECB process may be used with numerous electrically conducting materials including steel, stainless steel, aluminium, copper, titanium and molybdenum. ECB can buff ultra-high purity components to a mirror finish without any residual stresses and micro-cracks. ECB can remove altered surfaces layers and achieve ultra-flat surfaces without contaminants and micro-dust particles. The ECB process can be used for almost any size part or component from thin tubes of a few millimetres in diameter to large tanks producing buffed surfaces with a maximum surface roughness of 100 nm. Due to this flexibility, Kato et al. [12] demonstrated ECB on complicated structures including niobium cavity cells and endgroups.

2.4 Electrochemical Deburring (ECDe)

2.4.1 Introduction

Electrochemical deburring (ECDe) is a process of removing 'burrs' from the manufactured components especially from and at the areas which are difficult to access with any other deburring process. A burr is a small three-dimensional sharp projection protruding from a manufactured and/or finished surface. There are many types of burrs produced by different manufacturing and finishing processes, namely compressive burr, corner burr, edge burr, entrance burr, exit burr, feather burr, flash burr, hanging burr, parting-off burrs, roll over burr and tear burr [3]. The presence of burrs may affect functional aspects (i.e. assembly, handling, positioning, mounting, wear and breakdown), physiological aspects (injury during further processing, assembling, use, maintenance, repair and utility, etc.) and aesthetic aspects (impression, sale, advertising, etc.) of a product. Precise control of the manufacturing process parameters and process conditions can reduce the occurrence of burrs to a certain extent, but demand for high-quality finishing and appearance of products necessitates complete removal of all types of burrs before a product is marketed.

The main deburring processes can be classified into five categories [3]: (i) **mechanical deburring** which minimizes the burrs using brushes, scrappers, cutting tools, etc., in processes such as hand deburring, power brushing and scrapping; (ii) **abrasive deburring** uses abrasives in different forms (loose agitated, jet, putty) to remove the burrs in processes such as tumbling, barrel finishing, spindle finishing, vibratory deburring, sand blasting, magnetic loose deburring, abrasive flow machining (AFM), and abrasive water jet deburring, using loose abrasives, semi-solid putty and liquid abrasive flow; (iii) **thermal deburring** is a process where burrs are burnt away using some heat source for a short duration in processes such as the thermal energy method, flame melting, resistance heating and hot wire; (iv) **chemical deburring** dissolves burrs in a chemical medium in processes such as chemical barrel finishing, chemical spindle finishing, chemical vibratory finishing, chemical magnetic loose brush, etc.; and (v) **electrochemical deburring (ECDe)** removes burrs by electrolytic dissolution.

Among the different types of deburring processes, ECDe is used for remotely located and inaccessible areas where other deburring processes are not effective.

2.4.2 Process Details

Figure 2.8 shows a typical arrangement for ECDe of holes in which the part to be deburred is made the anode and is placed in a fixture, which positions a specially designed cathode tool in close proximity to the burrs to be removed. An appropriate electrolyte is supplied at a suitable pressure (0.3–0.5 MPa) to the gap between the cathodic deburring tool and the burrs. When a suitable DC current (50–500 A) is

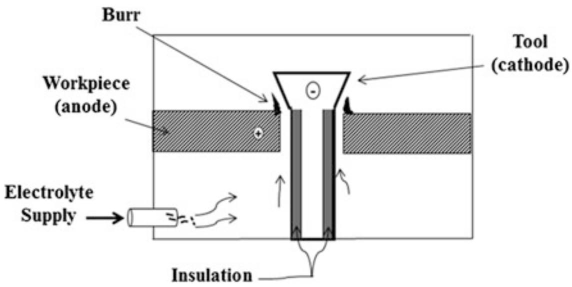

Fig. 2.8 Typical arrangement for ECDe of a hole [3]

supplied, the burr dissolves forming a controlled radius. The cathode tool has as much working areas as practical so that several interfaces are deburred at any given time. The tool surfaces at interfaces where deburring is not required are insulated. The deburring tool should also have a similar contour as that of the workpiece, thus maintaining an inter-electrode gap in the range of 0.1–0.3 mm. The tool tip should overlap the machined area by 1.5–2 mm in order to produce a proper radius. The use of a rotating and feeding tool electrode enhances the deburring process by creating turbulent flow in the inter-electrode gap. The spindle rotation is reversed to increase the electrolyte turbulence. Selecting a suitable electrolyte plays an important role in the ECDe process. Commonly used electrolytes are aqueous solutions of either sodium chloride or sodium nitrate [3].

2.4.3 Advantages and Applications

The main advantages of ECDe are as follows: (i) replacement of costly hand deburring process; (ii) increased product quality and reliability; (iii) removal of burrs at the required accuracy, uniformity, radius, and edge quality; (iv) reduced personnel and labour cost; and (v) possibility of automating for higher productivity.

ECDe can be used to deburr gears, spline shafts, milled components, drilled holes and punched blanks. The process is particularly efficient for hydraulic system components such as spools and sleeves of fluid distributors. Normal cycle time for ECDe is between 30 and 45 s. ECDe can finish a burr of 0.5 mm height to a radius of 0.05–0.2 mm with a surface roughness up to 2–4 μm [13].

2.5 Electrochemical Superfinishing (ECSF)

2.5.1 Introduction

Conventional superfinishing process removes surface micro-irregularities with slowly and continuously reciprocating and oscillating abrasive sticks along the length of a rotating workpiece. It may however retain surface micro-irregularities such as waviness and out of roundness. Electrochemical superfinishing (ECSF) came into existence specifically to overcome the limitations of conventional superfinishing. ECSF combines the advantages of electrolytic dissolution associated with ECM process and the mechanical abrasion action of conventional superfinishing overcoming their individual limitations.

2.5.2 Equipment and Working Principle

In ECSF, the ED is assisted with the mechanical abrasion from a separate cathodic tool electrode or a metal-bonded diamond abrasive stick (Fig. 2.9) for finishing. The workpiece is made of the anode by connecting it to the positive terminal of a DC power supply, while the tool or a metal-bonded diamond stick is wired as the cathode. The workpiece is usually rotated, while a combination of reciprocating and oscillating motion is induced at the cathodic tool. The abrasive particles protruding from the stick maintain the required inter-electrode gap between the anodic workpiece and cathodic tool. Light stick pressure is used to avoid metallurgical

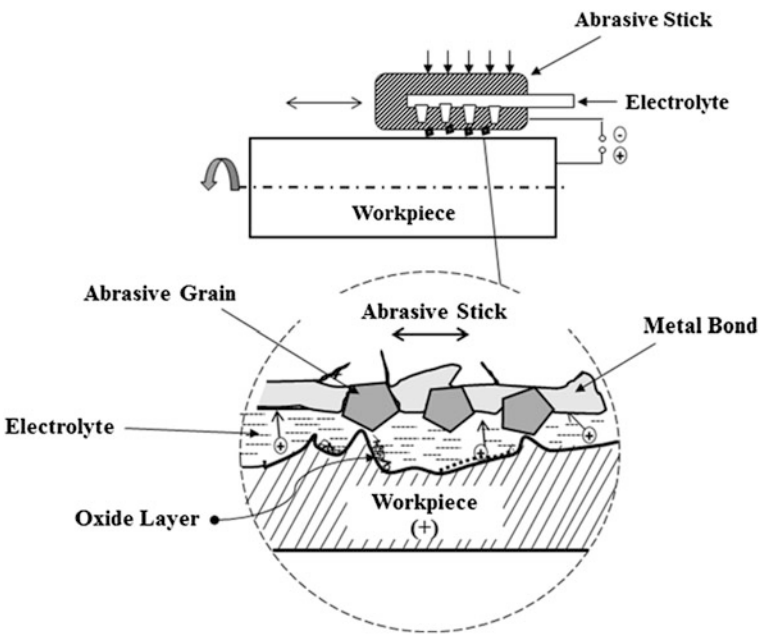

Fig. 2.9 Working principle and mechanism of material removal of ECSF process using metal-bonded diamond abrasive stick

damage due to a scrubbing motion by the abrasive sticks and to produce a superfine surface.

2.5.3 Process Mechanism and Parameters

Similar to the ECH process, the ED in ECSF process is also accompanied by the formation of a passive metal oxide film on the anode surface. Initially, the abrasive particles scrub away the surface irregularities protruding from the ideal surface (as shown in Fig. 2.9). During the next ED phase, these irregularities are subjected to an increased ED as compared to those areas still covered with the protective oxide film. Under such circumstances, the protecting metal oxide film can be used to correct the geometric inaccuracies such as cylindricity and roundness errors. Tolerances of about ±0.013 mm on diameter and a roundness and straightness of less than 0.007 mm can be achieved with this process [13].

Datta and Landolt [14] observed high instantaneous current densities on the use of pulsed DC voltage. This is possible because each current pulse is followed by a relaxation phase of zero current, which allows for the removal of reaction products and the heat generated by the Joule effect from the inter-electrode gap. Hofy [15] investigated a linear increment in MRR with current density during a series of experiments on pulsed electrochemical superfinishing. A rise in the scrubbing speed, voltage and duty cycle leads to an increase in the MRR. The high energy available enhances the oxide film removal process with a consequent rise in the ED phase. The percentage contribution of the ED phase varies between 0 at 20 % duty cycle and about 95 % at a 100 % duty cycle. The contribution of the mechanical abrasion actions increases with an increase in scrubbing speed.

The most significant process parameters of ECSF are similar to those identified for ECM. These include DC voltage, type; concentration and temperature of electrolyte, the parameters related to the mechanical abrasion action, namely frequency and amplitude of oscillations; abrasive grain characteristics and abrasive stick pressure.

2.5.4 Applications

The higher material removal capabilities combined with its ability to finish to close tolerances enable the ECSF process to be used in a wide range of industry. It eliminates the need for initial grinding which is required before conventional superfinishing. ECSF can be used to produce required dimensions in difficult-to-machine materials particularly to those parts that are susceptible to heat and distortion. The ECSF process effectively eliminates the thermal distortion problem (normally found in conventional superfinishing) as the majority of material removal occurs electrochemically in an electrolyte-cooled atmosphere. This also enables it to produce burr-free components. Hofy [15] reported reduction of roundness error from 24 to 8 μm and average surface roughness value between 2.25 and 0.65 μm after ECSF for 2 min at 19 V, 67 % duty cycle and a scrubbing speed of 18.55 m/min.

2.6 Electrochemical-Type Advanced Drilling Processes

Electrochemical-type advanced drilling processes (ADPs), which utilize an acidic electrolyte include electrochemical drilling (ECD), capillary drilling (CD), shaped tube electrodrilling (STED), electrolytic jet drilling (EJD) and jet electrolyte drilling (JED). Among various advanced hole drilling processes, electrochemical-type ADPs meet the various requirements of micro/small deep hole drilling (i.e. hole diameter less than 1 mm with aspect ratio, i.e. ratio of hole depth to hole diameter, more than 20) with high productivity and better hole geometry and resulting in minimum surface damage to the workpiece material. The main advantages of these processes include better surface finish, absence of residual stresses, no tool wear, burr-free and distortion-free holes and simultaneous drilling of large number of holes [16]. Table 2.1 presents details of important process parameters and capabilities as relevant for different electrochemical-type ADPs. The basic working principles for the different processes are depicted in Fig. 2.10.

2.6.1 Electrochemical Drilling (ECD)

ECD is a controlled electrolytic drilling process into an electrically conducting workpiece material, operating as the anode, utilizing a tubular shaped tool (preferably made of brass, copper or stainless steel). The outer surface of the tool is insulated except at the tip where machining occurs and where the required inter-electrode gap is maintained (Fig. 2.10). Hole drilling occurs in the anodic workpiece material by ED by applying a suitable DC current across the inter-electrode gap in the presence of an appropriate electrolyte (an aqueous solution of salts such as NaCl, $NaNO_3$ or their mixture) that is pumped through the tubular tool at the required pressure and temperature. The electrolyte also flushes the reaction products away while also removing the heat generated during the process to obtain and maintain an improved MRR. The ECD process has two significant limitations, i.e. tool insulation loss and stray removal. Tool insulation loss in ECD occurs mainly due to clogging of the drilled holes by the salt-based electrolytes. Stray removal implies the removal of materials from the side wall of the hole. Zhu and Xu have attempted to address these limitations by using good-quality insulation and/or using a dual pole tool which uses a metallic bush-insulated coating [17]. This improves the machining accuracy and process stability.

Table 2.1 Comparison of process parameters and capabilities of electrochemical-type advanced drilling processes [16]

Parameter	Electrochemical drilling (ECD)	Shaped tube electro drilling (STED)	Capillary drilling (CD)	Electrolytic jet drilling (EJD) or electrolytic stream drilling (ESD)		Jet electrolyte drilling (JED)
				Penetration	Dwell	
Type of electrolyte	NaCl, $NaNO_3$	HNO_3, H_2SO_4	HNO_3, H_2SO_4, HCl	HNO_3, H_2SO_4, HCl		HNO_3, H_2SO_4
Electrolyte pressure (bar)	3–10	3–10	3–20	3–10		10–60
Tool	Tube-shaped tool made of brass, copper and stainless steel	Titanium tube	Glass capillary with gold, platinum or titanium wire	Glass nozzle with capillary end with gold, platinum or titanium wire		Platinum nozzle
Tool feed (mm/min.)	Equal to linear MRR	1.0–3.5	1.0–4.0	1.0–3.5	No tool feed	No tool feed
Operating voltage (V)	10–30	5–15	100–200	150–850	150–850	400–800
Hole diameter (mm)						
Minimum	1.0	0.65	0.2	0.125	0.125	0.125
Maximum	7.5	6.35	0.5	1.0	1.0	1.0
Aspect ratio (ratio of hole depth to hole diameter)						
Typical	8:1	16:1	16:1	16:1	–	16:1
Maximum	20:1	300:1	100:1	40:1	10:1	30:1
Hole depth (mm)	125	125	–	19	5	–
Avg. surface roughness R_a (μm)	0.3–1.6	0.8–3.2	–	0.25–1.6	0.25–1.6	–

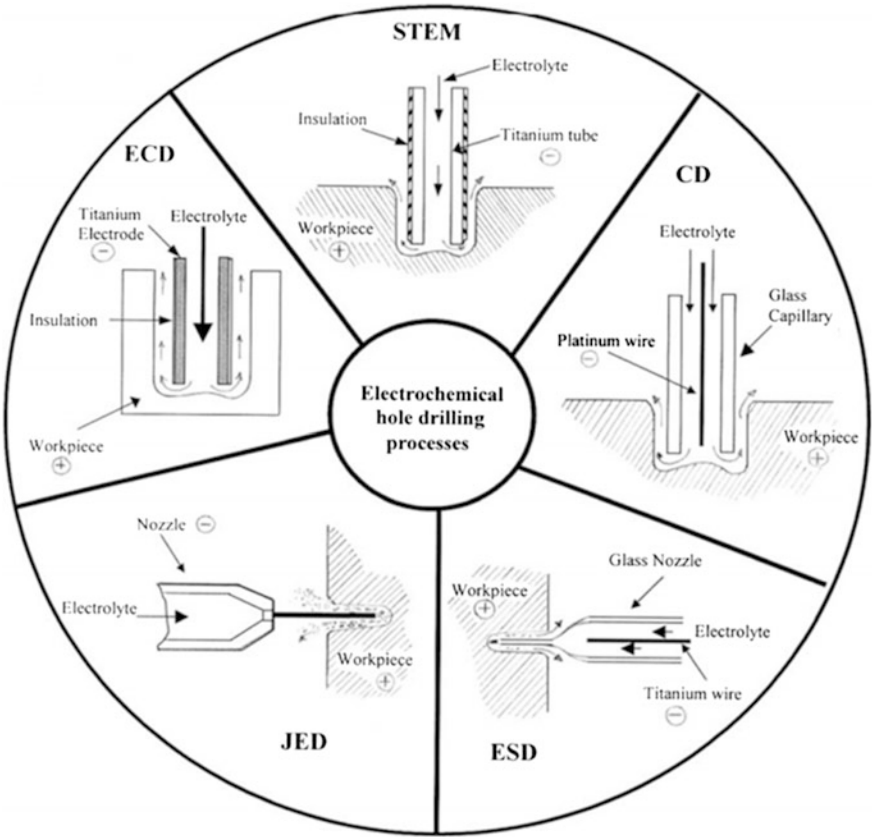

Fig. 2.10 Process principles of various electrochemical-type advanced drilling processes [16], with kind permission from Elsevier

2.6.2 *Shaped Tube Electrodrilling (STED)*

Drilling deep holes with aspect ratio in excess of 20 are challenging mainly due to the difficulty in removal of the machined material as the hole is being drilled. STED is a special process developed by *General Electric Co.* for drilling very high aspect ratio hole (up to 300), which cannot be drilled by any conventional process or ECD (due to formation of insoluble precipitates). STED is a modified version of ECD process that utilizes an acidic electrolyte which dissolves the material removed instead of forming a precipitate. Aqueous solution of acidic electrolytes such as sulphuric acid, nitric acid and hydrochloric acid with 10–25 % concentration is used in this process. A 5–15 V DC potential difference is applied, which is in comparison with ECD (10–30 V), slightly lower. The lower voltage requirement is primarily due to the use of more conductive acid electrolytes instead of the mainly neutral electrolytes as used in the ECD process. The STED process drills holes by controlled deplating of an electrically conductive material. The deplating action takes place as part of an electrolytic cell made up of a cathodic tool and the anodic workpiece separated by flowing electrolyte. The cathode is simply a metal tube of an acid-resistant material such as titanium and shaped to match the desired hole geometry. It is carefully straightened and insulated over the entire length except at the tip. The acid electrolyte is fed under pressure through the tube to the tip, and it returns via a narrow gap along the outside of the coated tube to the top of the workpiece. The electrode is displaced at a constant feed matching the effective workpiece dissolution rate (Fig. 2.10).

The absence of mechanical contact during STED ensures uniform wall thickness in repetitive production. The molecule-by-molecule dissolution of the material produced unstressed high integrity holes. STED is suitable for multiple hole drilling of either different or the same sized holes. STED is able to produce micro-holes, high aspect ratio holes, large shaped elliptical and rectangular holes and holes with contoured surfaces. It does, however, require extended and more complex operating practices to ensure environmentally sustainable production as a result of the corrosive and toxic nature of the acidic electrolytes used.

2.6.3 Capillary Drilling (CD)

The capillary drilling (CD) process is used to drill holes that are too deep to drill by EDM and too small to drill by STED. A glass capillary tube is used as a drilling tool through which electrolyte flows under pressure in the range of 3–20 bar. A platinum wire sized to suit the fine tube bore is used as cathode. The wire is positioned approximately 2 mm above the tube tip to ensure minimal influence on the integrity and the direction of electrolyte flow at the tip. Higher DC voltages in the range of 100–200 V are used to overcome the resistive path of current flow due to longer electrolyte flow path. It has been successfully used for drilling trailing edge holes (dia. 0.2–0.5 mm, depth 8–16 mm) in high-pressure gas turbine blades. The process finds a wide range of applications for drilling holes in production components with positioning and diametral tolerance values up to ±0.05 mm [16].

2.6.4 Electrolytic Stream or Jet Drilling (ESD or EJD)

Electrolytic stream or jet drilling (ESD or EJD) is an efficient electrochemical-type ADP for drilling micro to small holes in any electrically conductive material without affecting its properties. In EJD, a negatively charged pressurized jet of acidic electrolyte exits through a finely drawn glass tube nozzle to impinge on the anodic workpiece, thereby achieving controlled ED. Nozzles used in EJD are made of glass tube which is drawn to a small diameter, thus forming a capillary at one end. A dilute aqueous solution of either sulphuric acid (H_2SO_4) or hydrochloric acid

(HCl) is used as electrolyte. HCl is preferred for drilling holes in corrosion-resistant materials such as aluminium and titanium, while H_2SO_4 is the preferred electrolyte for drilling holes in carbon steel, cobalt alloys, nickel alloys, chromium alloys, superalloys and stainless steel. The electrolyte exiting the nozzle is negatively charged either by using a small titanium/platinum/gold wire placed inside the large diameter section of the nozzle or by using a metallic sleeve. A suitable voltage is applied across the two electrodes. Material removal occurs through ED when the electrolyte jet strikes the workpiece [3]. A much longer and thinner electrolyte flow path requires a much higher voltage (150–800 V) to obtain sufficient current flow. The minimum diameter hole is strongly influenced by the nozzle diameter, electrolyte pressure and overcut [2]. A gap of 2–4 mm (known as standoff distance, SOD) must be maintained between the two electrodes.

There are two variants of EJD: *dwell EJD* in which the nozzle is not actively fed into the workpiece and *penetration EJD* in which the nozzle is displaced at a finite feed. In dwell EJD, the nozzle tip is fixed at a predetermined distance from the work surface and drilling is therefore purely done by the electrolyte jet. This does however limit the depth of the hole to be drilled and the maximum accuracy that can be obtained. Dwell EJD is used for drilling shallow micro-holes and in circumstances where the workpiece configuration or machine capabilities do not permit movement of the nozzle. In *penetration EJD*, the nozzle is fed towards the workpiece with a finite feed rate to maintain a constant IEG. Penetration EJD can achieve aspect ratios of up to 40:1, whereas dwell EJD can only achieve aspect ratios up to 10:1.

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http://www.springer.com/978-3-319-25920-8

Hybrid Machining Processes
Perspectives on Machining and Finishing
Gupta, K.; Jain, N.K.; Laubscher, R.F.
2016, VIII, 68 p. 30 illus. in color., Softcover
ISBN: 978-3-319-25920-8