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A review of electrochemical macro- to micro-hole drilling processes

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Abstract

Electrochemical machining processes provide a viable alternative for drilling macro- and micro-holes with exceptionally smooth surface and reasonably acceptable taper in numerous industrial applications particularly in aerospace, electronic, computer and micro-mechanics industries. Advanced hole-drilling processes like jet-electrochemical drilling have found acceptance in producing large number of quality holes in difficult-to-machine materials. This paper highlights the recent developments, new trends and the effect of key factors influencing the quality of the holes produced by these processes. A comparative study of electro jet drilling with another non-traditional hole-drilling process (laser percussion drilling) has been presented which shows the potential and versatility of the electrochemical hole drilling processes.

Keywords: Electrochemical drilling; Acid electrolyte; Electro jet drilling; Laser drilling

1. Introduction

It is difficult to machine macro- and micro-holes in very hard and brittle materials by using traditional machining methods. Recent progress made in the field of aviation (cooling holes in jet turbine blades), space, automobile, electronics and computer (printed circuit boards), medical (surgical implants), optics, miniature manufacturing and others has created the need for small and micro-size holes with high aspect ratio in extremely hard and brittle materials [1,2]. The complexity and degree of precision required for components in these industries need such holes to be straight, accurate and exactly positioned. Electrochemical machining (ECM) based hole drilling processes possess the requisite capabilities in meeting the challenges posed [3].

ECM is an anodic dissolution process. It utilizes an electrolytic cell formed by a cathode tool and an anode workpiece with a suitable electrolyte flowing between them. The anode workpiece is dissolved according to Faraday's law when a sufficient voltage is applied across the gap between the anode and the cathode in which electrolyte is filled. Electrochemical processes for drilling small and fine holes by controlled anodic dissolution invariably use a weak acidic solution as electrolyte [4]. These include electrochemical drilling (ECD) and acid based ECM drilling processes: shaped tube electrolytic machining (STEM), capillary drilling (CD), electro-stream drilling (ESD), and jet electrolytic drilling (JED). The advantages of acid based electrochemical hole drilling processes are:

- Good surface finish;
- Absence of residual stress;
- No tool wear;
- No burr and no distortion of the holes;
- Simultaneous drilling of large number of holes.

The use of acid electrolytes in ECM hole drilling processes facilitate dissolution of metals and the removed material is carried away as metal ions thus making it possible to achieve smooth finish with closer tolerances and deep holes of high aspect ratio [5]. The salient features of the main non-traditional hole drilling processes are given in Table 1.

The purpose of this paper is to provide an overview of electrochemical hole drilling processes and new developments taking place in view of the fast emerging miniature manufacturing technology, and thereby deduce some possible future trends. A comparative study of the geometrical

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Nomenclature

C_{Pe}	specific heat of electrolyte (J kg^{-1} K^{-1})
D	diameter of the hole (mm)
E	electrochemical equivalent of the work material (kg C^{-1})
E_v	effective applied voltage (V)
F	Faraday's constant (C)
F_s	shape factor
I	current flowing through inter electrode gap (A)
J	current density (A mm^{-2})
K	electrolyte electrical conductivity (Ω^{-1} mm^{-1})
K_m	coefficient of electrochemical machinability
K_0	electrolyte electrical conductivity at T_0 (Ω^{-1} mm^{-1})
M	number of elements present in work material
N_i	atomic weight of the ith element present in work material
Q	Joule heat production (W m^{-3})
T	temperature of electrolyte (K)
T_0	initial temperature of electrolyte at the nozzle outlet (K)
U	electrical potential (V)
U_0	working voltage (V)
ΔU	total over potential (V)
V	volume of the hole (mm^3)
V_{gap}	voltage across the inter electrode gap (V)
V_m	maximum velocity of dissolution at the center of hole (mm min^{-1})
Y	inter-electrode gap (mm)
d	diameter of electrolyte jet (mm)
f	feed rate (mm min^{-1})
f_s	modified feed rate (mm min^{-1})
i_a	current density at anode (A mm^{-2})
i_A	current density at the centre of current pipe (A mm^{-2})
k	thermal conductivity (W m^{-1} K^{-1})
n_i	valency of the ith element present in work material
r_a	corner radius of hole (anode) (mm)
r_c	corner radius of tool (cathode) (mm)
t	time for which current flows (s)
Δt	small increment in time t (s)
v_d	average velocity of dissolution (mm min^{-1})
v_f	electrolyte flow velocity (m s^{-1})
x_i	percentage of ith element present in work material
y	machined depth (mm)
α_T	temperature coefficient of electrical conductivity
θ	angle of inclination between the feed direction and normal to the tool (or work) surface (°)
λ	field efficiency factor
η	current efficiency of anodic dissolution (%)
ρ_e	density of electrolyte (kg m^{-3})
ρ_m	density of work material (kg m^{-3})
ρ_s	specific resistance of the electrolyte (Ω m)

Subscript

0	condition at the start of machining

characteristics of small holes in SUPERNI 263A by electro jet drilling (EJD) and laser percussion drilling has been presented which proves the superiority of the electrochemical hole drilling processes over its rival processes.

1.1. Definition and nomenclature of hole

A hole has been defined as an opening in or through anything; a hollow place; a cavity in a solid body or area; or a three-dimensional discontinuity in the substance of a mass or body. The general perceptions of a hole drilled by ECD processes are summarized in Table 2.

2. Electrochemical drilling (ECD)

ECD may be described as a controlled rapid electrolytic dissolution process in which the workpiece is made anode (Fig. 1). The cathode tool is separated from the anode by a narrow gap through which an electrolyte flows. Upon passage of electric current through the electrolytic cell, the anode material dissolves locally [6]. The electrolyte which is generally a concentrated salt solution is pumped at high pressure through inter electrode gap in order to remove the reaction products, to dissipate the heat generated and to allow high rate of metal dissolution. A tubular shaped tool, preferably made of brass, copper or stainless steel is used. It is usually insulated on the entire outside surface except at the tip [7]. Some commonly preferred electrolytes are NaCl, $NaNO_3$, $NaClO_3$ and their mixtures [5].

The major limitations of ECD are the failure of the tool insulation and the stray removal [2,7,8]. Insulation failure in ECD occurs mainly due to clogging of the holes on account of the use of salt electrolytes. The stray removal that usually occurs on the internal side walls of the hole affects the process reliability significantly. The reduction of stray removal has been attempted by the use of good quality insulation. Recently, it has been attempted by using a dual pole tool [8]. The dual pole tool (Fig. 2) employs a metallic bush outside the insulated coating of a cathode tool to reduce the stray current at hole wall. It has been found that the use of dual pole tool reduces the hole taper as compared to insulated tool. This also improves the machining accuracy and process stability. It is evident from Fig. 3 that as compared to insulated tool, lesser hole taper is formed with the use of dual pole tool in that the deviation of

Table 1
Comparison of the capabilities of non-traditional micro- and macro-hole drilling processes [3,5,19,38]

Parameter	Non-traditional small hole drilling processes									
	EDM	ECD	STEM	CD	ESD	JED	LBM	EBM	PCM	USM
Hole size (mm)										
Min	0.13	1.0	0.50	0.2	0.1	0.125	0.125	0.025	0.025	0.075
Max	6.3	7.5	6.5	0.5	1.0	—	1.25	1.0	No limit	3.0
Hole depth (mm)										
Common max	3.15	125	125	–	18	–	5	2.5	1.6	1.6
Ultimate	62.5	300	900	–	25	–	17.5	7.5	5.0	25
Aspect ratio										
Typical	10:1	8:1	16:1	16:1	16:1	16:1	16:1	6:1	2:1	2.5:1
Maximum	20:1	20:1	300:1	100:1	40:1	30:1	75:1	100:1	5:1	10:1
Cutting rate (mm/s)	0.0125	0.125	0.025	–	0.025	–	<1	0.25	4.25×10^{-4}	0.425
Hole tolerance ($\pm$)	0.025	0.025	0.03	0.03	0.03	0.05	0.05–0.20	0.025	0.08–0.10	0.025
Finish (μ in AA)	63–125	16–63	32–125	–	10–63	–	32–250	32–250	32–125	16–32
Operating voltage	30–100	10–30	5–15	100–200	150–850	400–800	4.5 kV	150 kV	–	220
Work material	Electrically conductive	Electrically conductive	Electrically conductive	Electrically conductive	Electrically conductive	Electrical-lyconduc-tive	Any	Any	Chemically active	Harder than 40 R_c
Surface integrity	Heat affected surface, no burr	No residual stress, no burr	No residual stress, no burr	No residual stress, no burr	No residual stress, no burr	No residual stress, no burr	Presence of HAZ, taper	Presence of HAZ	No residual stress, undercut-ting at sides	Gentle

the hole diameter along the hole depth is found to be equal or less than 0.03 mm.

2.1. Tool design in ECD

Anode profile prediction (or analysis) problem and tool design problem are the two major categories of ECM tool design. The analysis problem deals with the prediction of work-profile obtainable from a given tool while operating under the specified machining conditions whereas the tool design problem deals with the computation of tool shape and size which would yield a given work profile under specified machining conditions [10]. A typical cross-section of a circular hole produced by a cylindrical tool in ECD is shown in Fig. 4. The inter-electrode gap (IEG) shown in Fig. 4 has been divided into four regions on the basis of the mode of electrolyte flow namely stagnant, front, transition, and side [9]. For estimating the complete anode profile, material removal in all the four regions should be known.

The anode profile obtained during ECD experimental tests [9,11] with bare brass tool with NaCl electrolyte on carbon steels and those obtained by finite element techniques were compared and good correlation was found. Eq. (1) was used to predict the corner radius (r_a) of electrochemically drilled hole by using a tool of corner radius (r_c) whereas Eqs. (2) and (3) provided the magnitude of over cut [11]. When the cathode surface is inclined at an angle θ with the normal to the feed direction of tool, the modified feed rate was calculated using Eq. (3)

$$r_a = A\,e^{Br_c} \tag{1}$$

where A and B are constants and were determined experimentally

$$Y = Y_0 + (C' - f)\Delta t \tag{2}$$

where $C' = \eta JE/F\rho_m$ and $J = E_v K/Y$

$$f_s = f\cos\theta \tag{3}$$

2.2. Simulation of ECD

The technology of drilling small holes electrically has been driven by cooling holes in aero-engine gas-path components such as blades, guide vanes, after-burners and casings which are made of difficult-to-machine (DTM) materials that operate at temperatures as high as 2000 °C. The gas turbines have to be provided with holes in order to

Table 2
Hole size designations

Hole designation	Hole diameter (mm)
Bore	>25
Large hole	10–25
Small hole	1–3
Fine hole	0.1–0.25
Micro-hole	0.005–0.25

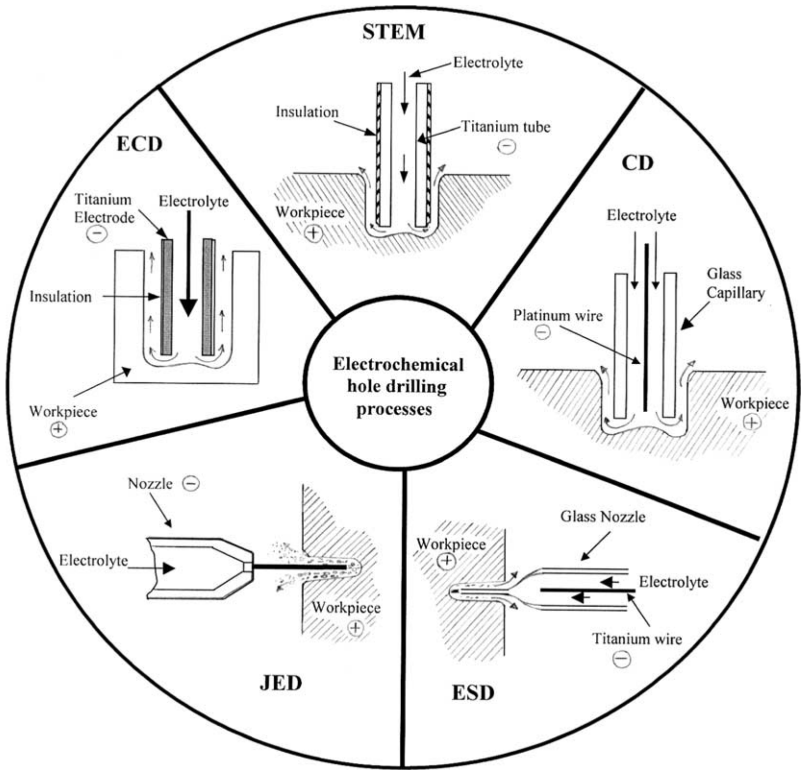

Fig. 1. Electrochemical hole drilling processes.

provide cooling. These holes are made using ECD techniques. Since this process is complex, computer simulations are very useful. The process simulation is a technique to support the manufacturing engineer's experience for reduced lead-time, lowest cost, good product quality and better understanding of the process. The simulation of ECD significantly reduces and in some cases eliminates the iterative process of performing large number of well-defined experiments on test pieces [10].

A simulation model for material removal and overcut was proposed [12] by considering variation of electric potential and thermal-fluid properties and without ignoring any transport properties such as electrolyte temperature, conductivity and void fraction. Finite difference method was used to solve the electric potential field and a body fitted transformation technique was applied to precisely predict the gradient of the electric potential field. A one-phase two-dimensional fluid flow model was included in earlier developed ECD simulation model by the same authors [12] for predicting the flow and thermal fields between electrodes in an ECD process [13]. The workpiece shapes predicted by this model has shown close agreement in general with experimental results. Results have revealed that some transport properties such as electrolyte flow velocity and electrolyte pressure vary abruptly in the transition region. Eq. (4) was used to predict the removal rate and the new shapes of workpiece [13]

$$\frac{\partial y}{\partial t} = \frac{\eta EJ}{i_a} - f\cos\theta \tag{4}$$

In order to increase the heat transfer in the holes of gas turbine blades, the wall of the cooling passage is provided

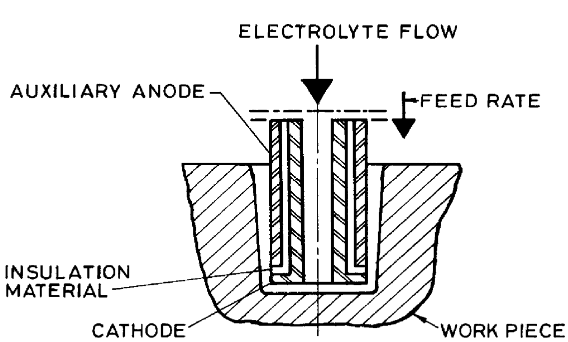

Fig. 2. Dual pole tool in ECM of hole [8].

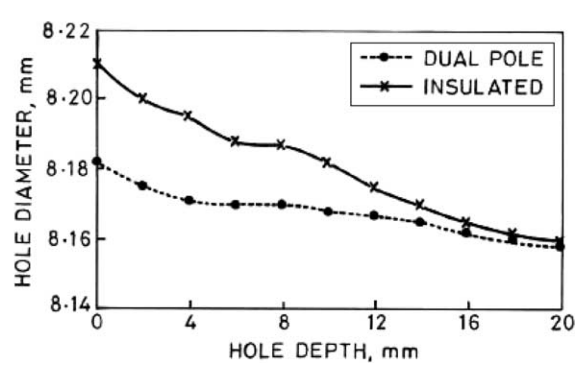

Fig. 3. Profiles of machined holes by using the dual pole tool and the insulated tool [8].

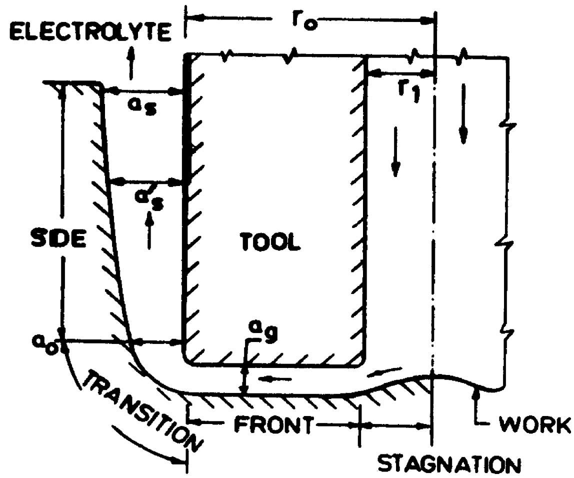

Fig. 4. Electrochemically drilled hole with four distinct regions of electrolyte flow [9].

with multiple ribs. These irregularities are called turbulators. The drilling of turbulated cooling holes is costly, as these require a large number of trial experiments on test pieces. A simulation model has been proposed for ascertaining the effect of the variation of turbulators shape on the selected parameters [14]. In this model, the transfer of charge and heat transfer were taken as the influential parameters, which critically affect the ECD process as determined by Eqs. (5)–(8), respectively

$$J = -K \text{ grad } U \tag{5}$$

$$\text{div } J = 0 \tag{6}$$

$$\text{div}(-K(T)\text{grad } U) = 0 \tag{7}$$

$$\rho_e C_{Pe}\left(\frac{\partial T}{\partial t} + (v_f, \text{grad } T)\right) = -k\Delta T + Q \tag{8}$$

Current density J being an important parameter in ECD was calculated by using Mixed Hybrid Finite Element Method (MHFEM) for the reasons of accuracy. Fig. 5 shows the results of a simulation run of a fully interactive ECD simulation model [14]. At intervals of 50 s the shape of the boundary was displayed. The ribs on the wall of the cooling holes were obtained by changing the voltage and drilling speed. The results of this simulation indicated that the shape

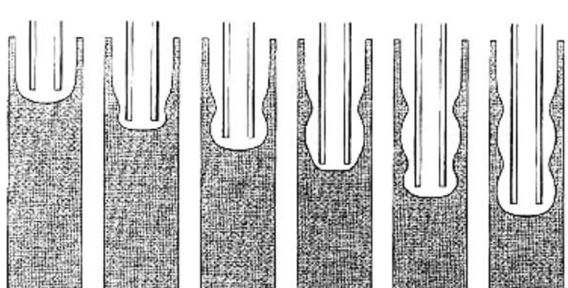

Fig. 5. Results of a simulation run of an ECD simulated model [14].

of the turbulators is not very pronounced. The validation of the model was performed by comparing the obtained geometry from a simulation run with a scaled photograph of a drilled hole produced experimentally. The simulation system was designed to provide real time interaction with the user. It means that the process parameters, i.e. voltage and drilling speed need not to be programmed before the start of simulation but can be changed at run time [14].

2.3. Intelligent knowledge based system

The process planners usually have to turn to the literature or experts for selecting a particular EC drilling process for a specific application due to its complexity and the interrelationship between its process variables [10]. In the absence of adequate information, the ECD product development cycle time and cost increase whilst quality and productivity decrease. Expert system or Intelligent Knowledge Based System (IKBS) can be adopted to overcome these hurdles. IKBS can provide a ready online knowledge consultancy system guiding product designers and manufacturing engineers to select appropriate process conditions.

An IKBS for ECM has been developed in a computer based concurrent engineering environment on a Hewlett Packard model 715/80 workstation based on object-oriented techniques [15]. The database of the proposed IKBS has the attributes of 72 different workpiece and eight tool electrode materials, two electrolyte solutions and seven types of electrochemical machines having various current capacities and types of operations. IKBS can retrieve information from each database such as machining cycle time and cost, penetration rate, efficiency, and effectiveness of a particular design feature for an ECM shaping operation such as hole drilling. Comparative machining cycle times and cost are determined for electro discharge machining (EDM) and electrochemical arc machining (ECAM) in relation to ECM.

Table 3 shows a comparison of the IKBS system with experimental electrochemical hole drilling. The experimental setup used for this purpose consisted of a 500 A ECM unit with 20% sodium nitrate electrolyte flowing at $30\,\text{l min}^{-1}$ and at a maximum electrolyte pressure of $1020.4\,\text{kN m}^{-2}$ [15].

3. Electrochemical micro-hole drilling

ECM has not been earlier used for drilling micro-holes because of (i) non-localization of electric field, (ii) taper generation, and (iii) passive layer formation particularly in steel alloys. Recent use of ECM for micro-hole drilling has been made possible by using (i) pulsed current, (ii) micro-gap control between the cathode and the anode, (iii) balanced electrode, and (iv) side insulated tool [16,17]. The side insulation of tool (cathode) and micro-gap control contribute directly to localized machining. The pulse current across the cathode and anode helps to

Table 3
Comparison of experimental ECM and IKBS drilling results [15]

Feature produced	Electrode type	Dia. (mm)	Depth (mm)	Machining time (min)		Penetration rate (mm/min)	
				Experimental	IKBS	Experimental	IKBS
Hole	Brass	76.2	50	83.3	70.4	0.6	0.71
	Copper	50.8	50	25.0	19.87	2.0	2.52
	Brass	50.8	50	25.0	23.6	2.0	2.12

agitate electrolyte so as to promote the electrochemical reaction.

In micro-machining with DC voltage, the electrolyte gets easily boiled by the high concentration of the machining current. As the dregs produced during machining process may adhere on the surface of the workpiece and tool electrode, machining is difficult to continue. However, if pulsed voltage is used these problems can be overcome. The temperature of the electrolyte falls down, and dregs are swept-off during the pulse off duration. Fig. 6(a) and (b) shows a micro-hole machined electrochemically under DC current and under pulse voltage conditions, respectively. It can be noted from this figure that in comparison to DC current, the enlarged part of hole diameter compared to the electrode is much reduced when pulse current was used [16].

A platinum balance electrode (whose surface area was half of that of workpiece) with pulse voltage was used to obtain a deep micro-hole (8 μm diameter with 20 μm depth) in 304 SS [17]. The platinum balance electrode was set for the compensation of the difference of voltage drops between electrolyte and two electrodes. Because of relatively large immersed area of the workpiece compared with that of the tool, the resistance between the electrolyte and the workpiece is small and the voltage drop is also small. The low potential between the electrode and the workpiece helps in the formation of chromium oxide layer on the hole surface that layer in turn prevents the further dissolution of workpiece. The results indicated that the platinum balance electrode prevents the formation of chromium oxide layer (passive layer) on the hole surface during machining of micro-holes with low potential [17].

4. Shaped tube electrolytic machining (STEM)

The STEM was developed for drilling holes with large depth-to-diameter ratios, which could not be drilled conventionally. Initially such holes had been attempted by ECD but the ECD process produces insoluble precipitates that clog or restrict the electrolyte flow path. Essentially, the STEM process is a modified ECD process that uses an acid electrolyte so that the removed metal goes into solution instead of forming a precipitate. Acid electrolytes (sulfuric, nitric and hydrochloric) with 10–25% concentration are preferred in STEM [18]. In some cases researchers have tried neutral salt electrolytes (10%) with small percentage of acid electrolytes (1%) so as to minimize the sludge formation in the IEG [19].

The STEM process adheres to the operating principle of ECM. Holes are produced by controlled deplating of an electrically conductive material. The deplating action takes place in an electrolytic cell formed by the negatively charged metallic electrode (cathode) and the positively charged workpiece (anode) separated by a flowing electrically conductive fluid (electrolyte). The cathode is simply a metal tube of acid resistant material such as titanium shaped to match the desired hole geometry (Fig. 1). It is carefully straightened and insulated over the entire length except at the tip. The acid electrolyte under pressure is fed 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 given constant feed at a rate matching the rate at which workpiece material is dissolved [18–20].

STEM is suitable for multiple hole drilling of either different or the same sized holes. Grouped holes, are generally drilled parallel to each other, but they may be drilled at compound angles to each other by using guide bushings which direct the electrodes at desired angles from the direction of feed [20]. The operating voltage requirement in STEM (5–15 V DC) is usually less than conventional ECD (10–30 V DC). The lower voltage requirement is primarily the result of using more conductive acid electrolytes instead of neutral electrolytes in conventional ECD. The absence of mechanical contact during STEM ensures uniform wall thickness in repetitive

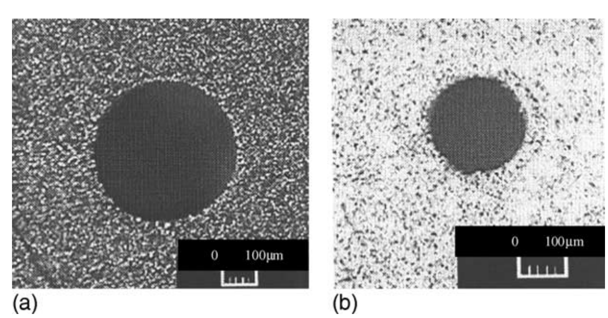

Fig. 6. (a) Electrochemically machined micro-hole using DC current (10% $NaClO_3$, tool diameter 302 μm, machining depth 200 μm) [16]. (b) Electrochemically machined micro-hole using pulse voltage (pulse duration 0.5 ms, pulse interval 0.5 ms, 10% $NaClO_3$, tool diameter 180 μm, machining depth 300 μm) [16].

production. The molecule-by-molecule dissolution of the material produced unstressed, high integrity holes.

Further improvements in the STEM process have been made to produce micro-holes, high aspect ratio holes, large shaped elliptical and rectangular holes and holes with contoured surfaces. These adaptations of STEM process have been made possible by carefully controlling the process parameters, utilization of complex tooling, state of the art electrode manufacturing, and the availability of sophisticated CNC controllers to govern the operation of STEM machine [21]. Still there is need to develop the better operating practices for ensuring environmental safety due to the corrosive and toxic nature of acid electrolytes and the toxicity of the generated fumes during machining a hole.

5. Electrochemical jet machining (ECJM)

ECJM is a term that encompasses all processes that use a pressurized charged acid electrolyte jet for machining of micro- and macro-holes as well as grooves. Processes like CD, ESD and JED as shown in Fig. 1 are the associates of ECJM [3]. The characteristics and limitations of these processes are summarized in Tables 4 and 5, respectively.

New areas of application are being looked for electrolyte jets. For instance, they are being used for the preparation of electron microscopic samples, etching of micro-parts, polishing of semiconductor materials, and electrochemical micro-machining [22–24]. These applications have been performed at low operating voltage (less than 100 V) with ECJM due to their low aspect ratios [24,26]. Consistent efforts are underway to improve the process capability (material removal rate and precision) of ECJM by exercising a close control on the machining parameters of these processes.

5.1. Capillary drilling (CD)

CD process (Fig. 1) is used to drill holes that are too deep to be drilled by electrical discharge machining (EDM) and too small to be drilled by STEM. The drill tube is a glass capillary through which electrolyte flows under pressure (3–20 bar). The cathode is a platinum wire, which is sized to suit the fine tube bore. The wire is positioned about 2 mm back from the tube tip to ensure minimal influence on the integrity and the direction of electrolyte flow at the tip [4]. Higher operating voltage (100–200 V) is needed in CD to overcome the resistive path of current flow due to longer electrolyte flow path [1,6]. The process 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. If required the glass tube may be slightly bent in a nose guide in order to facilitate minor differences in angle due to twist of the blade. The process is finding wide range applications for drilling holes in production components with positioning and diametral tolerances of ± 0.05 mm [1].

5.2. Electro stream drilling (ESD)

Also known as EJD, ESD is an efficient non-traditional drilling process for making macro- and micro-holes (Fig. 1). Here a negatively charged stream of acid electrolyte is impinged on the workpiece from a finely drawn glass tube nozzle [4]. The acid electrolyte (10–25% concentration) is passed under pressure (3–10 bar) through the glass tube nozzle. The electrolyte jet acts as a cathode when the platinum wire inserted into a glass well above the fine capillary is connected to the negative terminal of DC power supply. The workpiece acts as anode. A suitable electric potential is applied across the two electrodes. The material removal takes place through electrolytic dissolution when the electrolyte stream strikes the workpiece. The metal ions thus removed are carried away by the flow of the electrolyte. A much longer and thinner electrolyte flow path requires much higher voltage (150–850 V) so as to obtain sufficient current flow. The use of high potential can cause problem in designing an electrolyte system because the risk of stray voltage is large. Surface imperfections found frequently during ESD are a result of material inhomogeneity rather than process variability [5].

It has been observed [27] in EJD of 3 mm thick mild steel specimen using glass nozzle (0.25 mm internal dia.) in dwell feed mode that material removal rate increases with voltage up to 400 V beyond which it decreases because of initiation of spark. However, beyond 500 V it again increases when it just turns into glow discharge region as shown in Fig. 7. It was revealed that the current efficiency decreases with increase in voltage up to 500 V beyond

Table 4
Characteristics of some electrochemical hole drilling processes [5,29,38]

	Acid electrochemical drilling processes			
	STEM	CD	ESD	JED
Type of acid electrolyte	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	3–20	3–10	10–60
Tool	Titanium tube	Glass capillary with gold, platinum or titanium wire	Glass tube with capillary end with gold, platinum or titanium wire	Platinum
Tool feed (mm min^{-1})	1–3.5	1–4	1–3.5	0
Applied voltage (V)	5–15	100–200	150–850	400–800

Table 5
Limitations of electrochemical hole drilling processes [6,28]

Limitations	STEM	CD	ESD	JED
Slow for single hole	✓	✓	✓	✓
Machining of only conducting materials	✓	✓	✓	✓
Complex machining and tooling	✓	✓	✓	✓
Hazardous handling and disposal of acid electrolytes	✓	✓	✓	✓
High-voltage DC supply	×	×	✓	✓
Tool breakage	×	✓	✓	×

(✓) indicates a limitation and × (cross) no limitation.

which it improves. The reason may be the presence of a passivating layer on hole surface which at higher voltages get broken due to micro-sparking [27].

Based on Faraday's law, a model for EJD has been proposed [27] for theoretically estimating the material removal rate by considering a straight column of electrolyte in between the tool and the workpiece. The machining time for an alloy has been deduced by using Eq. (9)

$$t = \frac{F\rho_{\mathrm{m}}\rho_{\mathrm{s}}d^2}{8000IY}\sum_{i=1}^{M}\frac{n_i x_i}{N_i}(y^2 + 2Yy) \tag{9}$$

5.3. Jet electrolytic drilling (JED)

JED is a dwell drilling process (Fig. 1) which does not require entry of a nozzle into the machined hole. A jet of electrolyte under pressure (10–60 bar) is made to impinge on the workpiece to achieve the anodic dissolution of the workpiece material [3]. The nozzle through which the electrolyte jet emerges form the cathode tool while the workpiece is anode. The lower limit of a hole to be drilled is strongly influenced by the nozzle hole diameter, electrolyte pressure and overcut. A gap of 2–4 mm is required to be maintained between the two electrodes. In this process, high operating voltage (400–800 V) and electrolyte of high conductivity are used to obtain high current density required for achieving adequate stock removal [1,3].

5.4. Mathematical modeling of JED

The performance of ECJM process is mainly governed by the heating of electrolyte. In particular, the maximum stock removal rate is limited by boiling of electrolyte. A two-dimensional mathematical model of JED, describing the distribution of electric field and the effect of the change of conductivity of electrolyte (caused by heating) on the process performance has been proposed [3] for determining the relationship between the machining rate and operating conditions such as electrolyte jet flow velocity, jet length, electrolyte properties and applied voltage. The parameters i_{A} and V_{m} were evaluated using finite difference method by using Eqs. (10)–(11):

$$i_{\mathrm{A}} = \frac{\lambda K_0(U_0 - \Delta U)}{y}\left(1 + \frac{\alpha_{\mathrm{T}}}{2}\left(\frac{i_0 U_0}{\rho_{\mathrm{e}} C_{Pe} v_{\mathrm{f}} - \alpha_{\mathrm{T}}\frac{i_0 U_0}{2}}\right)\right) \tag{10}$$

$$V_{\mathrm{m}} = \frac{\lambda K_0 K_{\mathrm{m}} U_0}{\frac{Y}{\lambda} - \lambda\frac{\alpha_{\mathrm{T}} K_0}{2 v_{\mathrm{f}} \rho_{\mathrm{e}} C_{Pe}} U_0^2} \tag{11}$$

The value of V_{m} progressively decreases with time from a higher rate at the initial stage. As the cavity is formed, its concave shape leads to a decrease in current density. This effect is more significant than the increase in the distance from the cathode [3]. Fig. 8 shows the relationship between v_{d}

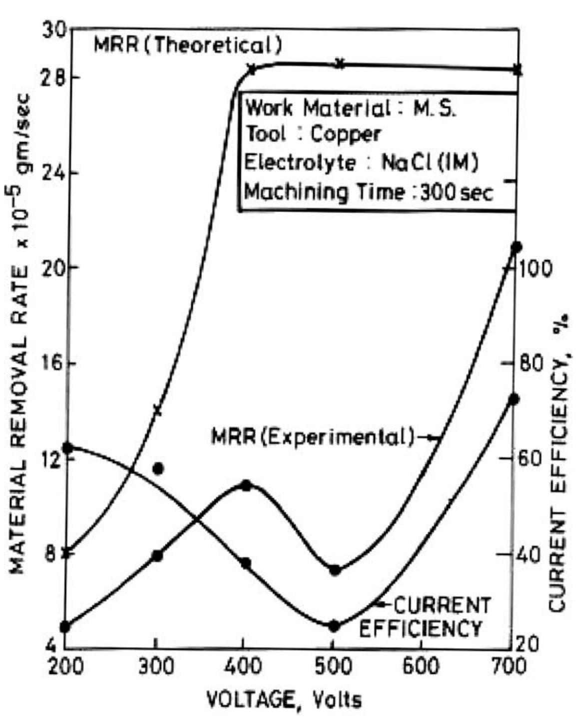

Fig. 7. Effect of voltage on material removal and current efficiency [27].

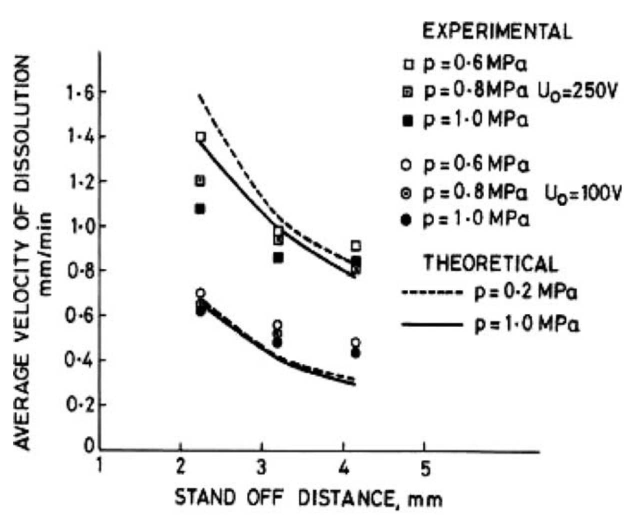

Fig. 8. Velocity of dissolution at the center vs. stand off distances [3].

and stand-off distance at different voltages and pressures. A comparison between the values of v_d calculated from the theoretical model and the measured values shows a close agreement as shown in Fig. 8.

5.5. Laser-jet ECJM

Research on the hybrid process of ECJM and laser beam has revealed its feasibility as a fast process for precise micro-machining. A schematic setup for this process is shown in Fig. 9. The electrolyte is pumped to a jet cell and exits through the small nozzle in the form of a free standing jet directed towards the workpiece (anode). The nozzle orifice of 0.5 mm diameter is made from a capillary tube. A platinum sheet, with a central hole through which a laser beam is directed, serves as the cathode. A microprocessor is used to control the power supply (attached to the electrochemical cell) as well as the on–off gating of the laser beam. In an experiment [23], the applied current density was ranged up to 75 A cm^{-2}. The linear flow velocity of the electrolyte was maintained constant at 10 m s^{-1} and nozzle-anode spacing at 3 mm. An argon laser beam with a constant output power of 22 W was passed through a beam expander and focussed with a 75 mm focal length lens to a point near the center of the jet orifice. The results of this study indicated that a laser-jet ECJM can be effectively used for high speed drilling of micro-holes in DTM metals.

Further, the use of laser-jet was found to significantly reduce the overcutting. A micro-hole machined in steel with and without a laser-jet at an applied current density of 0.6 A m^{-2} yielded nearly the same material removal rate with chloride solution. However, deeper hole depth (0.055 mm) was achieved with a laser-jet as compared to a hole depth (0.011 mm) obtained without a laser-jet. The ratio of volume of material removed to the hole depth (v/d) was used to judge the effectiveness of the laser-jet ECJM. It also served as a measure of stray current effects. A decreasing value of v/d would indicate smaller stray current and decreased overcutting. Fig. 10 shows the estimated v/d values as a function of applied current density in the presence and absence of the laser beam. The results show

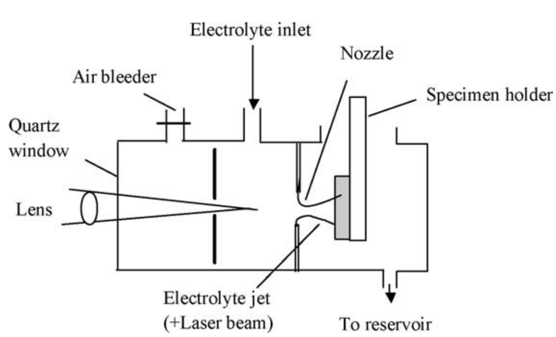

Fig. 9. Experimental setup for laser-jet ECM [23].

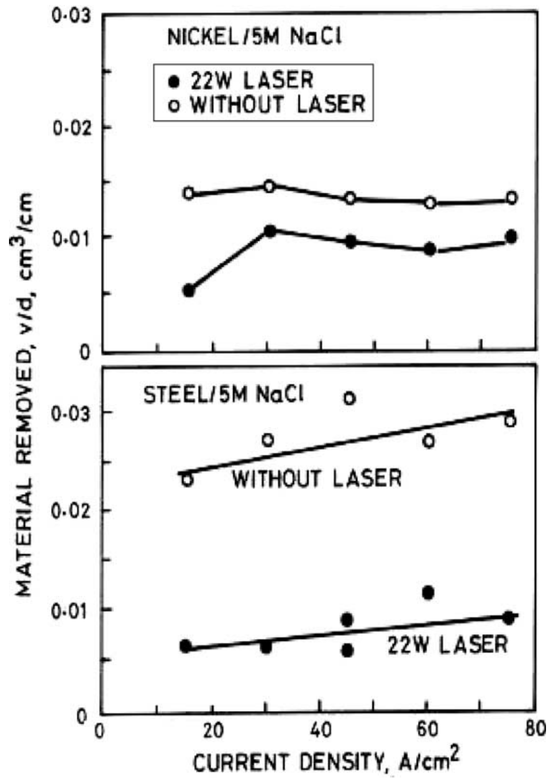

Fig. 10. Relationship between volumetric material removal per unit depth and the current density [23].

that the v/d values are smaller when a laser-jet is used, the influence being more pronounced for steel than for nickel. Studies have demonstrated that neutral salt solution can be effectively used for high speed micro-drilling of many metals and alloys [22,23].

In electrochemical jet etching of 150 μm thick nickel foil carried out with a non-passivating medium (Sodium chloride), the effect of a YAG pulsed laser beam on the shape factor has been seen to be of minor significance [24]. The shape factor can be defined as the ratio of the volume of the ideal hole (diameter D) to that of the hole actually machined

$$F_s = \frac{\pi}{4}\frac{D^2 y}{V} \tag{12}$$

Shape factors were calculated for holes exhibiting cylindrical geometry. The variation of this factor with the average current density and with the nozzle diameter is shown in Fig. 11(a) and (b). The shape factor appears to vary somewhat linearly with nozzle diameter and to increase with current density. Using large sized nozzles with moderate current densities results in factors up to 0.90. For these conditions, the diameter of the holes was fairly close to the nozzle diameter. Conversely, drilling with a 125 μm diameter nozzle at 400 kA m^{-2} yielded holes with a diameter 280 μm approximately [24].

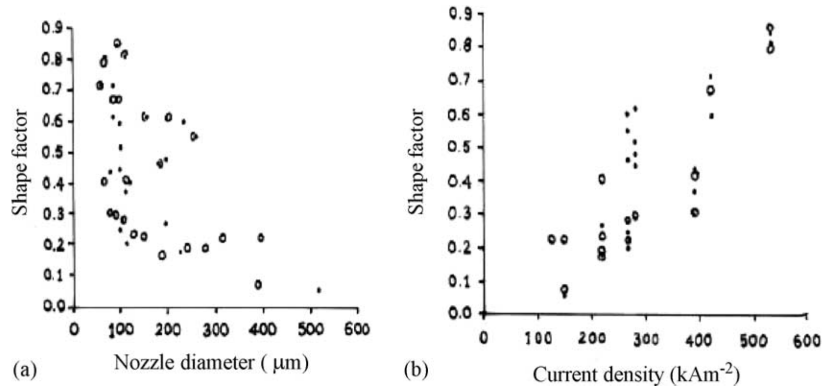

Fig. 11. (a) Shape factor against the nozzle diameter: (○) without laser assistance; (●) with pulsed laser assistance [24]. (b) Shape factor against the average current density: (○) without laser assistance; without laser assistance; (●) with pulsed laser assistance [24].

5.6. Applications

Application of electrochemical jets in machining micro-holes in thin metallic foils and in the fabrication of microstructures is becoming so high that the process has acquired a separate name as electrochemical micro-machining (EMM). Microfabrication by EMM may involve through mask and maskless material removal. The latter requires highly localized material removal induced by the impingement of a fine electrolyte jet. High aspect ratio holes have been drilled by using a fine cathode tool in the form of a capillary that is advanced at a constant rate towards the workpiece [22–25]. In through-mask EMM work material is removed selectively from unprotected regions of a one or two sided photoresist patterned workpiece. High aspect ratio micro-holes having straight walls have been drilled in metallic foils and sheets required in the manufacturing of printed circuit cards and boards.

ECJM has been employed also for obtaining micro-indents for promoting oil film formation on rolling bearings [26]. Experimental investigations have revealed (Fig. 12) the existence of an optimum gap length for every pressure of the jet that would result in a minimum diameter of the indentation. Higher jet pressures were considered suitable for getting smaller indentations as the minimum diameter was largest at the lowest jet pressure of 2 MPa [26].

Newly emerging technologies such as micro-engineered structures, advanced microelectronic packaging, sensors and actuators and micro-electro mechanical systems (MEMS) offer ample opportunities for wide ranging applications of ECJM.

6. Critical factors in micro- and macro-hole drilling

The attributes defining the quality of drilled hole produced by electrochemical processes are:

1. Minimum hole diameter;
2. Oversize or overcut;
3. Aspect ratio;
4. Conicity or shape;
5. Surface finish.

6.1. Minimum hole diameter

The size of the hole machined depends mainly on the type of electrolyte used. The use of salt electrolytes (i.e. $NaClO_3$, NaCl, $NaNO_3$, etc.) results in the formation of a large volume of sludge, which tends to restrict or clog the openings for the flow of electrolytes thereby limiting the minimum diameter of the hole that can be drilled [19]. Therefore, weak acid electrolyte (10–25% concentration) is preferred for drilling micro- and macro-holes. Other important factors which affect minimum hole diameter are the size of the electrode, strength of

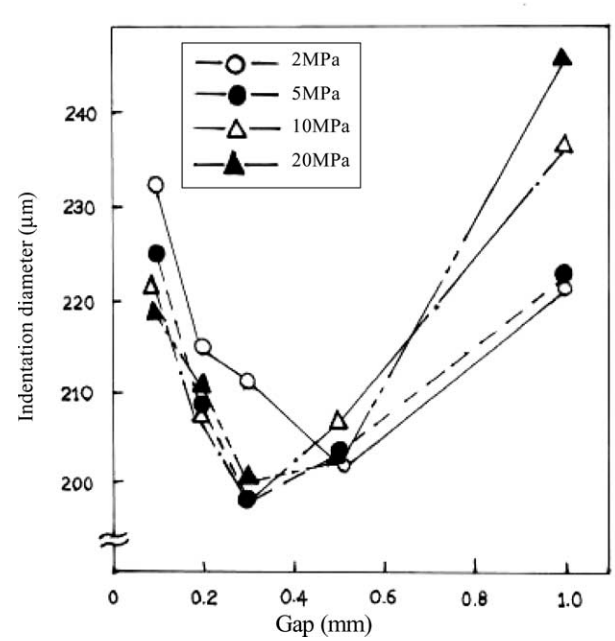

Fig. 12. Relationship between the diameter of indentation and the gap length at various pressures (machining conditions: nozzle diameter 130 μm, current 20 mA, depth of indentation 4 μm, electrolyte 20% $NaNO_3$) [26].

the electrode material and the thickness of the insulation coating.

6.2. Oversize or overcut

Control of hole oversize (or overcut) is one of the major challenges in ECM hole drilling. Overcut depends on several factors. Some of these are discussed below.

6.2.1. Effect of electrolyte characteristics

Overcut depends on the characteristics of electrolyte, e.g. concentration, flow, and its throwing power and sludge formation. Throwing power is a concept used by electroplaters to describe the ability of a bath to yield macroscopically uniform deposits [31]. Throwing power of the electrolyte is related to the dissolution kinetics at the anode surface which in turn is related to the character of any film formation at the anode and to the flow characteristics of the electrolyte [2]. Electrolytes having low throwing power are preferred in reducing overcut. The throwing power of the electrolyte can be reduced by the use of additives such as benztriazole (BTZ) or potassium dichromate to the base electrolyte [35].

In the ECM literature, electrolytes are generally categorized into two types: passivating (electrolytes containing oxidizing anions such as nitrates and chlorates) and non-passivating (electrolytes containing aggressive anions such as chlorides, bromides, iodides, and fluorides). ECJM with passivating electrolytes have been found to cause minimized stray cutting [23]. Electrolyte concentration critically affects the hole size as the higher conductivity of electrolyte facilitates the higher current flow thus enhancing the removal of material. Fig. 13 has clearly established the fact that the material removal rate increases with increase in electrolyte concentrations [36]. Electrolyte temperature directly affects the conductivity of the electrolyte. A temperature increase results in overcut increase up to the point at which the electrolyte vaporizes in the machining gap. The sensitivity of current to changes in electrolyte temperature necessitates close temperature control. By using the independent temperature controller, the stability in a region of ± 1 °C can be easily achieved [18].

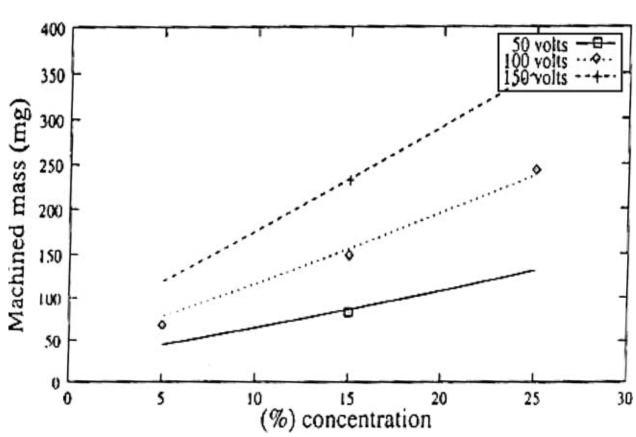

Fig. 13. Effect of electrolyte concentration on material removal for different voltages [36] (machining duration 30 min; electrolyte HCl; inside diameter of glass nozzle 0.5 mm; distance between nozzle tip and work surface 1 mm; distance between the wire tip and work surface 25 mm; work material HSS).

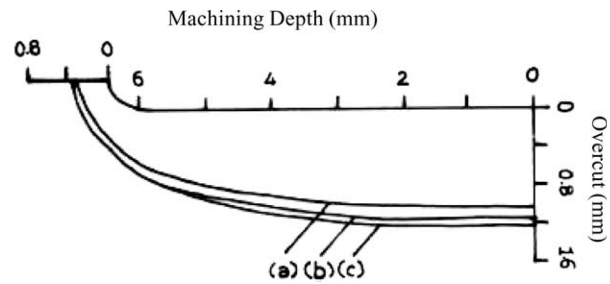

Fig. 14. Effect of different electrolyte flow rates on overcut. Values of inlet electrolyte flow rates: (a) 2.685, (b) 4.0275, and (c) 6.7125 $m^3\ min^{-1}$ [12].

Overcut is high in CD, ESD and JED as compared to STEM [1,3]. The reason for this is attributed to the electrolyte flow path length in these processes. As the area machined is that which is closest to the direct path of the electrolyte and the lines of current distribution follow the path of flow and since CD has the longer electrolyte flow path, the process results in higher overcut. However, too low an overcut would not allow entry of the glass capillary. Overcut is also high in ESD compared to the particular electrode diameter being used. ESD and JED tend to produce holes with bell mouthed entry and exit ports because of the electrolyte flow pattern [1,5].

Fig. 14 shows the effect of electrolyte flow rate on the overcut. This indicates that overcut enlarges as the electrolyte flow flux (rate) increases. The reason for this is attributed to reduced void fraction between the electrodes as gas bubbles are removed rapidly from the gap with increase in electrolyte flow flux [12]. In a hole, the overcut is maximum at the tip and reduces with depth of hole (Fig. 14).

6.2.2. Effect of tool insulation

Fig. 15 shows the numerical predictions of the workpiece shapes in ECD by using different kinds of tools, namely, bare tool, coated tool and bare bit tool [12]. It indicates that the overcut can be reduced by coating the tool. For deep holes, particularly it is necessary to use good quality coating

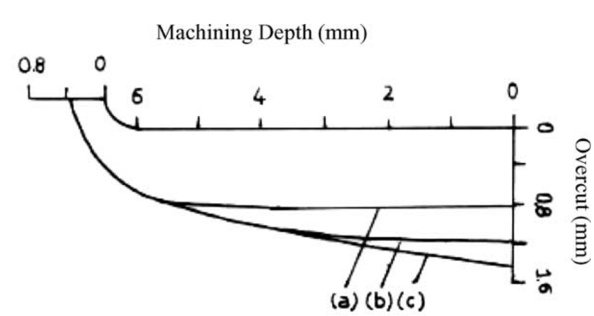

Fig. 15. Comparison of the workpiece shapes with different tools: (a) coated tool; (b) bare bit tool; and (c) bare tool [12].

as it has the tendency to peel off after a certain period of drilling due to the effects of heat and electrolyte pressure.

6.2.3. Effect of applied voltage

The experiments conducted by many researchers [27,33, 36,37] reveal that overcut increases with increase in applied voltage. An uncertain response of hole size occurs due to voltage changes resulting from variations in electrolyte conductivity due to electrolyte temperature variation in IEG and secondary effects of voltage on the effectiveness of electrode coating.

6.2.4. Effect of tool feed rates and tool types

Tool feed rate has significant influence on hole overcut. If instead of voltage, current is held constant within practical limits, hole area would be inversely proportional to feed. The relationship of overcut with machining depth at different feed rates is given in Fig. 16. Experimental investigations [12,13,33] have revealed that an increase in tool feed rate reduces the overcut. With increase in tool feed rate the void fraction increases and the electrolyte conductivity reduces resulting in decrease in overcut [12]. The accumulation of gas bubbles on the side surface of the cathode and the precipitation of the metal ions removed from the workpiece on the side-wall of the hole (or anode) together reduce the passage of current in the radial direction, which reduces side dissolution of the work material [32].

The optimization of the material removal rate at various constraints of radial overcut and hole taper in case of EJD has been attempted by using genetic algorithm [30]. It can be seen from Fig. 17 that the material removal rate (MRR) increases with the radial overcut for any taper T_a within the process parameters range considered ($100 \leq V_{gap} \leq 550$, $10 \leq$ concentration $\leq 25\%$, and $0 \leq f \leq 1$). For the radial overcut constraint of 0.16–0.20 mm, increase in taper from 8 to 13° increases MRR by about 1.25 times. The results predicted by genetic algorithm were shown to have close agreement with the experimental results for the selected range of operating conditions [30].

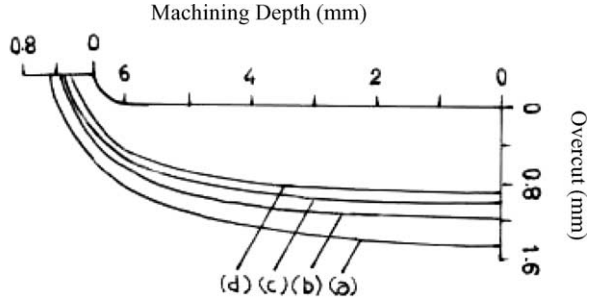

Fig. 16. Relationship of overcut with machining depth at different feed rates. Values of tool feed rates: (a) 2.80×10^{-3}, (b) 3.7×10^{-3} (c) 4.5×10^{-3} and (d) 5.33×10^{-3} mm^{-1} [12].

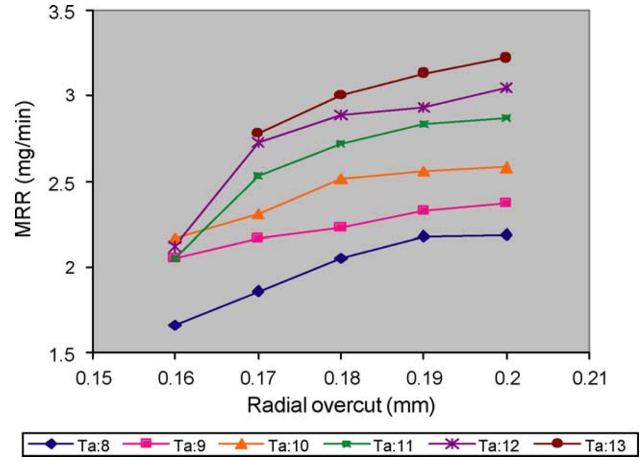

Fig. 17. Results of optimization at various constraints of radial overcut and hole taper [30].

6.3. Aspect ratio

Holes with high aspect ratio necessitate the use of acid electrolytes. Unlike salt electrolytes, the acid electrolyte dissolves the metal and the resultant metal ions are carried away by the electrolyte. The high acidity (low pH value) helps maintaining all the dissolved metal in solution in contrast to conventional ECM, which produces semi-solid precipitate with salt electrolytes [6,20,29]. This feature is essential for drilling deep holes as any blockade in the long narrow passage can spoil the quality of hole produced. The electrolyte becomes progressively more contaminated with dissolved metal ions during deep hole drilling.

6.4. Conicity and shape

Conicity (or non-parallel sides) of holes is another quality consideration in ECM hole drilling. The drilling of micro-size holes having straight walls in thin metallic foils is a major requirement in the fabrication of microelectronic components such as printed circuit cards and boards. In critical applications particularly in micro instruments, the straightness of the drilled hole is very important [22,25]. Other applications, which require parallel sides holes include manufacture of turbine blade for cooling purposes and metallic test blocks (for ultrasonic calibration) [34]. Conicity is caused by the rate of metal removal varying along the length of the hole. Another known cause of conicity of hole is the variations in gap resistivity, which in turn significantly affects the servo feed of cathode tool. To eliminate this problem an adaptive control system was developed [34] to drive the cathode tool in a way that it was independent of the gap resistivity. The function of control system was to differentiate between ‘false’ changes in gap voltage V_{gap} due to changes in gap resistivity and ‘true’ changes in V_{gap} caused by changes in gap sizes. Detection of the false condition was achieved by monitoring and correlating changes in feed rate

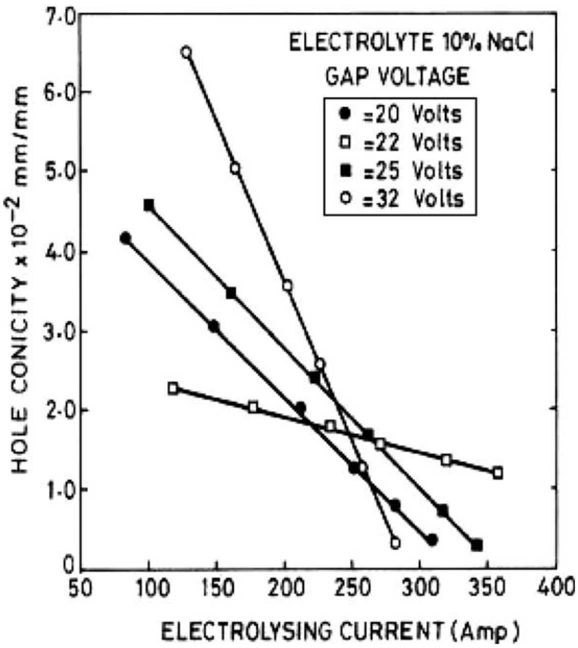

Fig. 18. Effect of electrolyzing current on the hole conicity at different gap voltages [33].

and electrical conditions (particularly machining current) between the base of the hole and the electrode tool tip and adjust machining parameters with the object of producing parallel-sided holes.

In order to know the conditions that lead to straight walls during drilling by electrochemical processes, the influence of the quantity of charge on the shape evolution was studied [22]. It was found that knife edged holes were obtained at low charges, while straight walls were obtained at high charges, i.e. high current.

Results of another study [33] also indicated that any increase in electrolyzing current reduces the conicity of hole. The reason for this was attributed to increased precipitation of removed metal ions on hole inner surface. This precipitate prevents excessive side machining, which in turn helps in reducing the conicity. Fig. 18 shows the effect of electrolyzing current on the hole conicity at different gap voltages. The rate of conicity decrease depends on the gap voltage. A linear relationship has been predicted between the electrolyzing current and the hole conicity in the gap voltages range of 20–30 V. The hole conicity can be reduced by using higher feed rates, and by insulating the side walls of the tool (cathode) with a non-conducting resin or by a ceramic coating or with a plastic sleeve [33].

The scanning electronic microscopy (SEM) images have been used to compare the quality of the holes produced by electro jet and laser-drilling processes. The SEM images (Figs. 19 and 20) of the longitudinal section of the small holes drilled in SUPERNI 263A indicated the non-cylindrical nature of the hole in both cases and conicity (or the degree of taper) is more pronounced in laser-drilled hole as compared to the EJD process [40,41].

6.5. Surface finish

Hole surface finish is an important characteristic in estimating the applicability of ECM drilling of holes in DTM alloys. The factors which have critical influence on machined surface roughness include work material grain size and orientation, current density, electrolyte type, its flow rate and condition, flow control, and forward reverse pulse imbalance [28,29]. One cause of poor surface roughness in multi-phase alloys such as titanium (Ti6Al4V) and SUPERNI alloys (Nimonic range of alloys) is reported to be the differential dissolution of the phases if the correct dissolution controlling anodic film is not generated [2]. Experiments have shown that machining with electrolytes that show an abrupt passive to transpassive transition give better dimensional accuracy and surface finish in comparison to non-passivating electrolytes [31].

Variation in electrode feed rate affects the hole surface finish. Usually, the tool feed rate, which is mainly dependent on work material-electrolyte conductivity pair

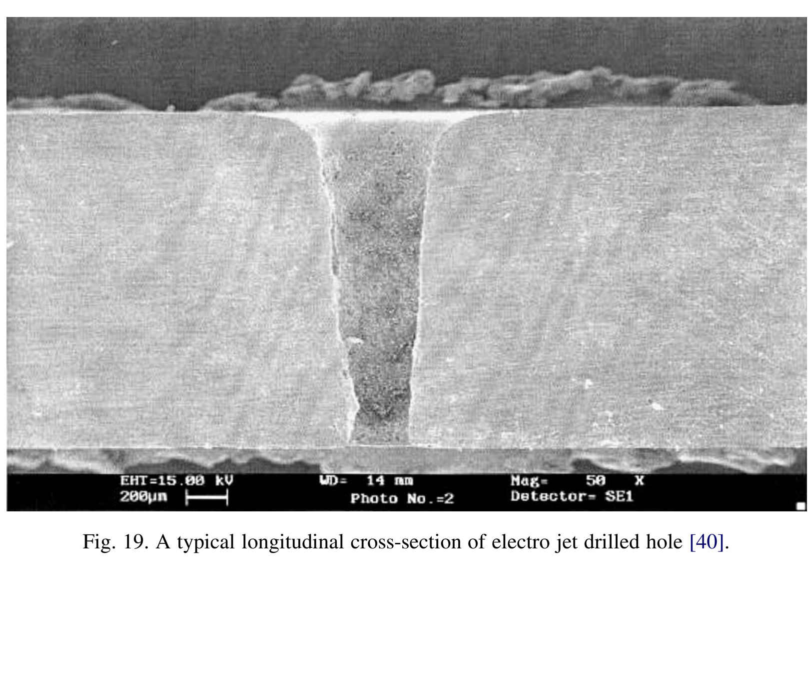

Fig. 19. A typical longitudinal cross-section of electro jet drilled hole [40].

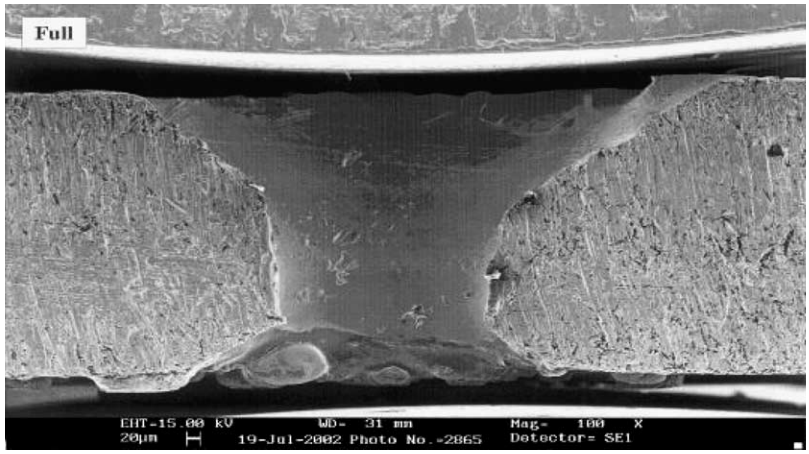

Fig. 20. A typical longitudinal cross-section of laser drilled hole [41].

is established during the developmental trial to be compatible with other parameters and is held constant thereafter. The good surface finish can be achieved at a tool feed rate, which exactly matches the material dissolution rate. Fig. 21 shows the effect of tool feed rates on surface roughness in case of EC drilled holes in low carbon steel at different gap voltages. Tower feed rates, greater roughness was attributed to the non-uniformity in anodic dissolution rate. Too high tool feed rate also increases the surface roughness of the machined hole. This could be due to the decrease of the frontal gap at higher feed rates, which would result in increase of conductivity and flow speed of electrolyte [33].

An increase in electrolyte contamination results in rougher surface finish. Replacing a portion of the used electrolyte with the fresh one can control this problem to some extent [18].

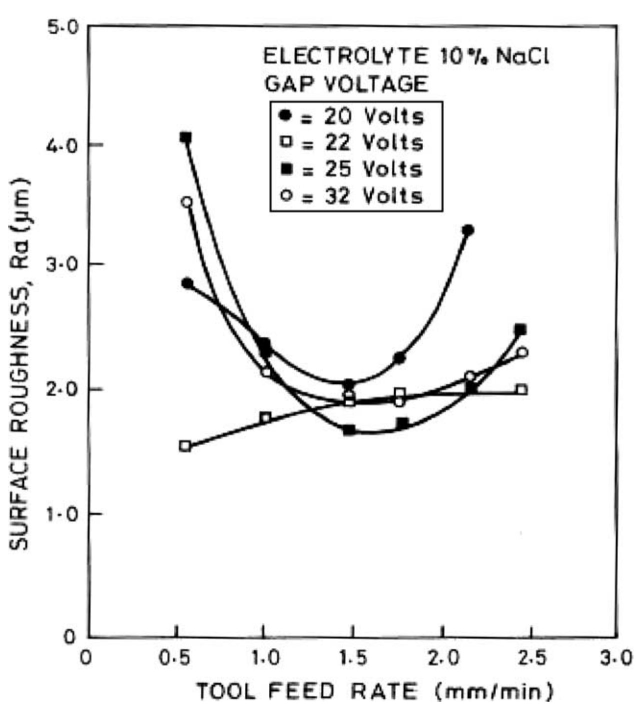

Fig. 21. Effect of tool feed rates on surface roughness [33].

7. Comparison of non-traditional hole drilling techniques

Besides electrochemical processes the other major non-traditional machining techniques used for drilling micro- and macro-holes are thermal processes like EDM, laser drilling (LD) and electron beam drilling (EBD). All these thermal processes do not generally satisfactorily satisfy the hole quality requirements with respect to either geometrical characteristics (viz. overcut, taper, and aspect ratio) or metallurgical characteristics (viz. heat affected zone, recast layer, and microcracking) or both. EDM is not economically viable for holes with high aspect ratios ($L/D > 10$). EDM and EBD involve removal of material by heating it to melting and vaporization state. This obviously leads to the formation of heat-affected zone and often micro-cracks on the work surface resulting in metallurgical damage of the work material [39]. Table 6 shows a comparison of various drilling techniques for aero components [42]. In many applications, the type and condition of material, hole size and depth to diameter ratios make electrochemical hole

Table 6
Comparison of hole drilling techniques for aero-engine components [42]

	ECD	EDM	LD
Minimum			
Hole diameter (mm)	0.5	0.3	0.1
Taper (mm/mm)	0.001	0.0005	0.01
Recast layer (μm)	–	25	25
Angle to surface (°)	15	20	15
Surface roughness (μm)	6	6	20
Maximum aspect ratio	250	25	50
Complex shapes	No	Yes	Yes
Simultaneous drilling	Yes	Yes	Yes
Tooling complexity	High	High	Low
Speed	Medium	Slow	Fast

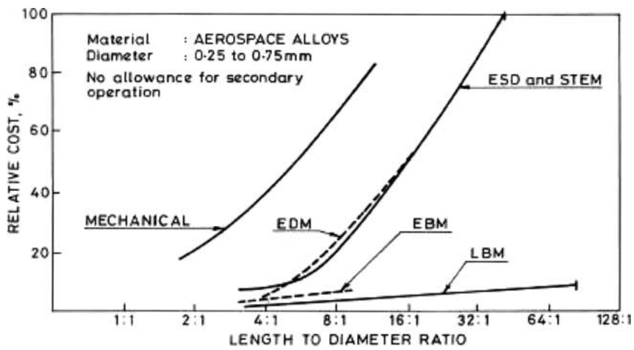

Fig. 22. Cost comparison for different non-conventional hole drilling processes [5].

drilling the only viable process. Cost comparisons are difficult considering the diverse nature of these processes and the variety or lack of post processing operations that may be necessary. For holes with low aspect ratios, the cost of EDM, STEM and ESD is low, but for higher aspect ratios their cost increases steeply. Fig. 22 shows one such cost comparison on a relative percentage basis taking into account the differing ranges of aspect values. This comparison is for holes in the range of 0.25–0.75 mm diameter drilled singly and with no allowance for deburring or for secondary operations [5].

8. Conclusions

(a) This paper provides an overview of electrochemical hole drilling processes, their critical features, range of their applications, and experimental and analytical investigations of the processes.
(b) For drilling cross-holes, and for simultaneous drilling of multiple holes of different shapes electrochemical hole drilling processes is a better choice in comparison to all other non-traditional hole drilling processes. The notable features of ECM drilling processes have been the absence of residual stresses and excellent surface finish which make these processes more attractive for drilling of holes for components exposed to high temperature.
(c) Appropriate means of handling and disposal of electrolytes, optimum selection of process parameters, systematic analytical and theoretical modeling and analysis, control on geometry of the drilled hole, and development of process control strategies are the main issues which need continued developments and further investigations for the commercial success of these processes in industry.

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