

## ELECTROCHEMICAL MACHINING

High strength heat-resistant alloys can be difficult to machine by conventional techniques. Electrochemical machining (ECM) offers an alternative. Hard metals can be shaped electrolytically and the rate of machining does not depend on their hardness. The tool electrode used in the process does not wear, and therefore soft metals can be used as tools to form shapes on harder workpieces, unlike conventional practice. The process is used to smooth surfaces, to drill holes, and form complex shapes. Its combination with other techniques yields fresh applications in diverse industries. Its effect on the environment lies with gas generation and waste metal disposal. Recent advances lie in computer-aided tool design, and the use of pulsed power, which has led to greater accuracy for ECM-produced components.

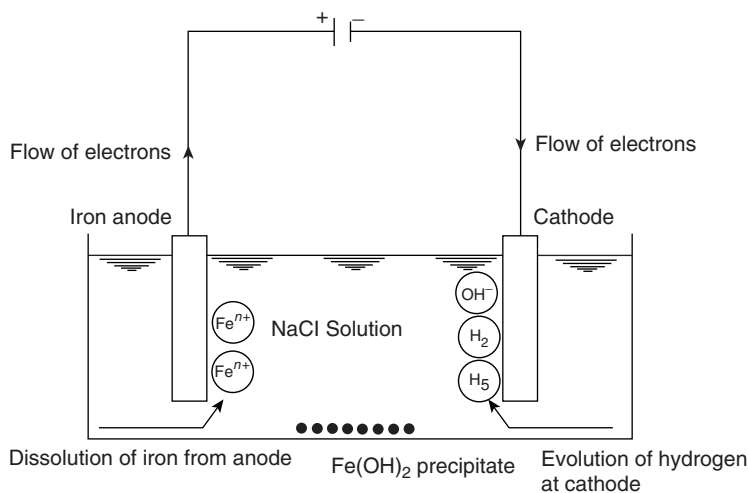
## 1. Principles of Electrochemical Machining

ECM relies on the laws of electrolysis. As shown in Figure 1 an anodic (positively polarized) iron metal is plated a distance away from a cathode metal (of negative polarity), both of which are placed in aqueous electrolyte solution. When a voltage is applied between the two electrodes, metal is dissolved electrochemically from the anode metal at a rate that is proportional to the product of the chemical equivalent (atomic weight divided by the valency of dissolution) of the latter metal and the current. The outcome of these reactions is that the metal ions precipitate out as iron hydroxide. At the cathode, only gas, normally hydrogen, is generated.

The rate of evolution of the gas generated at the cathode can also be determined from Faraday's law. The process, therefore, offers an alternative way of removing material from a workpiece, especially when the latter is made of an alloy, the hardness of which makes it difficult to machine by conventional methods. Thus, if a nickel anode were used it would dissolve, yielding nickel hydroxide and hydrogen gas. If brass, steel, or copper is used as the cathode, the reaction still generates hydrogen gas (Fig. 1).

A significant observation can now be made: The hardness or other mechanical properties of the anode do not affect the rate of metal removal from that electrode.

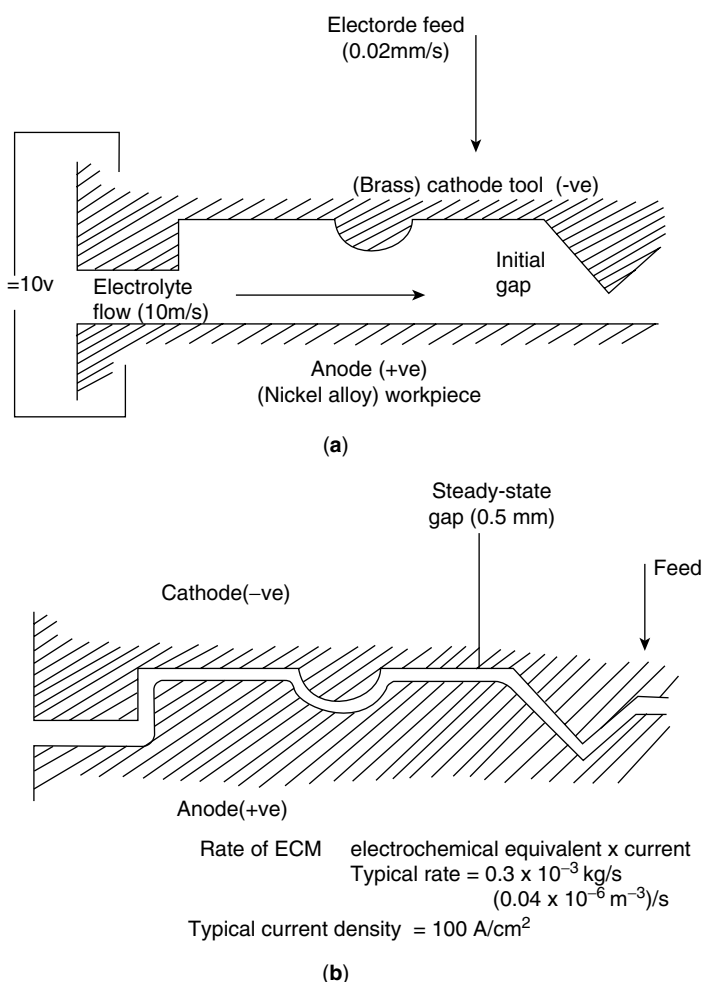
The aqueous electrolytes used, eg, 20% sodium chloride solution, have a specific conductivity of the order of only  $0.1 \text{ S cm}^{-1}$  at ambient temperatures. As the voltages applied across the electrolyte are restricted to 10–20 V, mainly in order to comply with safety requirements and to reduce energy usage, the metal dissolution rates that are comparable with those of established machining processes can be achieved only by narrowing the interelectrode gap to  $\sim 0.5 \text{ mm}$  in order to reach the currents of 100–10,000 A that are needed for the electrolytic action. This gap is usually kept constant at an equilibrium width by



**Fig. 1.** Basic electrolysis.

mechanically feeding the cathode tool toward the anode at a fixed rate, or vice versa. Typically, such a forward movement of 1-mm/min matches the rate at which the anode surface recedes through dissolution (see Fig. 2).

The accumulation of the products of the reactions at both electrodes, ie, the metal hydroxide at the anode and gas bubbles at the cathode, is undesirable. Being insulators, these products reduce the specific conductivity of the electrolyte. The electrolyte is also likely to boil because it is rapidly heated by the electrical power transmitted across the gap. Boiling of the electrolyte can lead to premature termination of machining. To wash away the electrolytic debris and keep the temperature of the electrolyte at practicable levels of between 20 and 40°C in the machining zone, the solution is pumped through the gap at velocities that are typically as high as 30 m/s; the corresponding electrolyte pressures are



**Fig. 2.** Configuration of electrodes for electrochemical machining. (a) Initial configuration, (b) final configuration.

$\sim 700 \text{ kN/m}^2$ . Breakdown in machining is thereby avoided. Under these conditions, shaping of the workpiece can be achieved.

Figure 2 illustrates the ECM process. A cathode tool is produced from a soft metal, such as brass or copper, to a shape that is approximately the image of that required on the anode workpiece, which usually would be a tough alloy metal. An aqueous solution of electrolyte, often sodium chloride or nitrate, is pumped between the two electrodes. When a voltage of  $\sim 10 \text{ V}$  is applied between them, the interelectrode gap tends to an equilibrium width, as the tool is moved mechanically toward the workpiece. A shape, complementary to that of the tool, is reproduced on the workpiece.

The main advantages of ECM are, therefore: no tool wear; the rate of machining is not affected by the hardness of the workpiece; and complicated shapes can be machined with a single tool-electrode, which can be of a softer metal than the workpiece.

## 2. Rates of Metal Removal

We can calculate the rates at which metals can be electrochemically machined using Faraday's laws:

$$m = \frac{A}{Z} \cdot \frac{It}{F}$$

where  $m$  is the mass of metal electrochemically machined by a current  $I$  (A) passed for a time  $t$  (s). The quantity  $A/ZF$  is called the electrochemical equivalent of the anode metal;  $F$  is Faraday's constant ( $96,500 \text{ C}$ ).

Table 1 shows the metal machining rates that can be obtained when a current of  $1000 \text{ A}$  is used in ECM; currents from  $250$  to  $10,000 \text{ A}$  are common. Metal removal rates in terms of volumetric machining are often more useful than mass removal rates, and both quantities are included. In Table 1, all the current is assumed to be used in ECM to remove metal. That is not always the case. Some metals are more likely than others to machine at the Faraday rates of dissolution. In addition to current, factors such as electrolyte type and the rate of electrolyte flow influence the rate of machining. For example, nickel has been found to machine at 100% current efficiency at low current densities, eg,  $25 \text{ A/cm}^2$ . [Current efficiency is defined as the percentage ratio of actual to theoretical (Faraday) rate of metal removal.] However, if the current density is increased to  $250 \text{ A/cm}^2$  the current efficiency is typically reduced to 85–90%. This is the result of other reactions at the anode such as oxygen gas evolution, which becomes increasingly preferable as the current density is raised.

Another relevant example is titanium alloy, the toughness and lightness of which makes it so attractive in the manufacture of aircraft engine components. This metal is also highly corrosion-resistant, owing to the presence of a surface oxide layer. As the toughness renders difficult conventional machining, ECM becomes an attractive alternative. However, the surface film on titanium impedes the effective use of current for metal removal, and so current efficiency is low,  $\sim 10\text{--}20\%$ , when the common ECM electrolytes are used (sodium chloride

Table 1. Theoretical Removal Rates for a Current of 1000 A

Metal	Atomic weight	Valency	Density, mg/m <sup>3</sup>	Removal rate	
				10 <sup>-3</sup> kg/s	10 <sup>-6</sup> m <sup>3</sup> /s
aluminium	26.97	3	2.67	0.093	0.035
beryllium	9.0	2	1.85	0.047	0.025
chromium	51.99	2	7.19	0.269	0.038
		3		0.180	0.025
		6		0.090	0.013
cobalt	58.93	2	8.85	0.306	0.035
		3		0.204	0.023
niobium (columbium)	92.91	3	9.57	0.321	0.034
		4		0.241	0.025
		5		0.193	0.020
copper	63.57	1	8.96	0.660	0.074
		2		0.329	0.037
iron	55.85	2	7.86	0.289	0.037
		3		0.193	0.025
magnesium	24.31	2	1.74	0.126	0.072
manganese	54.94	2	7.43	0.285	0.038
		4		0.142	0.019
		6		0.095	0.013
		7		0.081	0.011
molybdenum	95.94	3	10.22	0.331	0.032
		4		0.248	0.024
		6		0.166	0.016
nickel	58.71	2	8.90	0.304	0.034
		3		0.203	0.023
silicon	28.09	4	2.33	0.073	0.031
tin	118.69	2	7.30	0.615	0.084
		4		0.307	0.042
titanium	47.9	3	4.51	0.165	0.037
		4		0.124	0.028
tungsten	183.85	6	19.3	0.317	0.016
		8		0.238	0.012
uranium	238.03	4	19.1	0.618	0.032
		6		0.412	0.022
zinc	65.37	2	7.13	0.339	0.048

and nitrate). Consequently, with the growing industrial use of titanium alloys, and of ECM to shape them, much effort is being expended to find appropriate electrolyte solutions and process conditions which yield better efficiencies.

If the rates of electrolyte flow are too low, the current efficiency of even the most readily electrochemically machined metal is reduced; with insufficient flow the products of machining cannot be so readily flushed from the machining gap. The accumulation of debris within the gap impedes further dissolution of metal. The buildup of cathodically generated gas can lead to short-circuiting between tool and workpiece, causing termination of machining, with both electrodes becoming damaged. When complex shapes have to be produced, the design of tooling incorporating the right kind of flow ports for the electrolyte becomes a

considerable problem. For example, for the industrial Monel alloy, the main constituents of which are nickel and copper with percentages by weight of, respectively, 63 and 31.7% the alloy is calculated to have a chemical equivalent of 39.9 and 34.7 by two well-known methods, cf, chemical equivalents of nickel and copper are, respectively, 29.36 and 63.57 for valencies of 2 and 1. Caution is recommended therefore in calculating alloy chemical equivalents.

Although Table 1 provides data on machining rates for pure metals, various expressions have been derived from which the corresponding rates for alloys can be calculated. All these procedures are based on calculating an effective value for the chemical equivalent of the alloy.

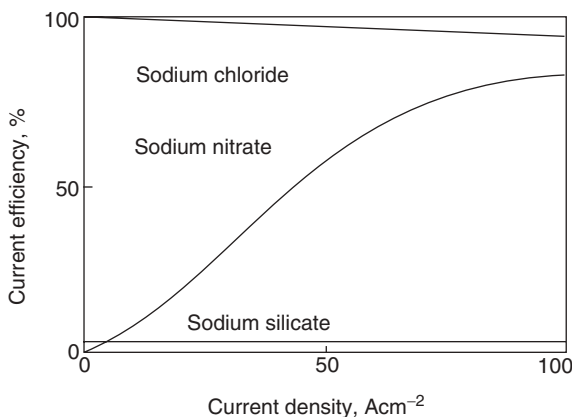
### 3. Aqueous Electrolyte Solutions

From the preceding paragraphs, we note that the current efficiency depends greatly on the choice of the electrolyte solution. In ECM, the main electrolytes used are aqueous solutions of sodium chloride and nitrate, and occasionally acid electrolytes. Typical concentration and density of these solutions are 400 g/l and 1100 kg/m<sup>3</sup>, respectively; kinematic viscosity is  $\sim 1 \text{ mm}^2/\text{s}$ . ECM is normally operated at electrolyte temperatures of 18–40°C.

The electrolyte solution warms during ECM owing to electrical heating caused by the passage of current. The machining action is often easier to control if the electrolyte is maintained at a higher temperature from the outset. This is usually achieved by heating the electrolyte in its reservoir before pumping it into the machining zone.

Sodium chloride and sodium nitrate solutions exhibit machining different characteristics for the same metals, (see Fig. 3). Occasionally, efficiencies higher than 100% are obtained, when actual grains of metal are dislodged by the traction forces of the electrolyte flow.

Although sodium chloride electrolyte generally has a higher efficiency than sodium nitrate over a wide range of current densities, the latter is often



**Fig. 3.** Variation of current efficiency with current density for different electrolyte solutions.

preferred in practice, as it permits closer dimensional accuracy of ECM, particularly in hole drilling. Other electrolytes include 5% hydrochloric acid solution; it is useful in fine-hole drilling since it dissolves the metal hydroxides as they are produced. Like NaCl electrolyte, the current efficiency is  $\sim 100\%$ . Sodium chlorate solution has also been investigated. However, industry has been reluctant to employ it as an ECM electrolyte owing to its ready combustibility, even though this electrolyte is claimed to give even better throwing power and closer dimensional control than sodium nitrate. Figure 3 also includes data on sodium silicate solution, an electrolyte known to produce sparking conditions in hole-drilling applications, leading to an electrodischarge erosion type of action.

#### 4. Surface Finish

The choice of electrolyte will also influence the quality of surface finish obtained in ECM. Depending on the metal, some electrolytes leave an etched finish, caused by the nonspecular reflection of light from crystal faces electrochemically dissolved at different rates. Sodium chloride tends to produce an etched, matte finish with steels and nickel alloys; a typical surface roughness would be  $\sim 1 \mu\text{mRa}$ .

The production of an electrochemically polished surface is usually associated with the random removal of atoms from the anode workpiece, whose surface has become covered with an oxide film. This is governed by the metal–electrolyte combination used. Nonetheless, the mechanisms controlling high current density electropolishing in ECM are still not completely understood.

For example, with nickel-based alloys, the formation of a nickel oxide film seems to be a prerequisite for obtaining a polished surface; a finish of this quality, of  $0.2 \mu\text{mRa}$ , has been claimed for Nimonic (nickel alloy) machined in saturated sodium chloride solution. Surface finishes as fine as  $0.1 \mu\text{mRa}$  have been reported when nickel–chromium steels have been machined in sodium chlorate solution. Again, the formation of an oxide film on the metal surface is the key to these conditions.

Sometimes the formation of oxide film on the metal surface hinders efficient ECM and leads to poor surface finish. For example, the ECM of titanium is rendered difficult in chloride and nitrate electrolytes because the oxide film formed is so passive. Even when higher voltages ( $\sim 50 \text{ V}$ ) are applied to break the oxide film, its disruption is so nonuniform that deep grain boundary attack of the metal surface can occur.

Occasionally, metals that have undergone ECM have a pitted surface while the remaining area is polished or matte. Pitting normally stems from gas evolution at the anode; the gas bubbles rupture the oxide film.

Process variables also affect surface finish. For example, as the current density is raised the finish generally becomes smoother on the workpiece surface. A similar effect is achieved when the electrolyte velocity is increased. In tests with nickel machined in HCl solution, the surface finish has been noted to improve from an etched to a polished appearance when the current density is increased from  $\sim 8\text{--}19 \text{ A/cm}^2$  with constant flow velocity.

## 5. ECM Tool Design

Design of the cathode tool is concerned with the establishment of a tool shape for producing an anode workpiece to specified dimensions and accuracy. Prediction of the appropriate tool shape to yield the correct workpiece configuration can be a formidable task, except for simple shapes (described below). These difficulties in tool design arise from the complexity of the ECM process conditions occurring in the interelectrode gap, and of the theoretical procedures that have to be solved.

Most investigations deal with a model of steady-state (equilibrium) ECM, based on Laplace's equation in order to determine the potential field in the inter-electrode gap. Design of the ECM tool consists of finding the cathode boundary geometry by which Laplace's equation and all boundary conditions are satisfied for a required anode workpiece shape. The procedure is known as an inverse boundary value problem of Laplace's equation. Early attempts to solve this problem by analytic and complex variable methods have largely been superseded by numerical techniques. Finite element (FEM) and boundary element (BEM) methods are mostly used: They iteratively adjust the electrode boundary until no further appreciable change of boundary is obtained, or an optimal value of a "target function" is achieved. In FEM, a "correction factor" has been used to adjust the tool shape generated, until the required workpiece geometry is yielded. The BEM method is claimed to be effective when tools with sharp discontinuities have to be designed.

Nonetheless, these methods, in most practical cases, only yield an approximate prediction to the electrode shapes required. More comprehensive methods are still needed to deal with flexibility in shapes, accuracy, and mathematical convergence in the numerical procedures used. As a result, in practice, subsequent empirical modification to the tool shape is still undertaken. As well as specification of the cathode tool dimensions, appropriate electrolyte flow channels have to be included in the design. In many cases, parts of the tool have also to be insulated, in order to avoid electrochemical dissolution in undesired regions of the anode workpiece. Consideration of tooling fixtures as well as shape design therefore has to feature in ECM tool design. The entire procedure can be time consuming and an expensive exercise.

## 6. Metal Shaping by ECM

ECM can be used to shape metals in three main ways: deburring, holedrilling, and three-dimensional shaping. These methods are covered below.

**6.1. Deburring.** Deburring, or smoothing, of surfaces (Fig. 4), is the simplest and a common use of ECM. A plane-faced cathode tool is placed opposite a workpiece that has an irregular surface. The current densities at the peaks of the surface irregularities are higher than those in the valleys. The former are, therefore, removed preferentially and the workpiece becomes smooth, admittedly at the expense of stock metal (which is still machined from the valleys of the irregularities, albeit at a lower rate).

Electrochemical smoothing is the only type of ECM in which the final anode shape may match precisely that of the cathode tool.

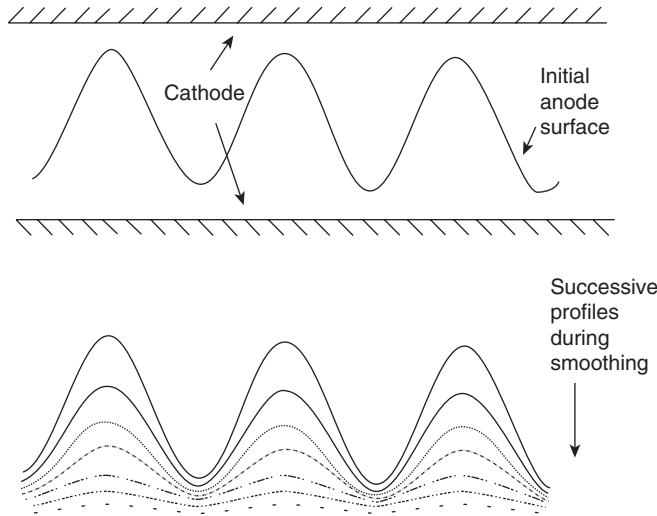


Fig. 4. Electrochemical deburring.

Electrochemical deburring is a fast process; typical times for smoothing the surfaces of manufactured components are 5–30 s. Owing to its speed and simplicity of operation, electrochemical deburring can be performed with a fixed, stationary cathode tool. The process is used in many industries and is particularly attractive for the deburring of the intersectional regions of cross-drilled holes.

**6.2. Hole Drilling.** Hole drilling is another principal way of using ECM (Fig. 5). The cathode-tool is usually made in the form of a tubular electrode.

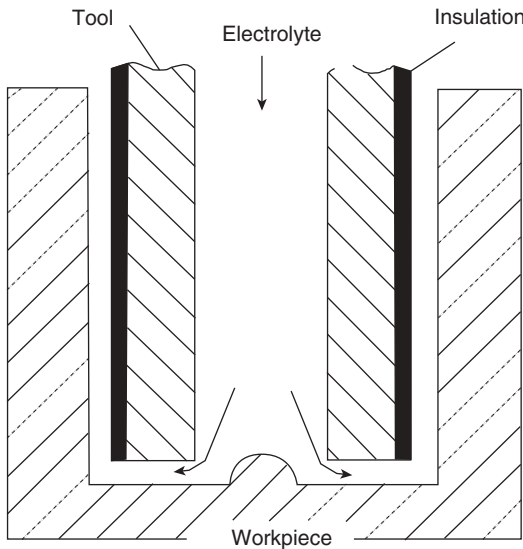


Fig. 5. Hole drilling by ECM.

Electrolyte is pumped down the central bore of the tool, across the main machining gap, and out between the sidegap that forms between the wall of the tool and the hole. Reversal of the electrolyte flow can often produce considerable improvement in machining accuracy.

The main machining action is carried out in the gap formed between the leading edge of the drill tool and the base of the hole in the workpiece. ECM also proceeds laterally between the side walls of the tool and component, where the current density is lower than at the leading edge of the advancing tool. Since the lateral gap width becomes progressively larger than that at the leading edge, the side-ECM rate is lower. The overall effect of the side-ECM is to increase the diameter of the hole produced. The distance between the side wall of the workpiece and the central axis of the cathode tool is larger than the external radius of the cathode. This difference is known as the "overcut". The amount of overcut can be reduced by several methods. A common procedure involves the insulation of the external walls of the tool (Fig. 5), which inhibits side-current flow.

Another practice line in the choice of an electrolyte such as sodium nitrate, which has the greatest current efficiency at the highest current densities (Fig. 5). In hole drilling, these high current densities occur between the leading edge of the drill and the base of the workpiece. If another electrolyte such as sodium chloride were used the overcut could be much greater. The current efficiency for sodium chloride remains steady at almost 100% for a wide range of current densities. Thus, even in the side gap, metal removal proceeds at a rate that is mainly determined by the current density in accordance with Faraday's law.

Holes with diameters of 0.05–75 mm have been achieved with ECM. For holes of 0.5–1.0-mm diameter, depths of up to 110 mm have been produced. Drilling by ECM is not restricted to round holes; the shape of the workpiece is determined by that of the tool electrode.

Finally, some significant differences between drilling and smoothing are noteworthy. With the former technique, forward mechanical movement of the cathode tool toward the workpiece is usually necessary in order to maintain a constant equilibrium gap width in the main machining zone between the leading face of the drill and the workpiece. A typical feed rate in ECM drilling would be 1–5 mm/min to drill holes ranging from 0.5 to 20 mm in diameter. In deburring, mechanical drive of the tool is often unnecessary.

Deburring typically takes 10–30 s for burrs of ~0.10–0.15 mm. A well-used application of drilling by ECM is the production of cooling holes in gas turbine blades for aircraft engines.

Two special techniques in drilling are worthy of discussion: The shaped tube electrolytic machining and electrostream.

**Shaped Tube Electrolytic Machining (STEM).** The drilling of cooling holes of a large depth-to-diameter ratio in high pressure turbine rotor blades can be accomplished by "shaped-tube electrolytic machining". The technique is usually called "STEM-drilling".

The turbine blades are cooled by passing cool air through radial (nonparallel) passages. These holes are also used to surround the turbine blades with a film of air that is at a lower temperature than the air entering the same section of the blade. A thermally insulating layer then effectively surrounds the blade,

which can operate at a temperature higher than the melting point of the material from which it is manufactured. The radial passage has normally been formed in some turbine blades when they are cast, and the film cooling holes produced by (electrodischarge machining) EDM or ECM. However, some blades, especially those made from single-crystal materials, have their radial passage machined out, usually because of difficulties in casting or forging them. Moreover, conventional or gun-drilling cannot tackle effectively these materials. Such blades often need holes with depth to diameter ratios of 160–1. Even EDM and laser machining have limitations and an ECM-based process, STEM-drilling has had to be devised.

The configuration of electrodes is similar to that of ECM. The cathode drill-electrode is made of titanium tube, its outer wall having an insulating coating. A nitric acid electrolyte solution at a temperature of  $\sim 20^{\circ}\text{C}$  ( $\sim 15\%$  v/v) is pumped down the tube at a flow rate of approximately 1 l/min. With an applied voltage of 10 V, and a typical cathode-tool feed-rate of 2.16 mm/min, a hole of typical diameter varying from 0.84 mm at inlet to 0.85 mm at outlet, can be produced with a 0.58 mm diameter drill tool through a depth of  $\sim 130$  mm of blade. In STEM-drilling, periodic reversal of polarity, typically 9–0.3s, is employed to prevent an accumulation of undissolved machining products on the surface of the cathode-drill.

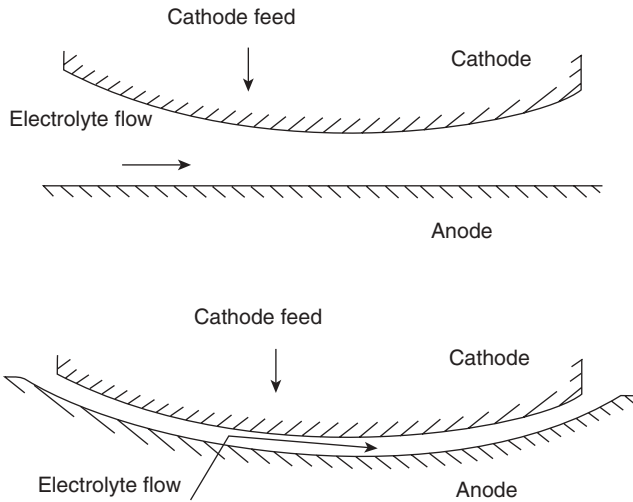
**Electrostream (Capillary Drilling).** Electrostream, also known as capillary drilling is another special electrochemical drilling technique. The cathode-tool is made from a drawn-glass nozzle, 0.025–0.05 mm in diameter, smaller than the desired size of the hole to be drilled. Within the glass nozzle is fitted a wire electrode that provides the means for electrical contact with the acid electrolyte. The kind of electrolyte has to be carefully selected to ensure that it is chemically compatible with the condition of the workpiece. Generally, hydrochloric or sulfuric acid solutions are used; the former for anode-materials like aluminium, some nickel and titanium alloys; and the latter for Hastelloy, Inco, Rene alloys, as well as carbon and stainless steels. Voltages of  $\sim 120$  V are employed, which are  $\sim 10$  times greater than those of ECM.

The drilling operation is conducted in a plastic chamber, suitably vented, with controls for the automatic rapid feed of the tool, which has to match exactly the rate of recession of the workpiece area being machined. The tool is also fitted with a rapid retraction mechanism to enable indexing to the next location, for multiple holes to be drilled. The acid electrolyte is kept separated from the electrode feed mechanism in order to protect the system from corrosion. Its temperature, pressure, concentration, and flow rate are carefully monitored for satisfactory machining.

With electrostream, holes from 0.13 to 0.89 mm, with depth to diameter ratios of up to 40:1, can be drilled. Holes can be drilled at angles as shallow as  $10^{\circ}$ . The technique also enables the drilling of cross-holes deep within a workpiece.

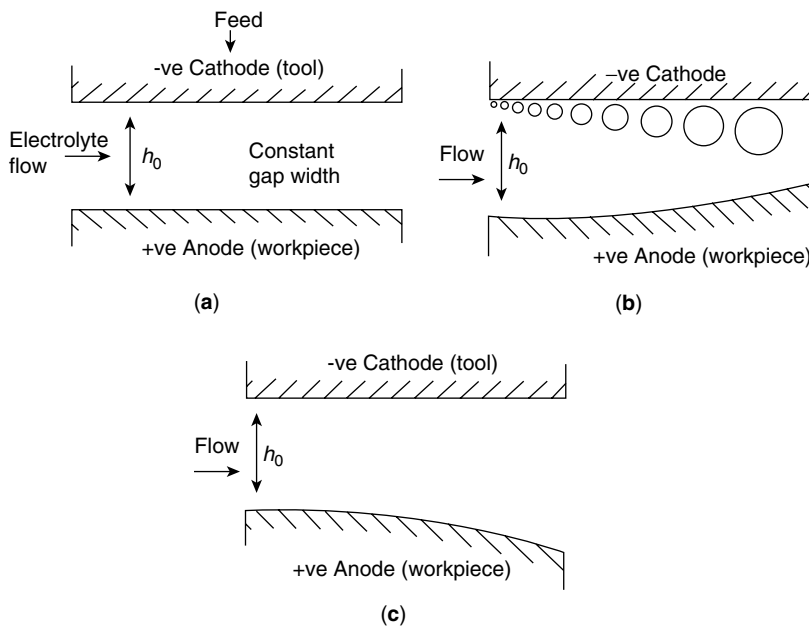
A principal application of electrostream is the drilling of cooling holes in nickel-based alloys.

**6.3. Three-Dimensional Shaping.** The third main application is ECM contour shaping. Figure 6 shows a typical case in which a three-dimensional shape is to be formed on a workpiece. The effective use of this technique requires



**Fig. 6.** Cavity sinking by ECM.

that a constant equilibrium gap be maintained between the two electrodes by use of a constant rate of mechanical feed of one electrode toward the other. To achieve the required dimensional accuracies, electrolytes such as sodium nitrate are commonly employed. Nitrate solutions permit better tolerances than their



**Fig. 7.** Taper in Interelectrode gap. (a) Constant gap. (b) Hydrogen gas effect (c) Joule (electrical) heating effect.

chloride counterparts. Current density is more sensitive to electrode gap distance with nitrate solutions, so the latter are more effective in the preferential removal of protuberances.

Electrolyte flow plays a significant role in contour shaping. The electrolyte usually has to be maintained at high pressures to flush away the products of machining before they can interfere with the machining action. Thus, careful design of tooling is necessary to provide the right entry and exit ports. Indeed, adjustments often have to be made to the profile of the cathode tool because the cathodic gas bubbles affect the specific conductivity of the solution. These bubbles can cause a tapering in the profile.

Figure 7 illustrates this effect, which arises in contour shaping. The problem is rendered even more complicated by the electrical heating of the electrolyte, which causes the specific conductivity to rise, with a consequential widening taper in the downstream direction. The two effects, of gas bubbles and electrical heating, act in opposite ways, but unfortunately seldom eliminate each other.

## 7. Industrial Applications of ECM

Examples of typical applications from industry are formed in the following sections.

**7.1. Aircraft Engine Industry.** A well-established use of ECM lies in the manufacture of turbine blades. The technology has been developed to the stage where a blank hard alloy bar may be electrochemically shaped to that needed for a blade of complex geometry. A production process has been described whereby broaching, electro-discharge machining (EDM), automated deburring, and a 360° ECM operation yield the airfoil platform, and leading and trailing edges, to high accuracy in a single operation.

The aircraft industry also drills small cooling holes of diameter 0.5–3.0 mm, with a depth/diameter ratio of 300:1 by shaped-tube electrolytic machining (STEM) in superalloys.

**7.2. Medical Industry.** ECM has found ready application in the manufacture of artificial hip implants, especially in a chromium–cobalt alloy, stainless steel, and titanium alloy, owing to its advantages over conventional machining in dealing with these hard metals.

**7.3. Car Industry.** In the industry, the firing chambers of internal combustion engines are electrochemically machined, in order to remove precisely metal so that the volumes of each chamber are similar. The outcome is then higher fuel efficiency and more control over emissions.

**7.4. Offshore Industry.** Seawater, even with a specific conductivity of about one-fifth of that of standard ECM electrolytes, has proved to be a useful working fluid for electrolytic grinding (ECG), and for stopping fatigue cracks in steel rigs used by the oil and gas industry. Similarly, a form of wire-electrode ECM has been developed for removing boat-shaped samples for metallurgical inspection from the legs of oil rigs.

**7.5. Manufacturing Industry.** The ECM process has also been attractive in the manufacturing industry, eg, for rubber mould production.

**7.6. Electronics.** In the electronics industry, etching of microparts has been achieved by ECM techniques, and in some cases has been found to be superior to conventional chemical etching. Two techniques through-mask or mask-less material removal, are employed.

In the former, material is removed selectively from unprotected areas of a one- or two-sided photoresist patterned workpiece. The technique has been applied to microelectronic components such as copper lines for printed circuit boards, or print bands for high speed printers.

In maskless ECM, a fine electrolyte jet emerging from a small cathode nozzle is used to provide highly localized electrochemical metal removal. The technique has been applied to production of microindents of diameter 200  $\mu\text{m}$  and depth 4  $\mu\text{m}$  on roller bearings.

## 8. Hybrid ECM Processes

The combination of ECM with other processes is occasionally used to provide advantage not possible with the single techniques. Some popular methods are described below.

**8.1. Electrochemical Grinding.** Electrochemical grinding (ECG) is a well-established hybrid ECM process. A grinding wheel, in which an insulating abrasive such as diamond particles is set in a conducting bonding material, is made the cathode tool. The nonconducting particles act as a spacer between the wheel and the workplace, providing a constant interelectrode gap. The abrasive action accounts for  $\sim 10\%$  mechanical removal, ECM being the main process (90%). The technique is particularly effective when an oxide is nonconducting layer is present on the workpiece. Applications range from the production of tungsten carbide cutting tools, hypodermic needles, removal of fatigue cracks from underwater structures, and honeycomb seal rings in aircraft engine components.

**8.2. Electrolytic In-Process Dressing (ELID).** In this technique, a grinding wheel is made the anode, and is spaced  $\sim 0.1$  mm from a cathode electrode (graphite, stainless steel, or copper). A chemical solution type of grinding coolant, diluted by water, is used both as a grinding fluid and electrolyte. The metallic bond wheel is predressed electrolytically before grinding. The working current decreases, owing to generation of an insulating oxide layer at the wheel surface. The process is self-regulating. Fresh cutting points are continually exposed, so that the grinding force is kept low. ELID was first applied to the manufacture of silicon wafers. Recent applications of ELID have been concerned with ceramics, optical materials, and bearing steels. Surface finishes reported are  $\sim 0.011$ – $0.039$   $\mu\text{mRa}$ , with 20-s cycle times.

**8.3. Hybrid ECM—with Lasers, Ultrasonics, Electrolyte Jets.** The techniques in the sections Electrochemical Grinding and Electrolytic In-Process Dressing are well established. The combination of ECM with lasers, ultrasonics, and high velocity electrolyte jets is occasionally described, although these methods are still mostly under development.

**8.4. EDM/ECM.** Attempts have been made to combine EDM with ECM on a single machine tool. The EDM roughing electrode is used first to shape the workpiece with a dielectric fluid. The EDM electrode is retained for the

next stage. Replacement of the dielectric by an aqueous electrolyte, then enables ECM to proceed for removal of the heat affected metallurgical zone, left by EDM, and to smooth the workpiece surface. The technique reduces the total machining time for both roughing and finishing. In other investigations, the use of two working fluids, dielectric and electrolyte has been superseded by a single weak (of low concentration) electrolyte solution, that has been used to produce forging dies. The main action is that of spark erosion in the electrolyte solution.

## 9. Environmental Effect of ECM

ECM can affect the environment through generation of waste substances during electrolysis and subsequently their disposal.

A consequence of the electrochemical process is evolution of cathodic (and anodic) gaseous by-products, eg, hydrogen gas. Anodic metal dissolution gives rise to solid, eg, hydroxides and solid-liquid mixture, acids, nitrates, oils, or heavy metals. The subsequent processing of waste electrolyte, and disposal of its ECM machining products, or “sludge” is carried out with electrolyte settling tanks, centrifuges, and filter presses.

The ECM of alloys containing chromium can present considerable environmental implications as the process is considered to yield hazardous hexavalent chromium ions. Some users use chemical reduction techniques to convert the hexavalent chromium in waste ECM electrolyte solution into the safe trivalent chromium form, which may then be precipitated as  $\text{Cr}(\text{OH})_3$ . However, careful pH control is needed during chemical reduction and precipitation that may affect the ECM electrolyte used.

## 10. The Present and Future Status of ECM

High rate anodic electrochemical dissolution is a practical method of smoothing and shaping hard metals by employment of simple aqueous electrolyte solutions without wear of the cathodic tool. ECM can offer substantial advantages in a wide range of cavity-sinking and shaped-hole production operations.

Control of the ECM process is improving all the time, with more sophisticated servo-systems, and better insulating coatings. However, there is still a need for basic information on electrode phenomena at both high current densities and electrolyte flow rates.

Tool design continues to be of paramount importance in any ECM operation. The ingenuity of tool designers will be tested continually as they endeavour to optimize electrolyte flows and metal removal rates to produce the required sizes and shapes of anode workpieces. The use of computer-aided design to predict cathode tool profiles will continue to advance.

Recently, developments in ECM practice have dwelt on the replacement of constant dc by pulsed currents (PECM). Significant improvements in surface quality have been claimed. Much smaller electrode gaps may be obtained, eg,  $<0.1$  mm, leading to improved control of accuracy, eg,  $0.02$ – $0.10$  mm, with dies,

turbine blades, and precision electronic components. The key to further advancement in PECM lies in development of a low cost power supply. Successful development of technique will enable on-line monitoring of the gap size, enabling closer process control. Despite these attractions, PECM should be regarded as complementary to, and not a substitute for, established ECM technology: The former is expensive and metal removal rates can be lower than those of the latter.

The advent of new technology for controlling the ECM process and the development of new and improved metal alloys, which are difficult to machine by conventional means, will assure the future of electrochemical machining.

## 11. Acknowledgments

Mrs. D. Armstrong, Miss K. Clarke, Mr. M. Young, Mr. B. Hawes, Miss L. Cardone, and Mr. R. Wallace are thanked for their help with the preparation of this article.

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