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Electro-Chemical Machining (ECM)

Introduction

The principle involved in electro-chemical machining is known since 1780, but it is only comparatively recently that the method has been used as a production process to any great advantage. ECM process can be considered as reverse of electroplating process. It was first developed at the Batteille Memorial Institute, California, USA, and later developed and perfected in a number of countries.

Principle of ECM Process

Chemical machining (chemilling) removes metal by controlled chemical attack, but it is a relatively slow process; the scope of the process can be extended by the use of electrolytic action as in the case of electro-chemical machining. ECM is described as "the controlled removal of metal by anodic dissolution of the workpiece in an electrolytic cell in which the workpiece acts as an anode and the tool as a cathode". The tool electrode has to be suitably shaped to get the required contour on the workpiece. The electrolyte is pumped through the gap between the workpiece and the tool, while direct current is passed through the cell at a low voltage, to dissolve metal from the workpiece. The shaping of the workpiece is done by controlled electrolysis (Fig. 1).

ECM in comparison with purely chemical methods of machining offers the possibility of much greater rates of metal removal and more precise control of the shape. ECM process enables the metal to be removed from the workpiece at a rate

which is independent of the hardness of the workpiece (Fig. 2) and is therefore suitable for machining tough, high temperature materials and alloys, the use of which characterizes the aero-space industries. The aero-space industries are using electrochemical machining techniques extensively to machine very hard materials and for providing complex shapes to these hard materials.

ECM can be used for machining conventional materials also.

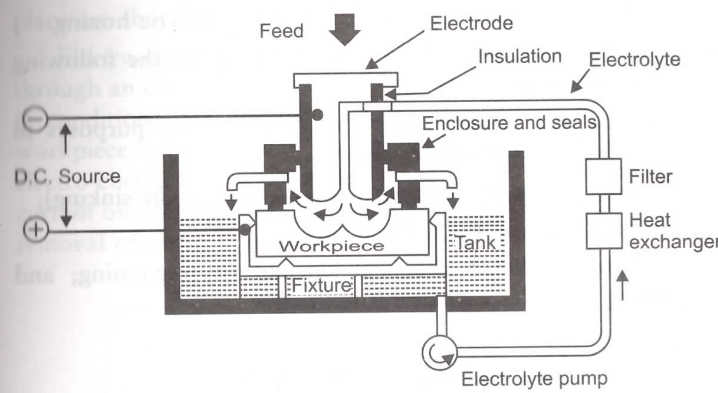


Fig. 1: Electrochemical Machining Process

Typical engineering materials that can be machined by ECM process with suitable electrolytes are:

Iron based alloys (Hardened Die steels);

Titanium;

Tungsten;

Tungsten Carbide;

Molybdenum;

Nickel based alloys;

Cobalt-Chromium-Tungsten alloys (Stellite type)

Stainless Steel, and

Nimonic Steel.

Different variations of electrolytic methods of machining are:

Electrolytic polishing (ELP);

Electrolytic pickling;

Electrolytic removal of broken tools;

Electro-Chemical Grinding (ECG) or electrolytic grinding;

Electro-Chemical Deburring (ECD) or electrolytic deburring;

Electro-Chemical Die Sinking (ECDS); and

Electro-Chemical Honing (ECH) or Electrolytic honing.

Electro-chemical machining can be used for the following types of operations:

Drilling (e.g. drilling deep holes for cooling purposes in aero-engines' turbine blades);

Shaping or Cavity Sinking (electro-chemcial die sinking);

Turning (i.e. electrochemical turning)

Cutting-off (Electrochemical sawing) or trepanning; and milling (i.e. electrochemical milling).

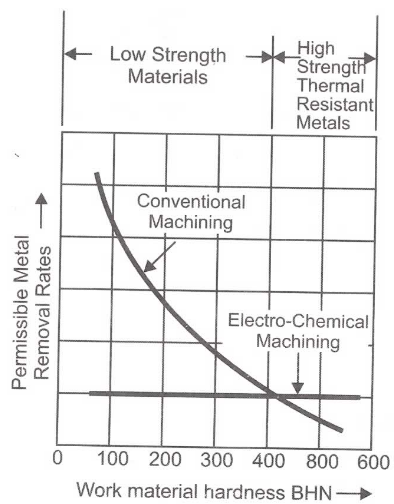


Fig. 2: Comparison of Permissible Metal Removal Rates in Conventional Machining and Electro-Chemical Machining

ECM Process Details

Electro-chemical process can be considered as the reverse of electroplating process. In electrochemical machining electrolytic action is used to remove metal and also to change the shape of the workpiece (i.e. forming of the workpiece to desired shape). The magnitude of current density is high (about 800 A/cm^2). This is 1000 times greater than the current density normally used in electroplating or in electrolytic pickling.

The close-up of working gap and the reactions that take place are shown in Fig. 3.

Electro-chemical machining involves the passage of current through an electrolyte in the gap between a workpiece and tool, if conditions are chosen correctly dissolution of anode or workpiece occurs (hence the term: "anodic dissolution"). In electro-chemical machining a shaped tool concentrates the current on those parts of the workpiece from which preferential removal of metal is required.

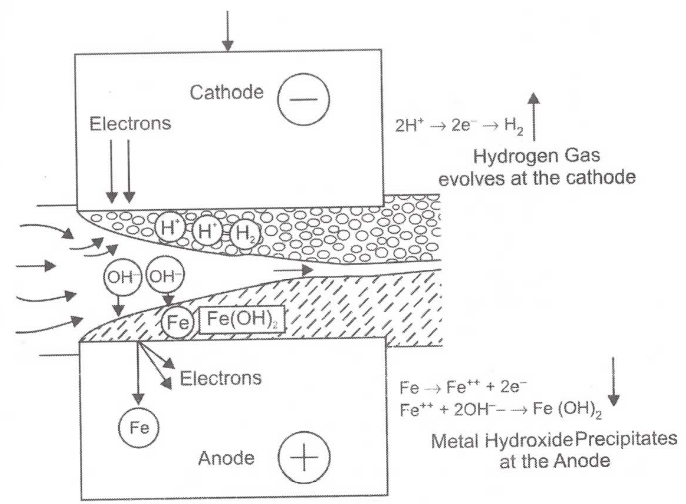


Fig. 3: Close-up of the working gap is shown. The reactions that take place as the Cathode moves slowly towards the anode are also shown. Hydrogen is liberated near the Cathode surface, and the metal hydroxides are formed at the Anode surface.

Metal removal rate depends on current density. Current density itself depends on:

(*a*) conductance of electrolyte
(*b*) voltage across the electrodes
(*c*) shape of electrodes
(*d*) distance between electrodes (i.e. gap)

In general current density is higher at points of closest approach of tool and workpiece. As machining proceeds and the tool is fed towards the workpiece, the surface of the workpiece is dissolved away so that eventually the workpiece shape tends to become complementary of the tool shape. (Fig. 4)

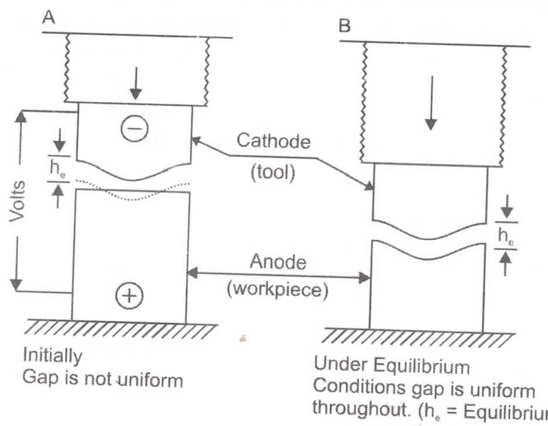


Fig. 4: Shaped tool approaching a plain workpiece. Initially, at different sections of the gap, the machining is not in equilibrium. At some points the working gap is smaller than the equilibrium gap. The tendency at these points is for metal to be removed faster from the workpiece to approach the equilibrium gap. At other points the gap is larger than the equilibrium gap and less metal is removed from the anode at these regions. The final result will be as in *B*. Once this point has been reached the gap is uniform across the Cathode (and this gap is called equilibrium gap). Under equilibrium conditions machining rate is same at all points across the gap. If the tool is fed down further, the same shape will be produced on the workpiece.

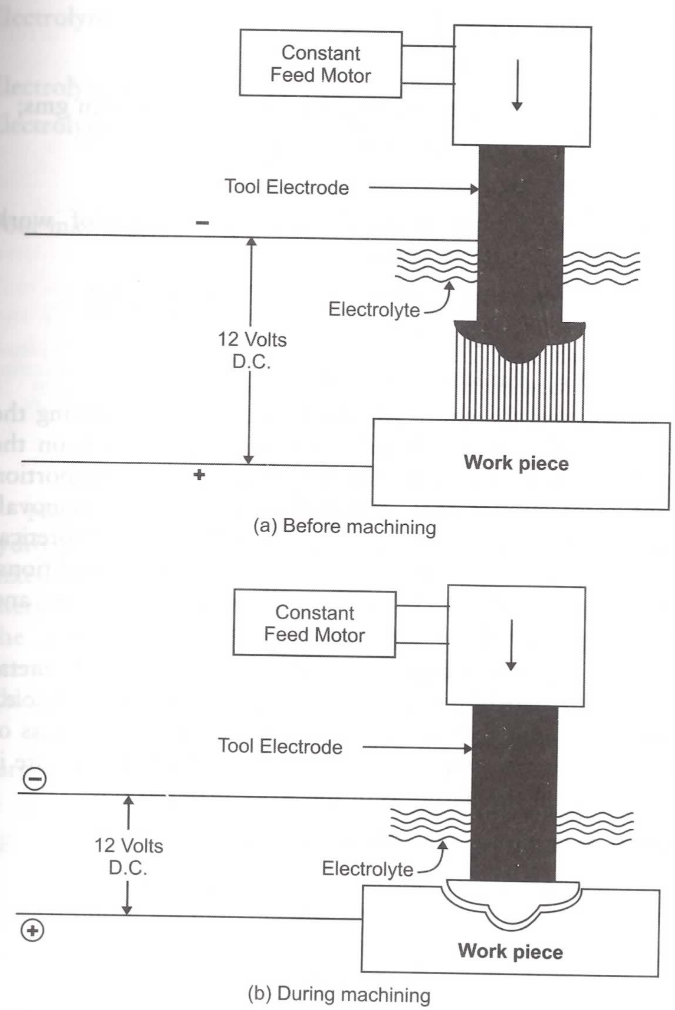


Fig. 5: Schematic Representation of the Principle of Electro-chemical Machining

Fig. 5 shows the principle of electro-chemical machining.

The theoretical metal removal rate in electro-chemical machining is expressed by the following formula based on the Faraday's Laws of Electrolysis:

$$m = \left(\frac{I.t.e}{96,500}\right)$$

m = theoretical amount of metal removed in gms;

I = current intensity in Amperes;

t = time in seconds;

e = electro-chemical equivalent (e.c.e.) of work material in gms;

$$= \frac{\text{Atomic weight(in gms) of Work meterial}}{\text{Valency(a number) of work material}}$$

96,500 = Faraday's constant.

In practice, the entire current is not used in dissolving the metal from the anode. Actual metal removal depends on the current efficiency achieved. Current efficiency is the proportion of the total current that is actually used in metal removal. However, machining rates equal to 75% and above of theoretical rates are obtained depending on the machining conditions. Theoretical machining rates depend on current value and workpiece chemical composition.

From the above equation it can be seen that the metal removal rate depends on the electrochemical equivalent (e.c.e.) of work material only and does not depend on the hardness of the work material, which means that the metal removal rate is independent of the hardness of the work material (Fig. 2).

Typical Machining Conditions in ECM

Theoretical metal removal rates	:	8 to 16 cm^3/min per 10,000 A (= 0.8 – 1.6 cm^3/min per 1,000 A)
Gap: (between tool and workpiece)	:	0.125 mm (However it can vary from 0.025 to 0.750 mm)
Current density	:	200 A/cm^2 to 800 A/cm^2 (actual currents vary from 100 – 2,000 A)
Voltage	:	10 – 20 V (D.C.)
Feed rate	:	0.1 – 1.0 mm/min (depends on current density and gap to be maintained; 0.1 mm/min is the usual value)
Electrolyte	:	10% by weight sodium chloride (rest being water)
Electrolyte velocity	:	30 – 60 m/sec
Electrolyte pressure	:	10 – 30 kgf/cm^2 (This high pressure sets up large hydrostatic forces and electro-magnetic forces)
Tool material	:	Copper (However, stainless steel is preferred since it has high corrosion resistance against dissolution in electrolyte). If electrolyte and tool material are chosen correctly there will not be any wear on the tool. However, it has to be ensured that electrolyte does not attack the tool material and that no plating occurs on the tool.

No chips occur as in ordinary machining, but only salts or hydroxides of workpiece metals are produced and these get mixed with the electrolyte. Production machines consist of filtering units and chemical precipitators (i.e. sludge removers). The purification of the electrolyte, either continuous or intermittent is needed for steady machining rates. Water is added to replenish the consumption by electrolysis.

Plastic tanks and pipes are used for corrosion resistance purposes.

Sketch of an ECM installation (Vertical Type) is shown in Fig. 6.

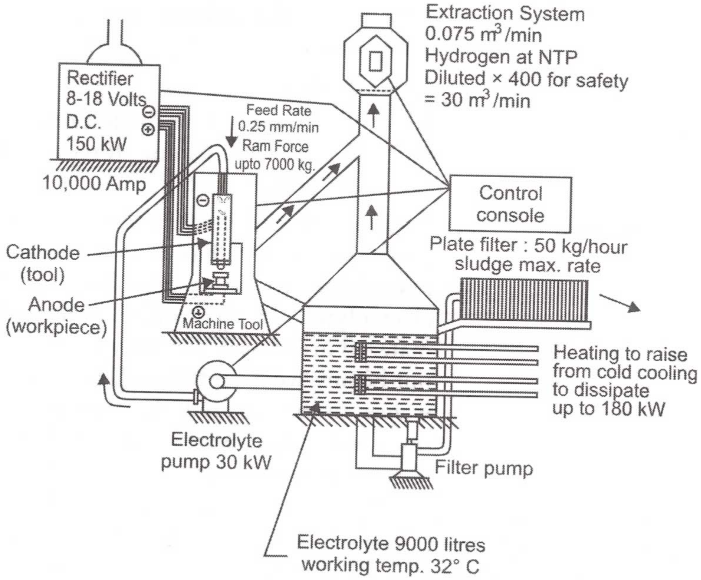


Fig. 6: Typical 10,000 Amperes E.C.M. Installation (Vertical Type)

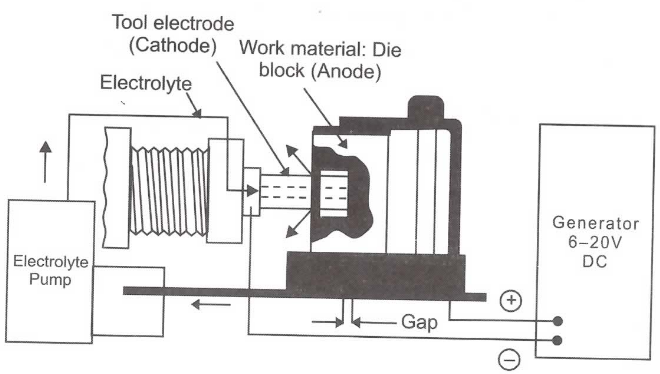
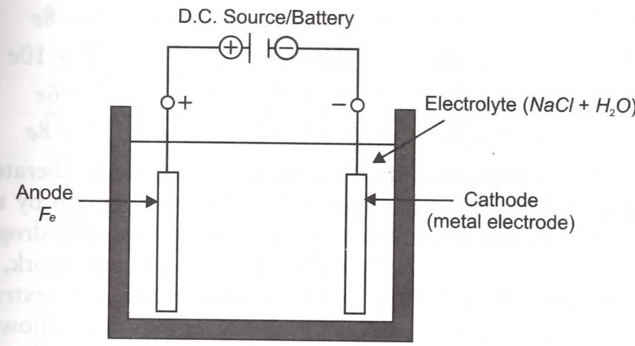


Fig. 7: Electro-chemical Die Sinking Machine (Horizontal Type)

Fig. 7 shows a horizontal type electro-chemical die sinking machine.



(a) Movement of Electricity in an electrolyte solution is associated with the movement of particles of matter carrying either +ve (Anions moving towards Cathode) or –ve charges (cations moving towards Anode).

$$\boxed{\begin{array}{l} NaCl + H_2O \rightarrow Na^+Cl^- + OH^- + H^+ \\ Fe \rightarrow Fe^{2+} + 2e^- \end{array}}$$

$$2H^+ + 2e^- \rightarrow H_2 \uparrow$$

$$2Na^+ + 2OH^- \rightarrow 2Na\,OH$$

$$Fe\ 2^+ + 2Cl^- \rightarrow Fe\ Cl_2$$

$$2Na\ OH + Fe\ Cl_2 \rightarrow 2Na\ Cl + Fe\ (OH)_2 \downarrow$$

(b) Possible chemical reactions when an Iron anode is immersed in an electrolyte made of aqueous solution NaCl conducting current to a metallic cathode

Fig. 8: Simple Electrolytic Cell showing the Chemical Reactions

Chemical Reactions that occur in ECM

A series of chemical reactions take place in the electro-chemical machining of metals and ultimately the metals (viz. workpiece materials) are reduced to their basic metal hydroxide forms (Fig. 8). Some examples of metals and how they are transformed into their basic metal hydroxide forms are given below: (The metal hydroxides formed near the workpiece surface gets dissolved with the electrolyte and are carried away with the fast moving electrolyte solution).

$$Fe + 2H_2O \quad \rightarrow \quad Fe\ (OH)_2 \downarrow + H_2 \uparrow$$

$$Co \quad \rightarrow \quad Co^{++} + 2e$$

$$WC + 5H_2O + 8e \rightarrow H_2WO_4 + CO + 4H_2\uparrow + 8e$$
$$WC + 6H_2O + 10e \rightarrow H_2WO_4 + CO_2 + 5H_2\uparrow + 10e$$
$$TiC + 4H_2O + 6e \rightarrow H_2T_iO_3 + CO + 3H_2\uparrow + 6e$$
$$TiC + 5H_2O + 8e \rightarrow H_2T_iO_3 + CO_2 + 4H_2\uparrow + 8e$$

It can be noted that in all cases, hydrogen gas is liberated. The evolved hydrogen is swept out of the working gap by the electrolyte. Precautions are taken to prevent pockets of Hydrogen accumulating either in the machine tool or in the pipe work, or over the tank of electrolyte, and the usual practice is to extract a sufficient volume of air from these regions and allow a corresponding entry of fresh air such that the evolved Hydrogen is diluted by a factor of about 400 times. The arrangement made for extraction of hydrogen in ECM installation can be seen in Fig. 6.

Features of the ECM Process

1. Material removal is proportional to current strength at the anode.
2. The sole purpose of cathode (tool) is to provide the required geometry to the workpiece and for charge exchange; the tool does not take part in the chemical reaction, hence there is no tool wear.
3. Due to chemical reaction, Hydrogen gas is released:

   $$Fe + 2H_2O \rightarrow Fe(OH)_2\downarrow + H_2\uparrow$$

   metal hydroxide forms as a precipitate (red deposit)
4. The electrolyte quickly becomes polluted with the metal hydroxides formed. The metal dissolved migrates in the first instance to the layer of liquid adjoining the anode. If the metal hydroxides are not removed quickly and efficiently, the process is brought to a standstill very quickly, or in other words **passivation of the process** occurs. In order to counteract the passivation of the process and to keep the properties of the electrolyte as far as possible constant, the electrolyte must be propelled through the gap between the electrodes and workpiece at a very high velocity. (Fig. 9)

5. The temperature of the electrolyte rises quickly owing to its d.c. resistance. So resistivity of the electrolyte decreases.
6. Hydrogen is removed from the electrolyte, hence concentration of the electrolyte increases. This also causes a decrease in the resistivity of the electrolyte.
7. No burr is formed and hence extremely fine finishes are obtained.

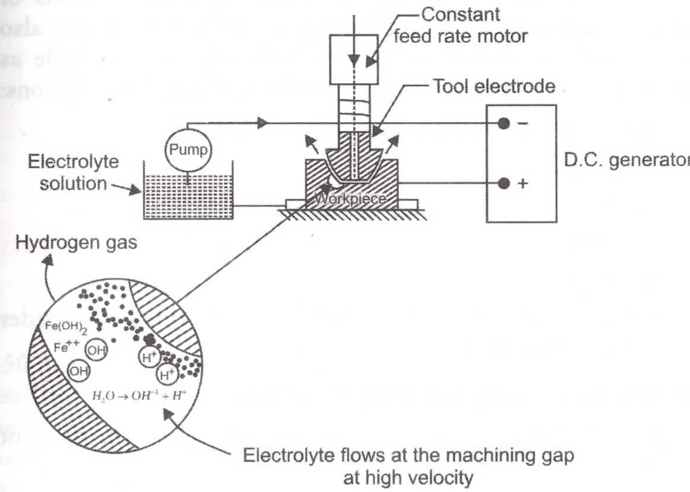


Fig. 9: Electrochemical Machining Set-up

Power Supply Requirements for E.C.M.

The power supply for an ECM is usually the most expensive single item of the installation and may account for a substantial part of the total cost of the complete machine.

Electro-chemical machines require a low voltage d.c. supply and as the mains supply available is usually high voltage a.c., a step-down transformer and a rectifier are required. It is also essential to provide adequate protective circuits for the transformer, rectifier and the machine itself against overload and short-circuit conditions.

$$\text{Current Efficiency} = \left\{ \frac{\text{Actual metal removed per unit time}}{\text{Theoretical metal to be removed per unit time}} \right\} \times 100\%$$

Generally at high current densities, current efficiency is also more and approaches a value of about 90-95%.

Electrolytes used in ECM

The electrolytes normally used are aqueous solutions of inorganic compounds, but other types of electrolytes can also used in certain circumstances. The following are available as salts and can be mixed with water to form electrolyte solutions:

NaCl; (Brine Solution, very commonly used)

$NaNO_3$;

$NaNO_2$;

$NaClO_3$; and

$NaClO_4$;

Titric acid can also used in which case the metal hydroxides formed gets dissolved.

Factors Governing the Choice of Electrolyte

Fig. 10 shows a simple electrolytic cell with the movement of ions.

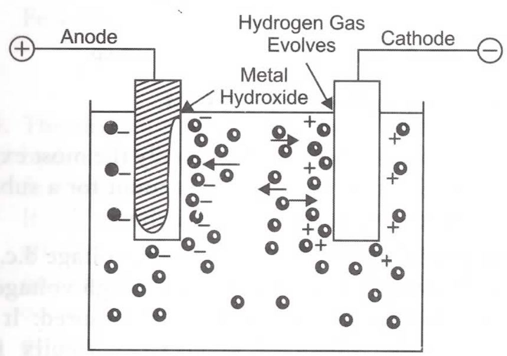


Fig. 10: Simple Electrolytic Cell showing the movement of ions

The electrolyte in ECM provides ions to carry the electric current in the cell between anode and cathode so as to allow electrolytic dissolution of anode. These ions may also take part in electrode reactions.

Fig. 11 shows an electrolytic cell illustrating the distribution of current flow.

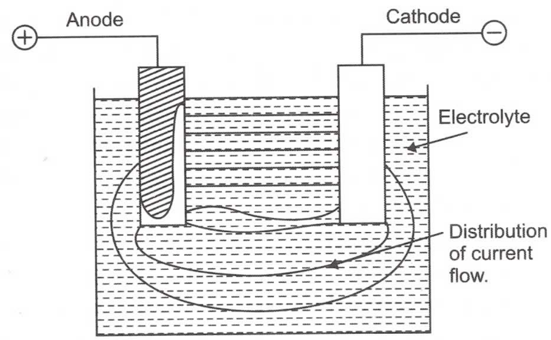


Fig.11: Simple Electrolytic Cell showing the distribution of current flow

The electric current densities used in ECM are usually large, 150 A/cm², and hence to avoid large power losses, the electrolytes used must have high electrical conductivities. Usually they are based on compounds that dissociate highly in aqueous solution, such as strong acids, strong bases or salts derived from the corresponding acidic and basic radicals. The conductivity of highly conductive electrolytes is many times less than that of most metals. Hence substantial heating of electrolyte in the gap occurs. The electrolyte in the gap between workpiece and tool must, therefore, be carried away rapidly, and since flow is generally turbulent, high driving pressures are required. The electrolyte should, therefore, have a low viscosity in order to reduce pressure requirements. Low viscosity also facilitates the movement of ions and therefore increases the effective conductivity of the solution. Electrolyte should also have a high specific heat, high thermal conductivity and a high boiling point so as to minimise the tendency to boil.

The surface finish of the completed workpiece should be uniform in texture and free from imperfections. Although the flow characteristics of an electrolyte through the machining gap influence the uniformity of surface finish, the microfinish of an electro-chemically machined surface is governed mainly by the composition of the electrolyte.

The electrolytes and the products of machining must not be corrosive.

Alkaline electrolytes are not suitable for many metals, because of the formation of adherent insoluble anodic products which prevent or restrict the dissolution of the workpiece. These electrolytes are more suitable for metals whose compounds are those in which the metal is present in the anionic part rather than in the cationic part, of the molecule. Examples are Molybdenum and Tungsten.

Aqueous solutions of salts generally have lower conductivity than acids and bases, but their corrosive tendencies are less. Costs are also comparatively lower. A detailed specification of electrolytes to machine the wide range of metallic materials available is difficult. A universal electrolyte capable of machining any metal or alloy is not available. (The evolution of such an electrolyte is unlikely to take place).

When a new work material is to be machined, first sodium chloride solution is tried and addition of acids or other salts done until desired surface finish is achieved. Practical experiment is the best way of determining the correct electrolyte.

Velocity of Electrolyte

For maximum efficiency, the electrolyte must be pumped across the surface of the workpiece:

(*a*) to remove the contaminated electrolyte from the working gap,

(*b*) to minimise the effect of polarisation, and

(*c*) to restrict the rise in temperature of the electrolyte especially when operating at high current densities.

Flow velocities of 30 to 60 m/sec are required to maintain the desired metal removal rate. More recent work has indicated that provided the flow is turbulent, such high velocities are not necessary, so long as the current densities involved are not high

enough to cause the electrolyte to boil.

Quantity of heat produced at the working gap is given by the expression:

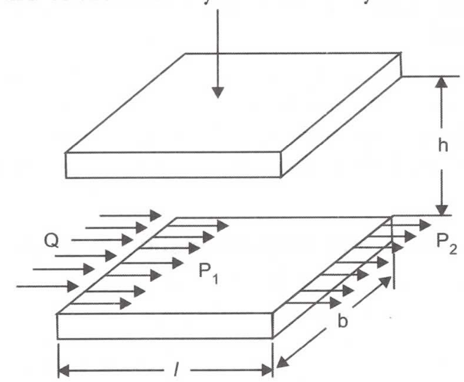
$$Q = I^2R\ (0.0024)\ \text{cal/sec}$$

where I = Current in Amperes, and

R = Resistance offered by the electrolyte in the gap; (Ohms)

$$= \frac{\text{Specific resistance of electrolyte X gap between tool and workpiece}}{\text{Area of cross-section of electrode}}$$

Sufficient quantity of electrolyte should be pumped at the desired velocity, so that the electrolyte takes away the heat produced. As a result of this, the temperature of the electrolyte at the exit of the gap is slightly more (about 5°C) than the temperature of the electrolyte at the entry.



$$Q = \text{Flow rate} = \frac{D_p \,.\, b \,.\, h^3}{12\ nl}$$

Dp = $P_1 - P_2$ (Pressure drop over a length 'l')

b = Breath of the gap perpendicular to the flow direction

h = Gap

n = Dynamic Viscosity of electrolyte

l = Length of the gap in the direction of fluid flow

Fig. 12: Hagen Poiseuille's Equation

Hagen Poiseuille's equation (Fig. 12) can be used to determine the pressure required to pump the electrolyte across the gap.

Tool Materials used in ECM

Electrodes required for ECM process can be made from any conductive material. Conductivity of the electrode is important because it affects the efficiency of the process. Low conductivity means more heat generated in the cathode and a greater voltage drop across the electrodes.

At the same time the electrode material must be able to resist the erosion effects of the electrolyte flow. Tool must be corrosion resistant and easy to manufacture. In most applications Copper, Brass or Stainless Steel are used. For close gap working (gap = 0.125 mm) the Copper-Tungsten alloys are desirable in order to minimise damage caused by arcing. In forming the blade aerofoils, electrode material used is usually a 12% Chromium steel.

The stainless steel electrodes which are used as tool materials in ECM process can be machined easily and readily finished to the correct shape electro-chemically using a Chloride-Nitrate electrolyte; i.e. tool electrodes can themselves be machined by ECM.

Process Variables and Characteristics in ECM

The process variables in ECM are many and they influence the characteristic effects on the workpiece.

Process variables	Process characteristics
1. Current density	1. Metal removal rate
2. Voltage	2. Process efficiency (Current efficiency)
3. Electrolyte viscosity	
4. Electrolyte pressure	3. Accuracy of workpiece (Dimensional accuracy and Form accuracy)
5. Electrolyte temperature	
6. Electrolyte velocity	4. Surface finish
7. Electrolyte composition	5. Surface texture
8. Feed rate of the tool	
9. Current distribution	
10. Electrolyte contamination	
11. Workpiece material	
12. Tool material	

Accuracy of the contours made depends on the values of frontal gap and side gap. Side gap controls the oversize of the hole produced. The influence of different working conditions on the gap width in ECM process is shown in Fig. 13. This should be considered in the design of the tool and in selecting the suitable parameters of the process.

Tool Design for ECM

In designing the tools for ECM two aspects are to be considered:

1. First is the determination of the tool shape; and
2. Second is the determination of the appropriate machining conditions, necessary to produce the required shape of the workpiece.

Theoretically the above would be possible to do so, but this is not fully practicable, and it is still necessary to make considerable amount of adjustment of tool shape on an empirical 'cut and try' basis. Theoretical methods of tool design are available which allow a first approximation to the final tool shape to be calculated. Appropriate machining conditions may also have to be obtained on trial and error basis.

Insulation of the tool at the side prevents side erosion in the workpiece Fig. 14(*a*). This arrangement may be considered in the design and making of the tool. This is especially advantageous when deep cavity sinking is required. Overcut of the hole produced is also a factor to be considered in the design of the tool. Fig. 14(*b*). There is an empirical relationship between overcut and frontal gap:

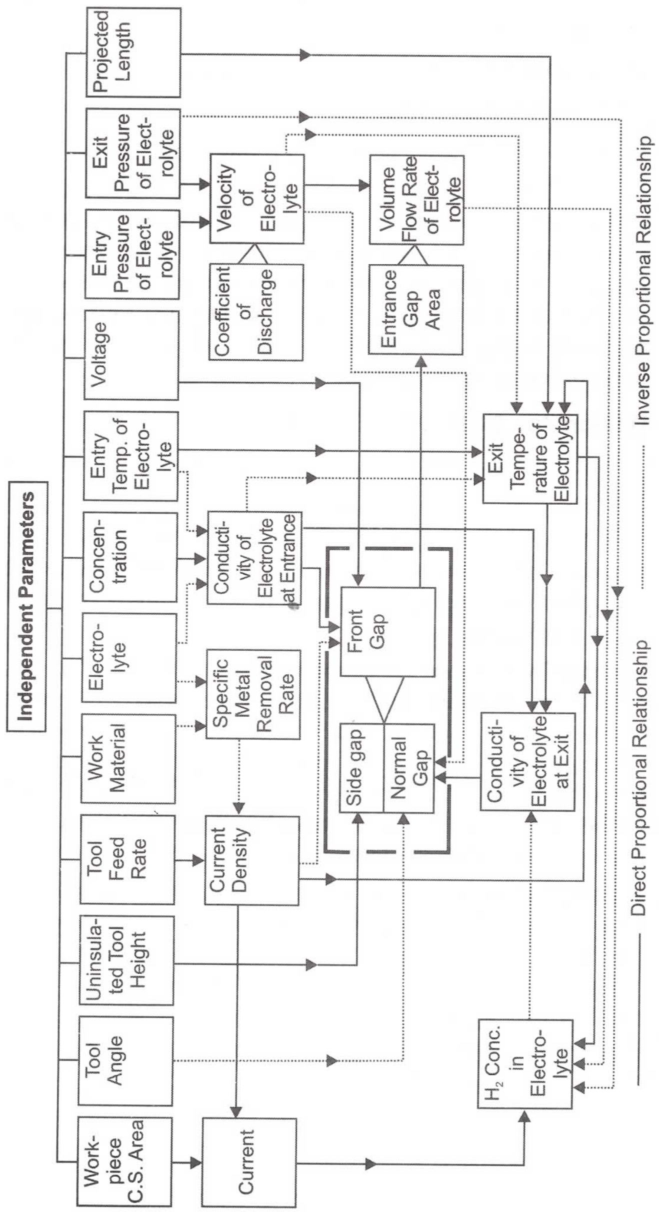


Fig. 13: The influence of different working conditions on the gap width in ECM process

Overcut = 0.65 (frontal gap)

The frontal gap is given by the expression:

$$\text{Frontal gap in cm} = (E - E_p)\,\frac{K.V_{sp}}{f}$$

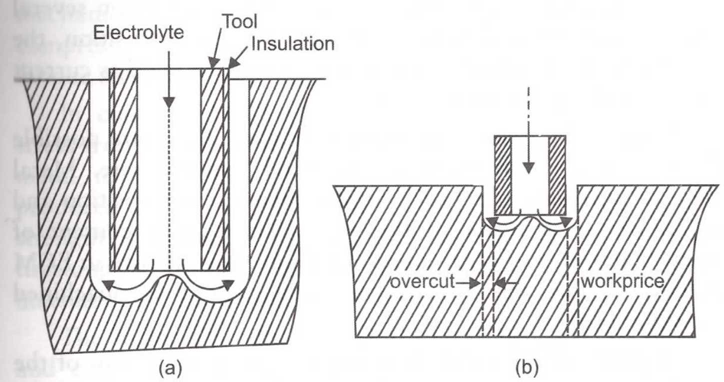


Fig. 14: (*a*) Use of insulated tools for electro-chemical drilling.
(*b*) Overcut in electrochemical drilling.

where E = Voltage across the electrodes, (Volts)

E_p = Polarization voltage, (Volts); this depends on anode material, cathode material, electrolyte, its specific conductance and current density.

K = Specific conductance of the electrolyte, (1/Ohm.cm)

V_{sp} = Specific volume metal removal rate (cm^3/Amp. min)

f = Feed rate (cm/min)

Specific volume metal removal rate viz. V_{sp} is given by the expression:

$$V_{sp} = \frac{A}{pmFZ}$$

where A = Atomic weight of the work material; (gms)

p = Density of the work material; (gms/cm^3)

m = Mass of metal removed; (gms)

F = Faraday's Constant; (96500 Coulombs/gm);

Z = Electron transfer (Valency of work material).

Surface Finish Obtainable in ECM

If machining conditions are properly chosen in ECM best surface finishes are possible. Surface finish depends on several factors such as: workpiece material, and its composition, the electrolyte used and other machining conditions such as current density and electrolyte flow, etc.

With ECM greater variations in surface finish are possible from alloy to alloy than in the metal removal rate. Metal removal mechanism depends on the chemical composition and metallurgical structure of the work. The carbon content of work material is of great importance since it is passive in ECM reactions. (For this reason cast iron cannot be machined satisfactorily).

A poor surface finish may result if the composition of the workpiece is different from place to place, particularly if the different constituents (i.e. phases) have significantly different electrode potentials. With low current densities, one constituent may be removed preferentially, the constituent with lowest discharge potential being removed first. If the major constituent is removed first the workpiece may be dissolved completely, leaving the other constituents as anode material. Non-conducting inclusions will also be deposited in this way. Alternately, if a minor constituent is removed first, and in such a case other constituents will not be removed until the cell potential increases to the appropriate level.

Effect of ECM on the Mechanical Properties of the Workpiece

With most of the metals and alloys, ECM has no significant effect on the mechanical properties such as yield strength, ultimate tensile strength, etc. With metals such as Beryllium and Tungsten, the surfaces are likely to be damaged by conventional machining processes. When Beryllium and Tungsten are machined by ECM process the mechanical properties of these materials show improvement.

In some instances, if the fatigue strength of a workpiece machined electro-chemically is compared with that of a mechanically polished or finished metal, ECM will appear to have lowered the fatigue strength or endurance limit by about 10 to 25%. However, it must be remembered that subsequent mechanical finishing methods frequently impart additional compressive stresses to the surface layers and these raise the fatigue strength of the materials.

In contrast, ECM removes stressed layers and leaves a stress-free surface that allows a true fatigue strength of the metal to be measured uninfluenced by the surface effects produced by a particular finishing operation. When fatigue strength is critical it can be increased by the use of some finishing treatments such as fine abrasive polishing after machining by ECM process.

The surfaces produced generally have better wear, friction and corrosion resistance properties than those produced by mechanical means. In ECM when operating conditions are not correct, non-uniform dissolution of metals and alloys can occur, leading to selective etching, Inter-Granular Attack (IGA) or pitting. Surface defects of this kind can affect mechanical properties considerably, e.g. intergranular attack to a depth of 10 microns can reduce the fatigue strength by about 15%.

Advantages of Electro-chemical Machining Process

ECM is advantageous for machining complex and curved shapes and profiles on very hard and tough materials.

The advantages can be summarised as follows:

1. Hard materials can be machined easily irrespective of their hardness.
2. No possibility of work distortion; holes in very thin sheet metals can be cut without stressing or distorting them.
3. Components or jobs with very small wall thicknesses can be machined easily (e.g. A honeycomb structure of 0.025 mm wall thickness in stainless steel material can be machined easily).

4. Work materials suffer no metallurgical changes and are free from surface and sub-surface cracks.
5. No tool wear occurs and the same tool can be used for any number of components or impressions.
6. Unlike conventional machining methods, components can be machined after heat-treatment thus eliminating the distortions and errors that may be introduced due to heat-treatment.
7. Surface finish produced is better on many materials eliminating operations like lapping.
8. Complex shapes can be produced in one operation eliminating a sequence of processes like milling, grinding, deburring, etc.
9. High rate of metal removal, which becomes particularly evident when very hard materials are machined is possible. The time required for completing a job by ECM is sometimes very short compared with the conventional machining methods.
10. No problem of disposal of chips as in conventional machining.
11. Components machined by ECM method have better wear, friction and corrosion resistant properties.
12. No burr is formed on the workpiece.

Disadvantages of Electro-chemical Machining

The process suffers from the following disadvantages:

1. Equipment required is relatively costly.
2. Problems encountered in its use are not familiar to those more accustomed to conventional metal working processes.
3. The process is not economical for small quantity production of dies and workpieces.
4. Specific Power consumption

$$\left\{ = \frac{\textit{Power consumed}}{\textit{Volume metal removal rate}} \right\}$$

is high. From the following it can be seen that ECM process consumes a large amount of power when compared with other machining processes.

Specific power consumption

for ECM	= 8.00 kW/cm^3/min
-do- for EDM	= 2.00 kW/cm^3/min
-do- for heavy duty grinding	= 0.50 kW/cm^3/min
-do- for turning on a lathe	= 0.50 kW/cm^3/min

5. Pitting or etching will occur if proper working conditions are not chosen during ECM.
6. Tooling costs are relatively high.
7. The design and manufacturing of tool electrode is very difficult and time-consuming.
8. If the feeding of the tool is stopped abruptly, due to the stagnation of the electrolyte, a small pip is left on the workpiece (Fig. 15).

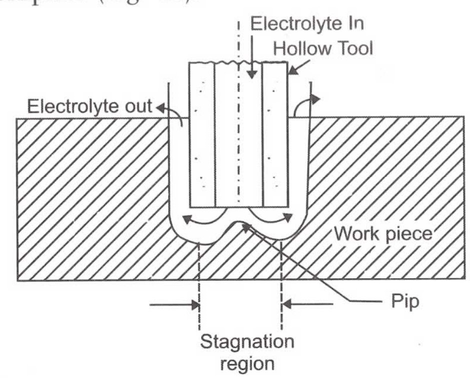


Fig. 15: Effect of stopping the tool abruptly. Due to stagnation of the electrolyte, small pip is left in the workpiece just below the middle of the tool.

Problems Encountered in the Application of ECM

Although the principle on which the ECM process is extremely simple several problems may be encountered in the successful application of ECM process. The problems are:

1. Local **passivation** of the anode (workpiece) occurs. When this occurs, the material to be machined does not

dissolve at all in certain places or dissolves only very slowly. As a result, when the cathode (tool electrode) advances it will come into contact with the anode (workpiece) which may result in a short-circuit damaging both workpiece and tool electrode.

2. The surface of the material being machined may be rough. It may show pronounced etching, pitting or clearly visible electrolyte-flow lines (or marks). The surface may also have a dull finish.
3. Dimensional accuracy may be unsatisfactory.

In order to solve the problems mentioned under 1 and 2 above, the theories relating to the various anodic metal processes such as etching, passivation, pitting, removal of surface irregularities and electro-polishing, have to be clearly understood and the various processes should be properly interpreted.

Dimensional Accuracy in ECM

The dimensional accuracy obtainable in ECM process is affected by the following factors:

(*i*) As a result of ohmic losses, the temperature of the electrolyte while passing through the machining gap will gradually increase. This leads to an increase in conductivity (e.g. 2% increase in conductivity per °C of increase in temperature) and, consequently, of the local current density. The width of the working gap will, therefore, become greater at the exit than it is at the point of entry of the electrolyte.

(*ii*) Hydrogen is formed on the cathode, and this will be carried along in the form of gas bubbles; as a result, conductivity will decrease. As the electrolyte during its passage through the gap will carry along an increasing amount of gas bubbles, conductivity will decrease more and more.

Effects (*i*) and (*ii*) are partially offset by each other.

(*iii*) The effect of the increase in temperature can be limited by increasing the flow velocity of the electrolyte. However, when the flow velocity of the electrolyte is increased beyond a certain limit, cavitation may occur, as a result of which the rate of dissolution decreases near the point where the direction of flow changes rapidly.

(*iv*) When the product to be made has a complicated shape with sharp corners, the current density distribution will become uneven and as a result too much material will be removed locally. Theoretically this could be solved by calculating the pattern according to which the current density is distributed over the electrode. The disadvantage is that this requires the use of a computer and the application of sophisticated calculations. The result of such calculations can be used to adapt and modify the shape of the cathode.

(*v*) Anode material is dissolved mainly in the machining gap (front) although some dissolution occurs at the sides, so that a hole made by ECM will always be slightly conical. This tendency can be counteracted by using an electrolyte with a very low "throwing power". Electrolyte such as Sodium Chlorate has excellent properties in this respect.

Points to be Considered for the Successful Application of ECM Process

1. If satisfactory results are to be obtained in the electro-chemical machining of carbon steel, the Cl^-/NO_3^- ratio of the electrolyte should be increased considerably over that of normally used ratio.
2. Minute dirt particles in the electrolyte may cause local blocking of the working gap and thus prevent the free flow of electrolyte as a result of which local passivation occurs. The electrolyte used should be kept extremely clean.
3. When machining Copper and Copper alloys, electrolytes containing chlorides (e.g. chloride solutions) should not be used as this leads to formation of a CuCl (Cuprochloride) layer on the anode. This results in passivation of the anode. This prevents the electrolyte

from attacking the work material. The use of nitrate or sulphate solutions does not give rise to passivation. Hence, while machining Copper and Copper alloys, nitrate or sulphate solutions are recommended.

4. The standard electrolyte (viz. 2 : 3 aqueous solution of Cl^-/NO_3^-) is unsuitable for machining of Aluminium. An improvement can be obtained by decreasing the Cl^-/NO_3^- ratio. An alkaline NaCl solution may also be used.

[**Note:** However, it may be noted that Copper, Copper alloys and Aluminium materials can be machined easily with conventional machining methods; if the profile is complicated then E.C.M. process can be used on these materials.]

(*a*) General Applications of ECM

All conductive materials can be machined by the ECM method, the hardness of the work material is immaterial and does not affect the metal removal rate. A finish of 0.1 to 0.3 micron can be obtained on Nickel based alloys. Another Advantage is that the component is left completely free from burrs and stresses. Complex shapes can be easily machined, but some ingenuity is required to ensure the proper supply of electrolyte to all parts of deep cavities. Trepanning of complex and irregular shapes on curved surfaces can be carried out easily (Fig. 16).

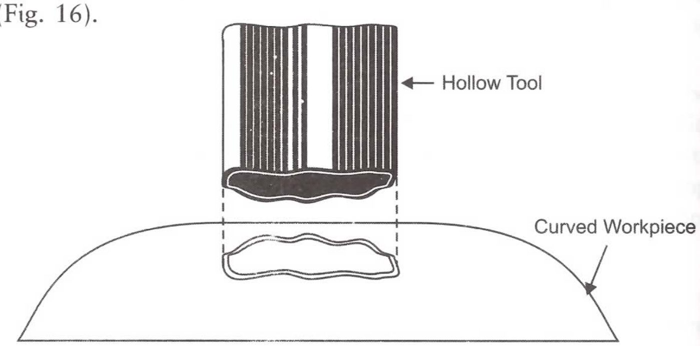


Fig. 16: Electro-chemical Machining of Irregular Shaped Holes

Blind holes which may be square, octagonal or splined can be machined easily. Through holes as small as 1.00 mm in diameter and 180 mm deep have been produced readily.

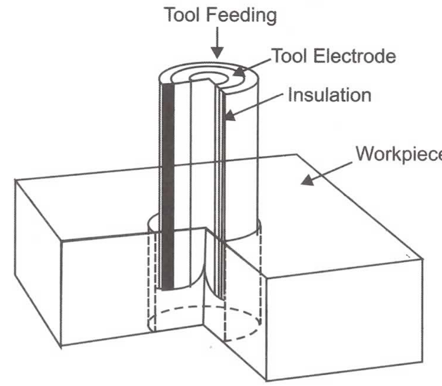


Fig. 17: Electro-chemical Drilling

(*b*) In Die Working

1. The ECM process is successfully used in sinking of dies and for contour machining in hardened and tempered die-blocks (Fig. 18).

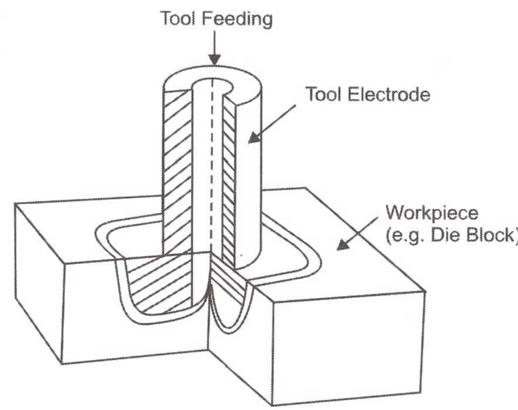


Fig. 18: Electro-chemical Contour Machining

2. The ECM process can be used in the machining of forging die blocks. Dies of hard materials such as forging die blocks can be finished easily and quickly by ECM. Dies can be machined in the fully hardened state, thus eliminating distortion on heat treatment. Hence harder materials can be used for dies and this increases the life of the dies.
3. ECM can be used to machine complex impressions in hot working die steels.
4. In general ECM can be used to machine complicated profiles in hard work materials.

(c) In Machining of Aero-engine Components

A special feature of ECM process is that it is possible to produce stress-free high quality surface. This enables the process to be applied especially to the machining of aero-engines' gas turbine blades. ECM is used in aircraft engine, air-frame and missiles and in rocket manufacture.

Typical Applications of ECM process in aircraft production practice are as follows:

1. In the machining of the aerofoil sections of aero-engines turbine blades (This is known as electro-chemical shaping of turbine blades) Fig. 19.
2. Deep drilling of coolant holes (circular or elliptical shapes) in turbine blades (Length of hole 150 mm; dia. of hole 0.75 mm) (Fig. 20).
3. Electro-chemical machining of compressor rotors.
4. Electro-chemical machining of cylinder sleeve ports.
5. Electro-chemical machining of stator blade recess (stator segments).
6. Disc face turning.
7. Electro-chemical thinning of trailing edges.
8. Electro-chemical machining of vane ends.
9. Electro-chemical machining of spherical seatings.
10. Machining of engine casing.

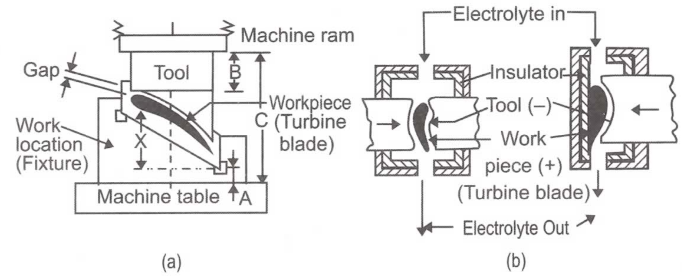


Fig. 19: Setups for machining turbine blades

(a) Shows vertical arrangement for mounting the blade; Positioning of blade depends on A, B and C.

(b) Shows horizontal arrangements, in the first both the surfaces of the blade can be machined; in the second only one surface of the blade can be machined.

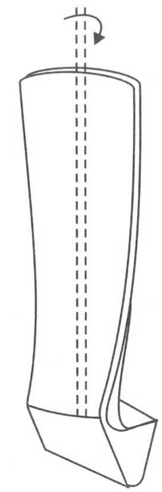


Fig. 20: Deep hole drilling by Electro-chemical Action

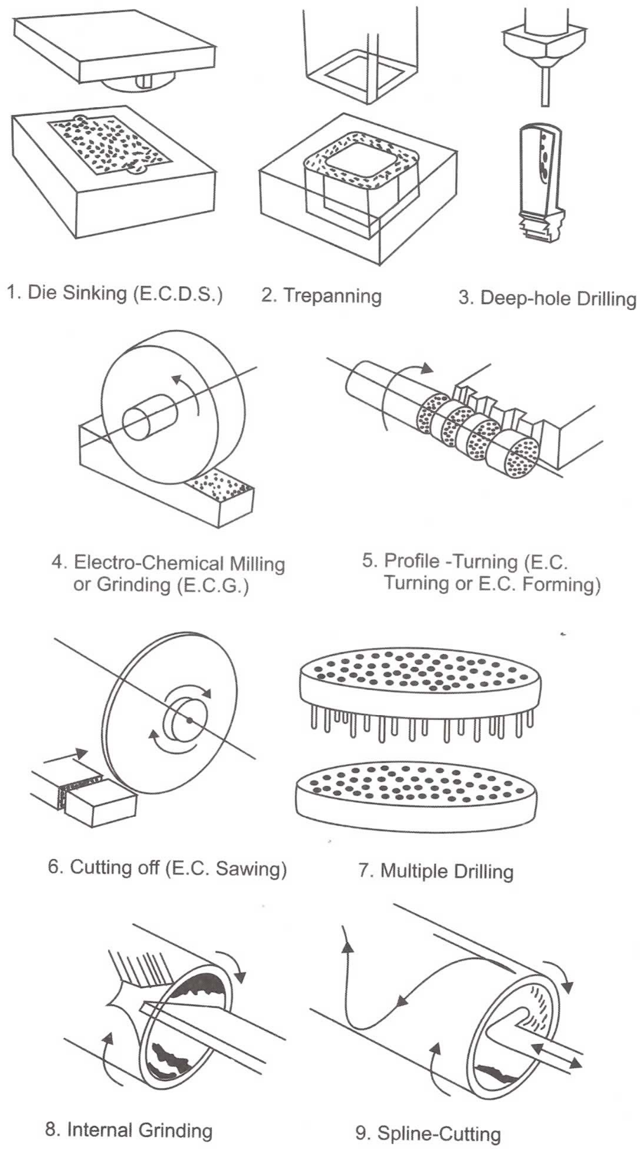


Fig. 21: Different Variations of Electrochemical Machining.

Electro-chemical sectioning of thick billets and bars can also be carried out. (This is known as Electrochemical Sawing.)

Different variations of ECM are shown in Fig. 21. Actual components or parts machined by ECM are shown in Figs. 22 to 25.

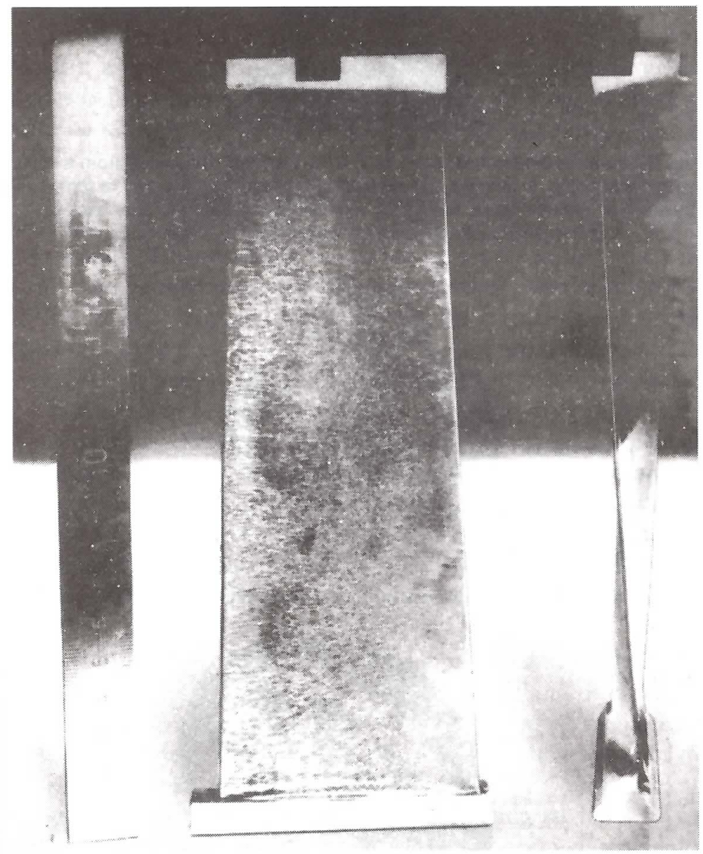


Fig. 22: Aero-engine turbine blade (aerofoil sections) machined by ECM process

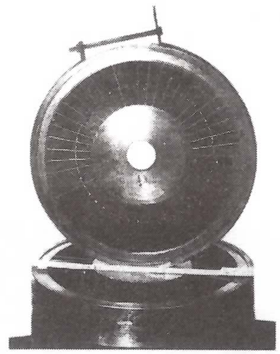


Fig. 23: Impeller blades machined by E.C.M. process; (machined from a solid disc by trepanning, in which a hollow cathode is sunk into the part to form each blade. A single cathode is fed axially and the disc is indexed after each cut). This is called integral blade machining by ECM process.

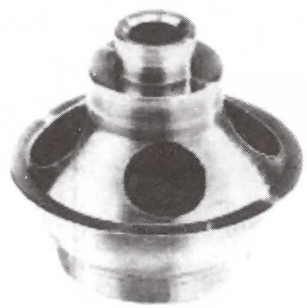


Fig. 24: Circular holes machined in inclined surface by ECM process

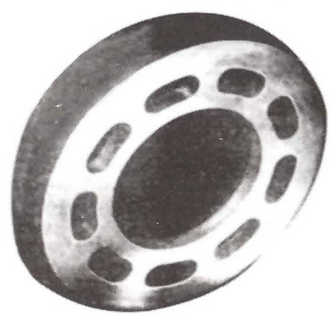


Fig. 25: Example of ECF (Electro-Chemical Forming) application.

Part name : Hydraulic Motor body
Material : Stainless Steel
Time taken : 1.25 min

(All the 9 slots are simultaneously formed by the vertical ECF machine)

Electro-chemical Shaping of Aero-engines' Turbine Blades

Basically electro-chemical machining is a cavity sinking process, its applications to the shaping of aero-engines' turbine blades being really a special case of cavity sinking. Shaping of blades and other components for gas turbine engines is done by ECM.

When the Electro-chemical Machining process is used for forming, i.e. for changing the physical shape of a metal component, it is necessary to identify the area from which the metal is to be removed while protecting other parts which are to be left in their original shape. Hence the fixtures used for the aerofoil forming of the blades not only locate and hold the component (blade) in the correct relationship with respect to the cathode, but also mask the surfaces where machining is not required, thus excluding the electrolyte. The fixtures are made of Tufnol (a type of plastic viz. resin impregnated compressed cotton fabric) which is non-conductive, having low-coefficient of expansion and excellent corrosion resistance properties. The seal is made of moulded rubber (silicone rubber). Fig. 26 shows fixture set-up for ECM of turbine blades.

When the component is exposed to a suitably shaped cathode in the electrolyte metal will be removed at a higher rate from those parts which are nearer the cathode, and thus there is a tendency to reproduce a complementary form of the cathode on the component. Hence, for producing the concave side of the aerofoil, the cathode should be shaped on the almost exact complementary convex aerofoil. The sweeping surfaces of gas turbines' blades so difficult to produce by conventional machining are obtained by the necessary flow of the electrolyte. The accuracy of the reproduction of the cathode form depends on the nearness of the component to the cathode i.e. the gap, electrolyte flow conditions and feed rate.

The cathode is made of stainless steel as this will withstand the corrosive effective of the electrolyte better. The other commonly used materials for cathode are Copper, brass and in some cases Tungsten-Copper.

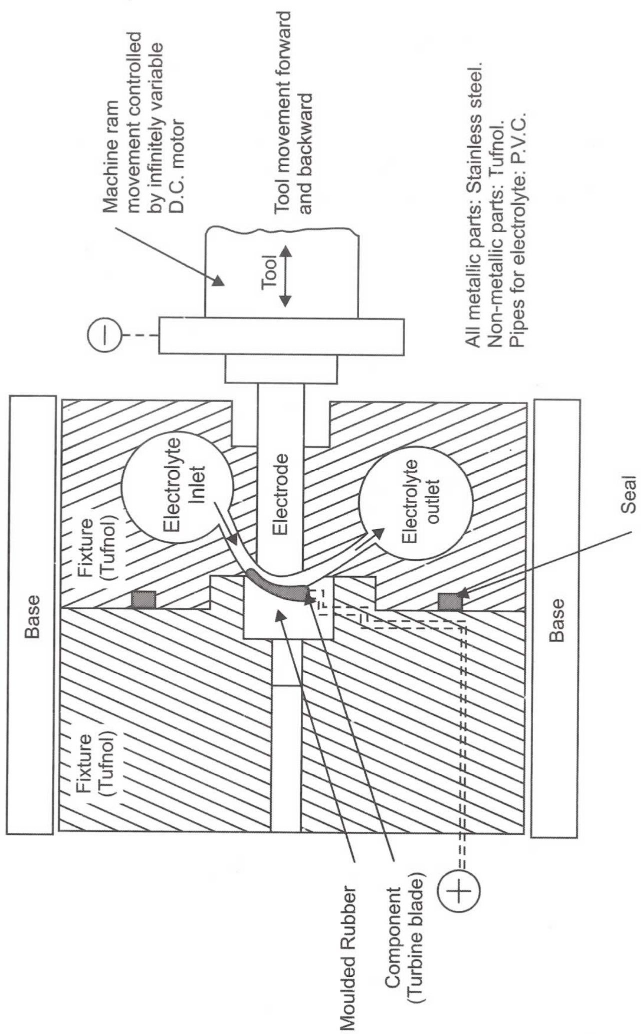


Fig. 26: Sectional view of fixture setup for electro-chemical forming of concave Aerofoil section of turbine blade. (Electrode material: Stainless Steel)

The action of the process is such as to continuously increase the gap between the cathode and the component and for this reason electro-chemical forming machines are provided with a feedback which keeps pace with the erosion of the metal and maintains as far as possible a constant gap. The feed rate is a critical parameter of the process and to facilitate this, the feed mechanism provided is extremely accurate. The gap maintained during the finishing stages of the process is of the order of 0.3 mm.

The electrolyte used is Sodium Nitrate ($NaNO_3$). The other electrolyte commonly used is Sodium Chloride (NaCl—common salt). The electrolyte (20% by weight) is pumped into the fixture at a pressure sufficient to ensure a flow fast enough to control the temperature raise in the working area and at the same time wash away the Hydrogen bubbles and metal hydroxides as they are formed. The temperature of the electrolyte is maintained around 45°C.

There are two by-products in the process, namely Hydrogen and the metal Hydroxides. The Hydrogen is removed by an Hydrogen extraction system and the metal hydroxides are separated from electrolyte by a centrifuge.

The D.C. Voltage applied to the system is 20 Volts.

Surface Treatment given to the Blades after ECM

After electro-chemical machining the blades are thoroughly rinsed and cleaned. Since the ECM process leaves a stress-free surface on the component, the fatigue strength of the blades machined by ECM process is comparatively less than the fatigue strength of the blades machined by conventional machining methods, (viz. copy milling). Moreover, there is a possibility of grain boundary attack (IGA), hence a reduction in the fatigue life of the blades. In the case of aero-engine's turbines, the fatigue strength of the blades is critical. Hence after the blades are electrochemically machined, they are finished by fine abrasive polishing (which introduces certain amount of compressive stresses) to increase the fatigue strength of the blades.

Economics of Electro-chemical Machining

Whether or not ECM is economical, depends on the complexity of workpiece shape and the difficulty of machining the workpiece material (namely the hardness and toughness of work material). The ECM machines are expensive; initial cost and the operating cost are high. 3 kWh is needed for 16 cm^3/min. of metal removal, whereas a conventional machining requires only 0.1 kWh, if the material is readily machinable. But with ECM the rate of metal removal is independent of hardness and toughness of workpiece. At present ECM is used for the machining of materials which because of their hardness or toughness can be machined only very slowly by conventional methods. The process can be economical for machining complex workpiece in softer materials also, since in ECM the whole surface of the workpiece can be machined simultaneously and the machining time required can be much less. In ECM metal removal rates of 1.6 cm^3/min for each 1000 Amperes of current are easily possible. Machines have been developed to give machining rates of even 50 cm^3/min.

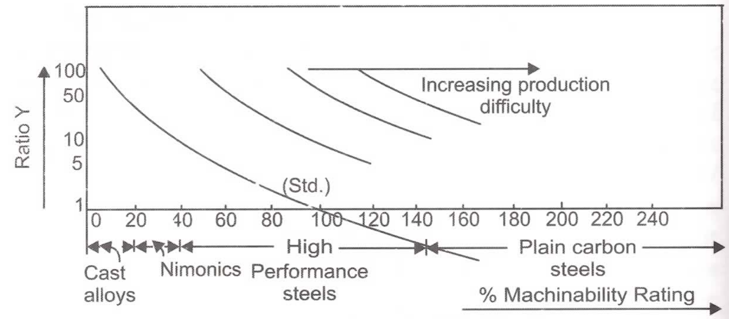
The economic aspects of the ECM process must be studied with reference to two classes of application:

1. In the first type, the component can be produced quite easily by conventional means (e.g. the work material is not very hard and the profile to be machined is quite simple), but because of the special capabilities of ECM (such as higher metal removal rates obtainable) certain economies in the cost of production can be achieved. In this class of application, direct cost comparisons can be made and if the application is selected wisely, ECM can show remarkable advantages.
2. In the second class of application, certain operations which are impossible to perform by conventional means (because either the work material is quite hard and tough or the profile to be machined is quite complex) become feasible and economical when ECM is used (Fig. 27). An outstanding example is the drilling of long slender holes in aero-engines' gas-turbine blades to provide passages for cooling air. Holes upto 20 cm long and 1 mm diameter are currently being produced in production quantities in a tough Nickel-based alloy. Such holes are impossible to produce conventionally, and hence a direct cost comparison cannot be made. However, considerable economy in jet engine fuel consumption and improved performance are achieved as a result of this blade cooling. In such cases, the economic gains are quite substantial but because of the interaction of other factors they cannot be assessed and compared accurately. ECM can also, in certain cases, extend the freedom of the designer and provide flexibility to introduce certain innovative features in the design of his product, which otherwise will be impossible.

For a typical application, the time required for copy milling is about 30 hours whereas ECM consumes 1 hour of production time only; the costs comparison for copy milling and ECM for the above application works out to be in the ratio of about 8 : 1 respectively.

The production cost per component in ECM is a function of the total number of components produced since the tooling cost is spread over the anticipated total production. And, since ECM tooling is many times more expensive than conventional tooling, a large number of components will have to be produced by ECM before the tooling cost is recovered. In the above example (quoted in previous paragraph), 2000 components were produced and ECM showed a clear economic advantage; and the 'break-even' point is 100 components only in this case.

Fig. 28 shows the economics of copy-machining, spark erosion machining and ECM. General rule is as follows:



$$\text{Ratio } Y = \frac{\text{Conventional Machining Time}}{\text{Electrochemical Machining Time}}$$

Fig. 27 : Economics of Electro-Chemical Machining Production difficulty consists of (*a*) complexity of the profile, and (*b*) hardness of the workpiece. For cast alloys and Nimonics, ECM is economical even if the profile is simple, say, circular shape. For easily machinable materials like plain carbon steels, ECM process is economical if the profile is complex.

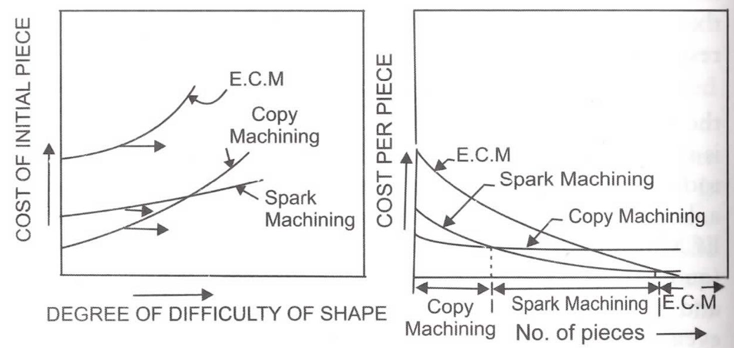


Fig. 28: Economics of Copy Machining, Spark Erosion Machining

1. Copy machining is economical upto a maximum production quantity of 25 to 30 pieces. Beyond this quantity, copy machining is not economical; but spark erosion machining may be economical.
2. Spark erosion machining is economical if the production quantity ranges from 25 to 30 pieces upto a maximum of 100 pieces. Beyond 100 pieces spark erosion is not economical; but ECM may be economical.

3. If the production quantity is above 100, ECM proces will be economical.

A study at the Rolls-Royce (U.K.) on the economics of ECM process, taking a depreciation period of 10 years and three shif working, reveals that the running costs of ECM are roughly 2 3 times greater than for conventional machines. The application for ECM must, for this reason, be carefully selected, since th time saving must be at least 5 : 1 for the process to b worthwhile (which means that the time required by conventiona machining is about 5 hrs whereas ECM consumes 1 hr. o production time only); often the ratio may be as high as 100:1

Ranking Chart for ECM Applications

A Ranking chart for ECM applications has been develope by the researchers. One takes the particular job or applicatio into consideration, gives scores depending upon where it fit into the scheme and compares the total score obtained with th different ranges given under Analysis. This chart can be used t take a quick decision as to whether or not ECM can be applie for a particular job or application.

If the total score obtained for a particular application is les than 30, the ECM process will not be applicable. If the scor obtained is between 30 and 60 probably there will be savings i ECM is applied; the proposal to use ECM is worth studying further. If the score obtained is between 60 and 80 there will b definite savings, and priority study should be made. If the scor obtained is over 80, the contemplated application is in fact a ideal application for ECM process.

The following Ranking chart can be used if a decisio concerning the ECM process is to be taken:

Ranking Chart for ECM Applications

(*A*) *Complexity of shape (Geometry)*	*Score*
1. Basic external diameters at planes; at right angles internal diameters	2
2. External, two-dimensional	5
3. Internal, two-dimensional	8

	4. External, three-dimensional	10
	5. Internal, three-dimensional	15
(A)	*Workpiece material*	
	1. Aluminium and Aluminium alloys, bronze, copper, cast iron, mild steel	0
	2. Alloy steels and stainless steel (Low strength)	5
	3. Alloy steels (High strength)	10
	4. Stellite, Titanium, ausformed or maraged tool steel	20
	5. Tungsten Carbide	40
(C)	*Production by Alternative methods*	
	1. Can be formed or cast	0
	2. Can be machined easily (ECM replaces only 1 operation)	1
	3. Can be machined easily (ECM replaces many operations)	4
	4. Can be machined, but copy milling or NCMT necessary	6
	5. Can be machined, but special broaches and cutters required	8
	6. Cannot be machined as single piece	15
	7. Not currently feasible	25
(D)	*Quantity sufficient to repay investment*	
	1. 1 part	0
	2. 10 parts	10
	3. 100 parts	20
	4. 1000 parts	30
(E)	*Extent of possible utilization of ECM equipment*	
	1. % utilisation of minimum upto 30%	2
	2. % utilization upto 70%	4
	3. % utilization 100% (fully utilized)	6

(F)	*Present status*	
	1. Job already tooled up	0
	2. Waiting for new job	20

Feasibility of obtaining the complex shapes (after certai design modifications) can also be studied: (For this stud exclude re-entrant forms, tolerances closer than ± 0.025 mm and dimensional details less than 0.5 mm).

1. Major design changes required (e.g. relax the tolerance and alter the shapes to the extent possible).
2. Minor design changes required (e.g. increase fille radius; Extent of surface finish variation permissible).
3. No design concessions i.e. no design changes permissible
4. Similar tooling already exists on proven job i.e. on job successfully completed.

Add all the scores obtained. The following Table can b used for an analysis :

Table 1:

Analysis:	Total Score below 30	ECM process not likely t show any savings. Defer th decision on the use of ECM.
	30–60	ECM process may result i savings. The proposal to us ECM is worth studying furthe
	60–80	Definite savings will b obtained if ECM process i used. Priority study should b made.
	Over 80	The contemplated applicatio is an ideal application fo ECM process.