Module

9

Non conventional Machining

Lesson

38

Electro Chemical Machining

Instructional Objectives

(i) Identify electro-chemical machining (ECM) as a particular type of non-tradition processes
(ii) Describe the basic working principle of ECM process
(iii) Draw schematically the basics of ECM
(iv) Draw the tool potential drop
(v) Describe material removal mechanism in ECM
(vi) Identify the process parameters in ECM
(vii) Develop models for material removal rate in ECM
(viii) Analyse the dynamics of ECM process
(ix) Identify different modules of ECM equipment
(x) List four application of ECM
(xi) Draw schematics of four such ECM applications

1. Introduction

Electrochemical Machining (ECM) is a non-traditional machining (NTM) process belonging to Electrochemical category. ECM is opposite of electrochemical or galvanic coating or deposition process. Thus ECM can be thought of a controlled anodic dissolution at atomic level of the work piece that is electrically conductive by a shaped tool due to flow of high current at relatively low potential difference through an electrolyte which is quite often water based neutral salt solution.
Fig. 1 schematically shows the basic principle of ECM.

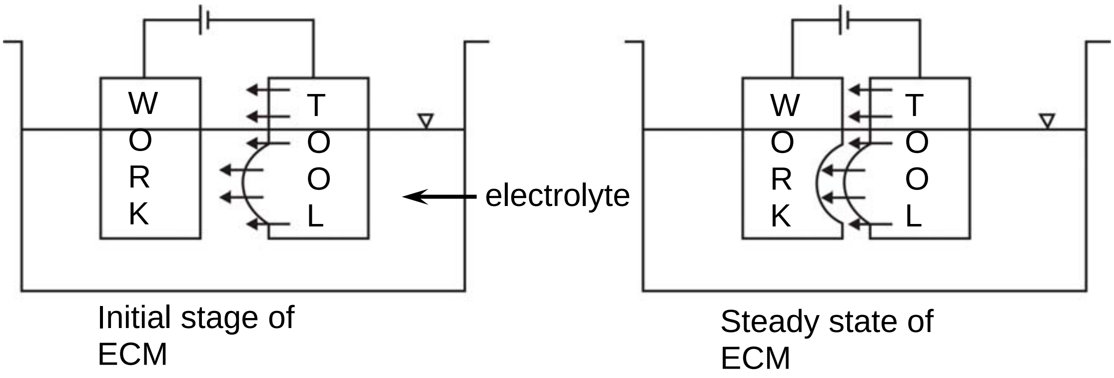


Fig. 1 *Schematic principle of Electro Chemical Machining (ECM)*

2. Process

During ECM, there will be reactions occurring at the electrodes i.e. at the anode or workpiece and at the cathode or the tool along with within the electrolyte.
Let us take an example of machining of low carbon steel which is primarily a ferrous alloy mainly containing iron. For electrochemical machining of steel, generally a neutral salt solution of sodium chloride (NaCl) is taken as the electrolyte. The electrolyte and water undergoes ionic dissociation as shown below as potential difference is applied

$$NaCl \leftrightarrow Na^+ + Cl^-$$
$$H_2O \leftrightarrow H^+ + (OH)^-$$

As the potential difference is applied between the work piece (anode) and the tool (cathode), the positive ions move towards the tool and negative ions move towards the workpiece.

Thus the hydrogen ions will take away electrons from the cathode (tool) and from hydrogen gas as:

$$2H^+ + 2e^- = H_2\uparrow \text{ at cathode}$$

Similarly, the iron atoms will come out of the anode (work piece) as:

$$Fe = Fe^{++} + 2e^-$$

Within the electrolyte iron ions would combine with chloride ions to form iron chloride and similarly sodium ions would combine with hydroxyl ions to form sodium hydroxide

$$Na^+ + OH^- = NaOH$$

In practice $FeCl_2$ and $Fe(OH)_2$ would form and get precipitated in the form of sludge. In this manner it can be noted that the work piece gets gradually machined and gets precipitated as the sludge. Moreover there is not coating on the tool, only hydrogen gas evolves at the tool or cathode. Fig. 2 depicts the electro-chemical reactions schematically. As the material removal takes place due to atomic level dissociation, the machined surface is of excellent surface finish and stress free.

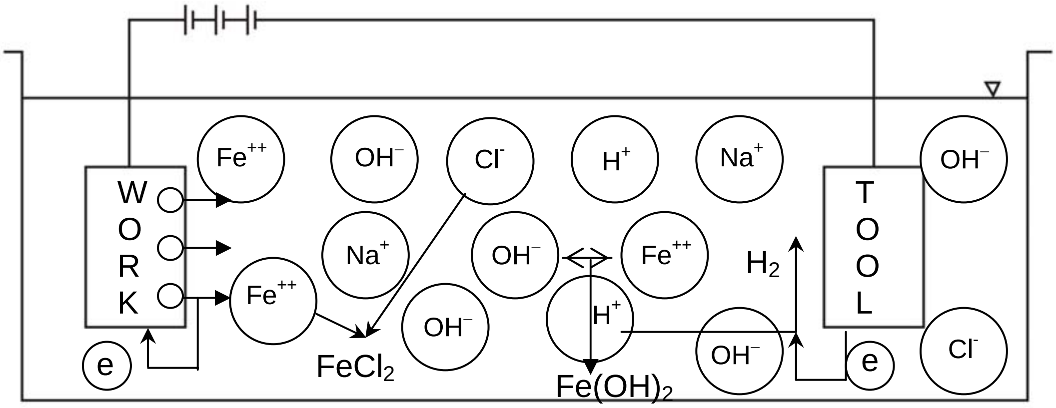


Fig. 2 *Schematic representation of electro-chemical reactions*

The voltage is required to be applied for the electrochemical reaction to proceed at a steady state. That voltage or potential difference is around 2 to 30 V. The applied potential difference, however, also overcomes the following resistances or potential drops. They are:

- The electrode potential
- The activation over potential
- Ohmic potential drop
- Concentration over potential
- Ohmic resistance of electrolyte

Fig. 3 shows the total potential drop in ECM cell.

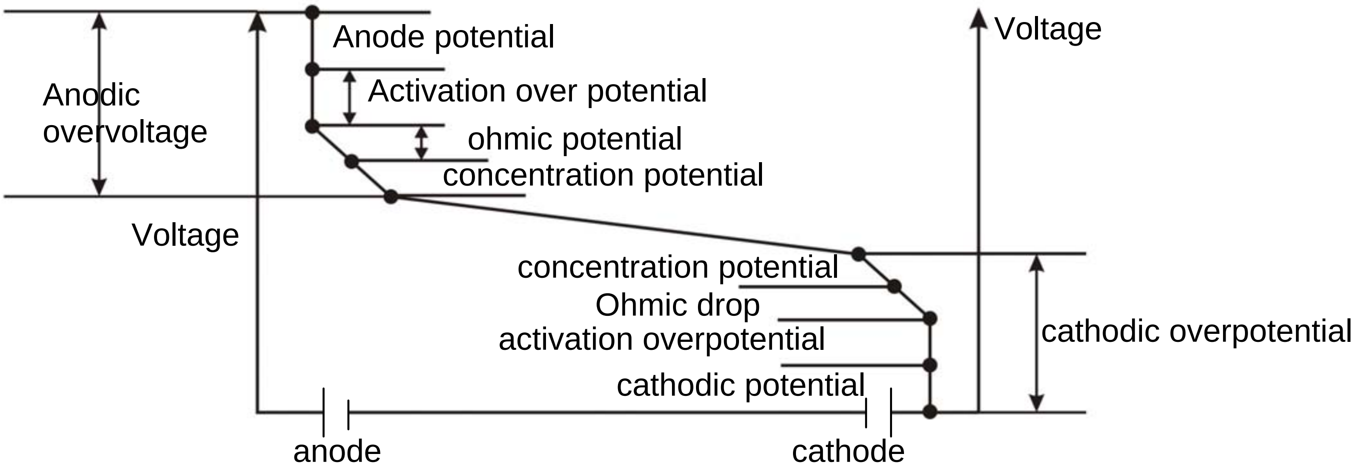


Fig. 3 *Total potential drop in ECM cell*

3. Equipment

The electrochemical machining system has the following modules:

- Power supply
- Electrolyte filtration and delivery system
- Tool feed system
- Working tank

Fig. 4 schematically shows an electrochemical drilling unit.

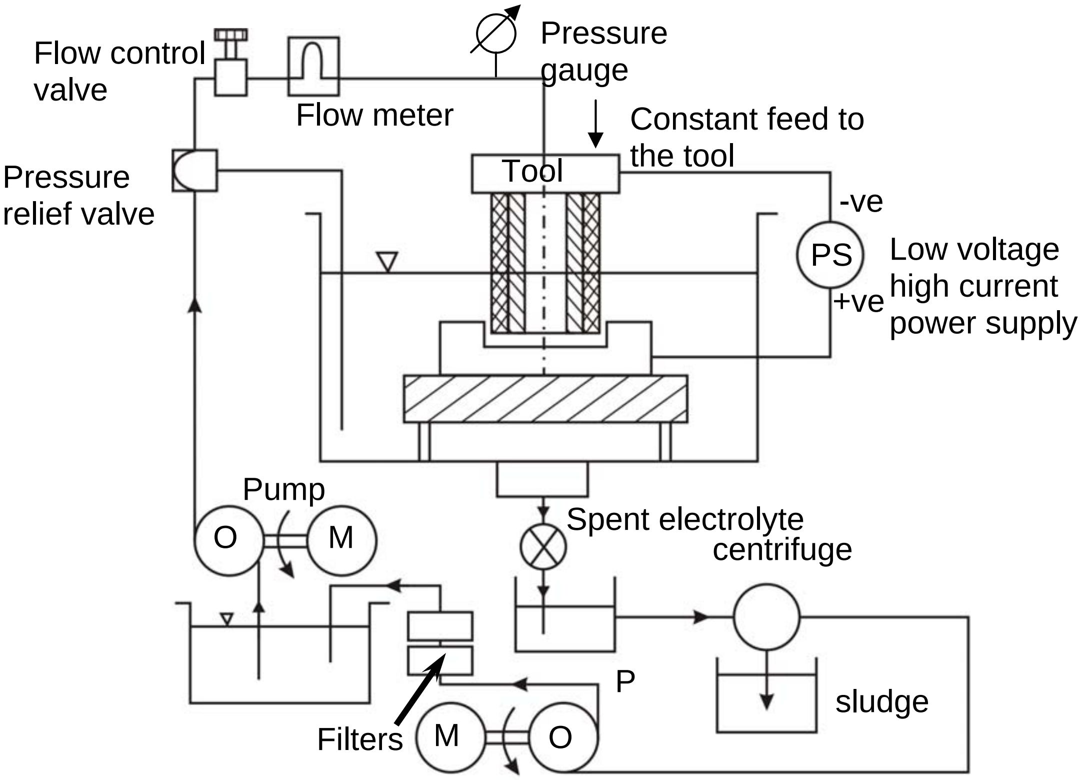


Fig. 4 *Schematic diagram of an electrochemical drilling unit*

4. Modelling of material removal rate

Material removal rate (MRR) is an important characteristic to evaluate efficiency of a non-traditional machining process.

In ECM, material removal takes place due to atomic dissolution of work material. Electrochemical dissolution is governed by Faraday's laws.

The first law states that the amount of electrochemical dissolution or deposition is proportional to amount of charge passed through the electrochemical cell, which may be expressed as:

$$m \propto Q,$$

where m = mass of material dissolved or deposited

Q = amount of charge passed

The second law states that the amount of material deposited or dissolved further depends on Electrochemical Equivalence (ECE) of the material that is again the ratio of the atomic weight and valency. Thus

$$m \,\alpha\, ECE \,\alpha\, \frac{A}{\nu}$$

Thus $m \,\alpha\, \dfrac{QA}{\nu}$

where F = Faraday's constant

= 96500 coulombs

$$\therefore \quad m = \frac{ItA}{F\nu}$$

$$\therefore \quad MRR = \frac{m}{t\rho} = \frac{IA}{F\rho\nu}$$

where I = current

ρ= density of the material

The engineering materials are quite often alloys rather than element consisting of different elements in a given proportion.

Let us assume there are 'n' elements in an alloy. The atomic weights are given as A_1, A_2, …………., A_n with valency during electrochemical dissolution as ν_1, ν_2, …………, ν_n. The weight percentages of different elements are α_1, α_2, …………., α_n (in decimal fraction)

Now for passing a current of I for a time t, the mass of material dissolved for any element 'i' is given by

$$m_i = \Gamma_a \rho \alpha_i$$

where Γ_a is the total volume of alloy dissolved. Each element present in the alloy takes a certain amount of charge to dissolve.

$$m_i = \frac{Q_i A_i}{F\nu_i}$$

$$\Rightarrow Q_i = \frac{F m_i \nu_i}{A_i}$$

$$\Rightarrow Q_i = \frac{F \Gamma_a \rho \alpha_i \nu_i}{A_i}$$

The total charge passed

$$Q_T = It = \sum Q_i$$

$$\therefore \quad Q_T = It = F\Gamma_a \rho \sum \frac{\alpha_i \nu_i}{A_i}$$

Now

$$MRR = \frac{\Gamma_a}{t} = \frac{1}{F\rho} \cdot \frac{I}{\sum \frac{\alpha_i \nu_i}{A_i}}$$

5. Dynamics of Electrochemical Machining

ECM can be undertaken without any feed to the tool or with a feed to the tool so that a steady machining gap is maintained. Let us first analyse the dynamics with NO FEED to the tool. Fig. 5 schematically shows the machining (ECM) with no feed to the tool and an instantaneous gap between the tool and workpiece of 'h'.

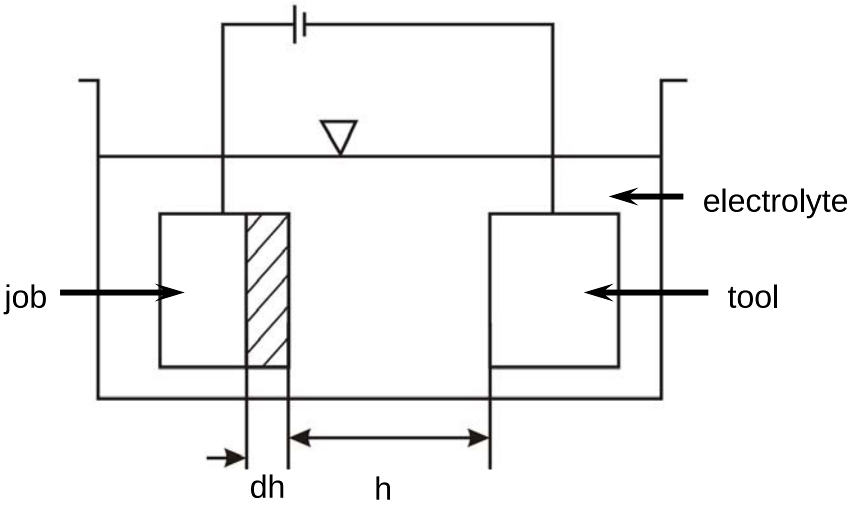


Fig. 5 *Schematic representation of the ECM process with no feed to the tool*

Now over a small time period 'dt' a current of I is passed through the electrolyte and that leads to a electrochemical dissolution of the material of amount 'dh' over an area of S

$$\therefore \quad I = \frac{V}{R} = \frac{V}{\frac{rh}{s}} = \frac{Vs}{rh}$$

then $\dfrac{dh}{dt} = \dfrac{1}{F} \cdot \dfrac{A_x}{\rho \nu_x} \left(\dfrac{Vs}{rh} \cdot \dfrac{1}{s} \right)$

$$= \frac{1}{F} \cdot \frac{A_x}{\rho \nu_x} \cdot \frac{V}{rh}$$

for a given potential difference and alloy

$$\frac{dh}{dt} = \frac{A_x V}{F \rho \nu_x r} \cdot \frac{1}{h} = \frac{c}{h}$$

where c = constant

$$= \frac{A_x V}{F \rho \nu_x r}$$

$$c = \frac{V}{F \rho r \sum \frac{\alpha_i \nu_i}{A_i}}$$

$$\therefore \quad \frac{dh}{dt} = \frac{c}{h}$$

$$hdh = cdt$$

At t = 0, $h = h_o$ and at $t = t_1$ and $h = h_1$

$$\therefore \quad \int_{h_o}^{h_1} hdh = c \int_{0}^{t} dt$$

$$\therefore \quad h_1^2 - h_o^2 = 2ct$$

That is the tool – workpiece gap under zero feed condition grows gradually following a parabolic curve as shown in Fig. 6

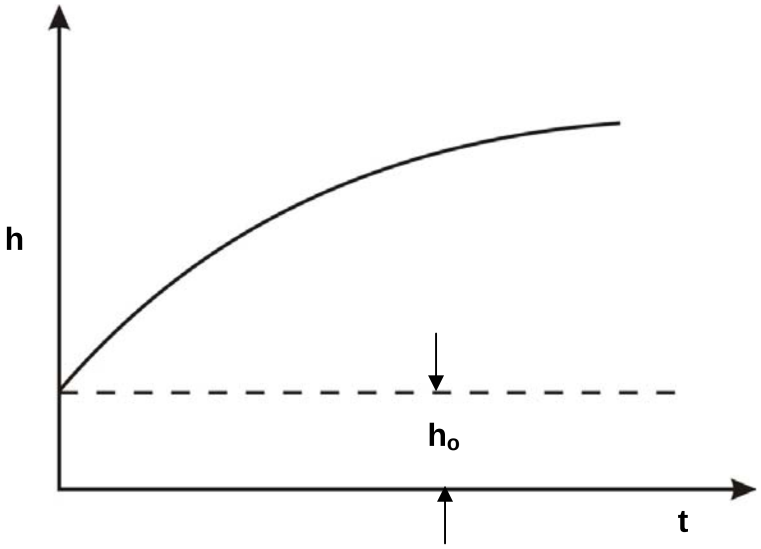


Fig. 6 Variation of tool-workpiece gap under zero feed condition

As $\frac{dh}{dt} = \frac{c}{h}$

Thus dissolution would gradually decrease with increase in gap as the potential drop across the electrolyte would increase

Now generally in ECM a feed (f) is given to the tool

$$\therefore \quad \frac{dh}{dt} = \frac{c}{h} - f$$

Now if the feed rate is high as compared to rate of dissolution, then after sometime the gap would diminish and may even lead to short circuiting. Under steady state condition the gap is uniform i.e. the approach of the tool is compensated by dissolution of the work material. Thus with respect to the tool, the workpiece is not moving

Thus $\frac{dh}{dt} = 0 = \frac{c}{h} = f$

$$\therefore \quad f = \frac{c}{h}$$

or $\quad h^*$ = steady state gap = c/f

Now under practical ECM condition it is not possible to set exactly the value of h* as the initial gap. Thus it is required to be analysed if the initial gap value would have any effect on progress of the process

Now $\quad \frac{dh}{dt} = \frac{c}{h} - f$

Now $\quad h' = \frac{h}{h^*} = \frac{hf}{c}$

And $\quad t' = \frac{ft}{h^*} = \frac{f^2 t}{c}$

$$\therefore \quad \frac{dh'}{dt'} = \frac{f/c}{f^2/c} . \frac{dh}{dt} = \frac{1}{f} . \frac{dh}{dt}$$

Thus $\frac{dh}{dt} = \frac{c}{h} - f$

$$\Rightarrow \quad f\frac{dh'}{dt'} = \frac{c}{h'h^*} - f = \frac{cf}{h'c} - f$$

$$\Rightarrow \quad f\frac{dh'}{dt'} = f\left(\frac{1-h'}{h'}\right)$$

$$\Rightarrow \quad \frac{dh'}{dt'} = \frac{1-h'}{h'}$$

$$\therefore \quad dt' = \frac{h'}{1-h'}dh'$$

Now integrating between t' = 0 to t' = t' when h' changes from h_o' to h_1'

$$\therefore \quad \int_0^{t'} dt' = \int_{h_o'}^{h_1'} \frac{h'}{1-h'}dh'$$

$$\therefore \quad t' = \int_{h_o'}^{h_1'} -\frac{d(1-h')}{(1-h')} + \int_{h_o'}^{h_1'} d(1-h')$$

$$t' = h_o' - h_1' + \ln\frac{h_o' - 1}{h_1' - 1}$$

now for different value of h_o', h_1' seems to approach 1 as shown in Fig. 7

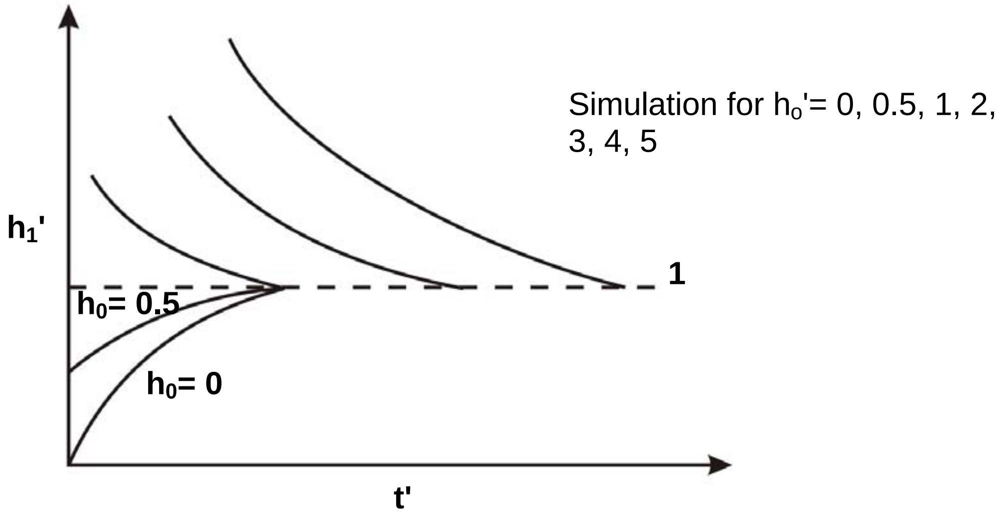


Fig. 7 *Variation in steady state gap with time for different initial gap*

Thus irrespective of initial gap

$$h' = \frac{h}{h*} = 1 \qquad \Rightarrow \frac{fh}{c} = 1$$

$$\therefore \quad h = \frac{c}{f}$$

or
$$f = \frac{c}{h} = \frac{A_x V}{F\rho \nu_x r} . \frac{1}{h}$$

$$\therefore \quad f = \frac{A_x}{F\rho \nu_x} . \frac{V}{rh} = \frac{A_x}{F\rho \nu_x} . \frac{i}{s}$$

$$\therefore \quad f = \frac{A_x}{F\rho \nu_x} . \frac{I}{s} = \text{MRR in mm/s}$$

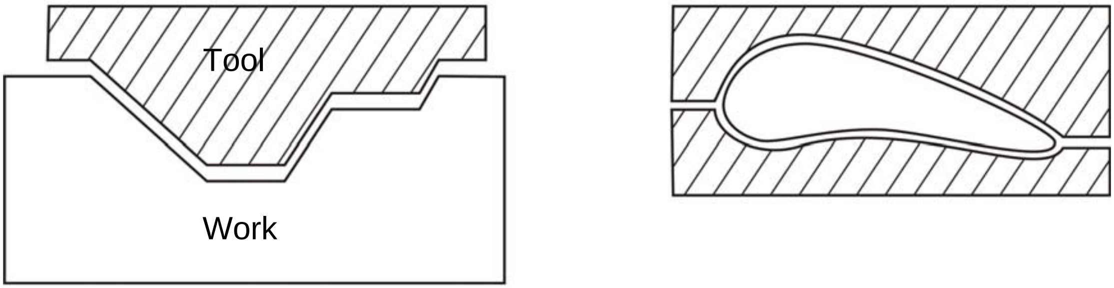
Thus it seems from the above equation that ECM is self regulating as MRR is equal to feed rate.

6. Applications

ECM technique removes material by atomic level dissolution of the same by electrochemical action. Thus the material removal rate or machining is not dependent on the mechanical or physical properties of the work material. It only depends on the atomic weight and valency of the work material and the condition that it should be electrically conductive. Thus ECM can machine any electrically conductive work material irrespective of their hardness, strength or even thermal properties. Moreover

as ECM leads to atomic level dissolution, the surface finish is excellent with almost stress free machined surface and without any thermal damage.
ECM is used for

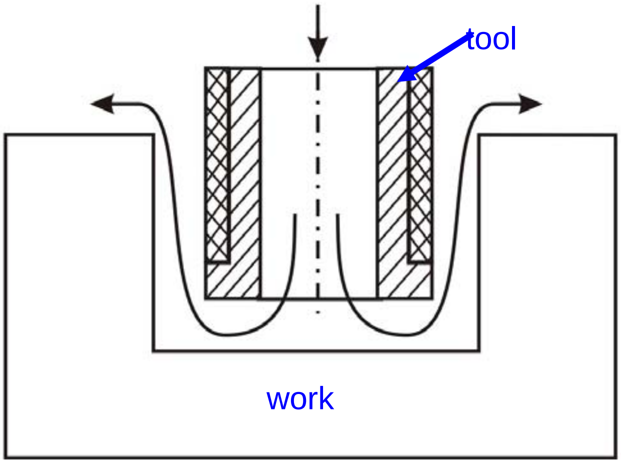
- Die sinking
- Profiling and contouring
- Trepanning
- Grinding
- Drilling
- Micro-machining



Die sinking

3D profiling

Fig. 8 *Different applications of Electro Chemical Machining*



(drilling)

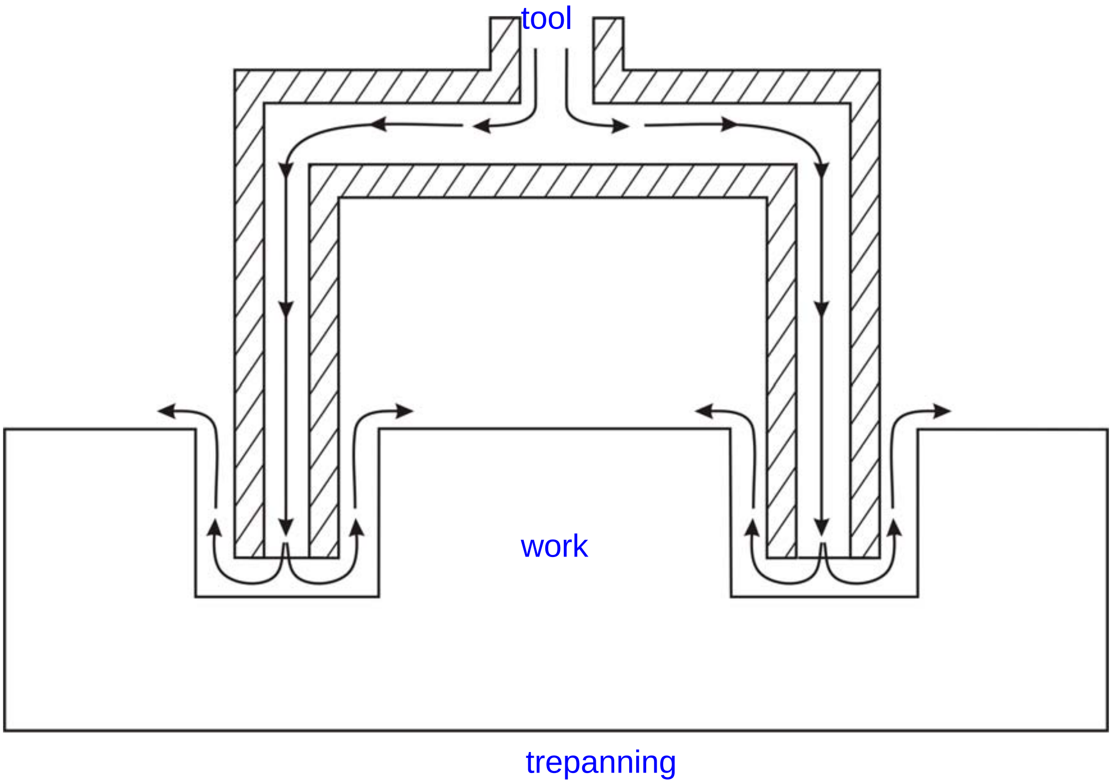


Fig. 9 *Drilling and Trepanning by ECM*

7. Process Parameters

Power Supply	
Type	direct current
Voltage	2 to 35 V
Current	50 to 40,000 A
Current density	0.1 A/mm^2 to 5 A/mm^2
Electrolyte	
Material	NaCl and $NaNO_3$
Temperature	20^{o}C – 50^{o}C
Flow rate	20 lpm per 100 A current
Pressure	0.5 to 20 bar
Dilution	100 g/l to 500 g/l
Working gap	0.1 mm to 2 mm
Overcut	0.2 mm to 3 mm
Feed rate	0.5 mm/min to 15 mm/min
Electrode material	Copper, brass, bronze
Surface roughness, R_a	0.2 to 1.5 μm

Quiz Test

1. For ECM of steel which is used as the electrolyte
    - (a) kerosene
    - (b) NaCl
    - (c) Deionised water
    - (d) HNO_3

2. MRR in ECM depends on
    - (a) Hardness of work material
    - (b) atomic weight of work material
    - (c) thermal conductivity of work material
    - (d) ductility of work material

3. ECM cannot be undertaken for
    - (a) steel
    - (b) Nickel based superalloy
    - (c) Al_2O_3
    - (d) Titanium alloy

4. Commercial ECM is carried out at a combination of
    - (a) low voltage high current
    - (b) low current low voltage
    - (c) high current high voltage
    - (d) low current low voltage

Problems

1. In electrochemical machining of pure iron a material removal rate of 600 mm^3/min is required. Estimate current requirement.
2. Composition of a Nickel superalloy is as follows:

Ni = 70.0%, Cr = 20.0%, Fe = 5.0% and rest Titanium

Calculate rate of dissolution if the area of the tool is 1500 mm^2 and a current of 2000 A is being passed through the cell. Assume dissolution to take place at lowest valency of the elements.

$A_{Ni} = 58.71$ $\rho_{Ni} = 8.9$ $\nu_{Ni} = 2$
$A_{Cr} = 51.99$ $\rho_{Cr} = 7.19$ $\nu_{Cr} = 2$
$A_{Fe} = 55.85$ $\rho_{Fe} = 7.86$ $\nu_{Fe} = 2$
$A_{Ti} = 47.9$ $\rho_{Ti} = 4.51$ $\nu_{Ti} = 3$

3. In ECM operation of pure iron an equilibrium gap of 2 mm is to be kept. Determine supply voltage, if the total overvoltage is 2.5 V. The resistivity of the electrolyte is 50 Ω-mm and the set feed rate is 0.25 mm/min.

Answers

Answers to Quiz Test

1 – (b)
2 – (b)
3 – (c)
4 – (a)

Solution to Prob. 1

$$MRR = \dot{m} = \frac{m}{t} = \frac{AI}{F\nu}$$

$$\therefore \quad MRR = \dot{\Gamma} = \frac{m}{\rho t} = \frac{AI}{F\rho\nu}$$

MRR = 600 mm^3/min = 600/60 mm^3/s = 10 mm^3/s = $10x10^{-3}$cc/s

$$\therefore \quad 10x10^{-3} = \frac{56xI}{96500x7.8x2}$$

As A_{Fe} = 56
ν_{Fe} = 2
F = 96500 coulomb
ρ = 7.8 gm/cc

$$\therefore \quad I = \frac{96500x10x10^{-3}x7.8x2}{56}$$

I = 268.8 A **Answer**

Solution of Problem 2

$$\text{Now,} \quad \rho_{alloy} = \frac{1}{\sum \frac{\alpha_i}{\rho_i}}$$

$$= \frac{1}{\frac{\alpha_{Ni}}{\rho_{Ni}} + \frac{\alpha_{Cr}}{\rho_{Cr}} + \frac{\alpha_{Fe}}{\rho_{Fe}} + \frac{\alpha_{Ti}}{\rho_{Ti}}}$$

$$= \frac{1}{\frac{0.7}{8.9} + \frac{0.2}{7.19} + \frac{0.05}{7.86} + \frac{0.05}{4.51}} = 8.07\ gm/cc$$

$$\text{Now} \quad MRR = \frac{m}{\rho t} = \frac{I}{F\rho \sum \frac{\alpha_i \nu_i}{A_i}}$$

$$= \frac{1000}{96500x8.07x\left\{\frac{0.75x2}{58.71} + \frac{0.2x2}{51.99} + \frac{0.05x2}{55.85} + \frac{0.05x3}{47.9}\right\}}$$

= 0.0356 cc/sec
= 2.14 cc/min
= 2140 mm^3/min

$$\therefore \text{Rate of dissolution} = \frac{\text{MRR}}{\text{Area}} = \frac{2140}{1500} = 1.43\ \text{mm/min}$$ **answer**

Solution to Prob. 3

$$h^* = \frac{c}{f}$$

where $c = \dfrac{VA_{Fe}}{F\rho_{Fe} r \nu_{Fe}}$

$$C = \frac{(V-2.5)x55.85}{96500x7.8x10^{-3}x50x2}$$

$$= \frac{(V-2.5)}{1347.7}$$

$$h^* = 2 = \frac{c}{f} = \frac{(V-2.5)}{1347x\dfrac{0.25}{60}}$$

$$2 = \frac{V-2.5}{5.615}$$

$\therefore \quad V = 8.73$ Volt. **Answer**